Derivation of A First Order Approximation of Particulate Matter From Aircraft

Paper # 69970

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ABSTRACT

The mass of particulate matter (PM) emitted from aircraft must be predicted for major actions at airports to comply with current federal regulations. However, this PM mass in the jet exhaust has not been effectively quantified to permit accurate emission factors to be developed. Certification methodologies are based on the Smoke Number (SN), which was essentially implemented to eliminate the visible exhaust of aircraft but does not provide needed mass emission factors. A literature review was conducted for the FAA, and based on available data and findings developed a first order approximation (FOA) method. This derived methodology had to have the flexibility to permit differences in fleet mix, aircraft modes (throttle settings), and airport altitudes to be considered. The accuracy of each possible method and the availability of data also were heavily weighed when considering this approximation method. The development of this methodology and preliminary evaluation are presented in this paper.

INTRODUCTION

In support of the Federal Aviation Administration's (FAA) Office of Environment and Energy, a document has been completed on Particulate Matter (PM) emissions from jet engines; **A Review Of Literature on Particulate Matter Emissions from Aircraft** (Wayson, 2003). This document contains both a literature review and, based on the findings of this literature review, a First-Order Approximation (FOA) to predict the emission rate of particulate matter by mode and jet engine model. This FOA is intended for use until such time when enough measurement data is available that the FOA is no longer needed.

LITERATURE REVIEW

The literature review was undertaken to evaluate the archival information available on PM emissions from jet engines in order to establish what is in the general body of knowledge. Over 100 documents were carefully read and sorted according to the pertinence of the information. In the case of multiple reportings of the same data or collected information, an attempt was made either to include the original document or the most comprehensive document. Documents that were considered repetitive or did not add new information were not used in the literature review. A total of 37 documents were identified as key documents and included in the literature review. This permitted the following findings to be made:

- Small PM may be a health concern.
- It is a good approximation that all PM emitted by modern transport aircraft has an aerodynamic diameter of less than 2.5 micrometers. This is an important concern and controlled by the EPA health-based standards for $PM_{2.5}$ as well as PM_{10} .
- The EPA PM standards are massed based (mass/volume of air) at receptor locations. However, the engine certification process does not require the measurement and reporting of the PM mass data. A smoke number is determined during the certification process. The International Civil Aviation Organization (ICAO) has promulgated the most complete aircraft engine emission database includes the measured smoke number and fuel flow rates by engine mode. Studies show that there is a correlation between the reported smoke number and mass emissions.
- There is a lack of measured data to assist in the analysis to determine if an airport is in compliance with the EPA standards.
- PM are irregular in shape and often coagulate. This coagulation process results in different PM characteristics for different age plumes. This leads to a bi-modal distribution. A lognormal distribution is still appropriate for the soot component (non-volatile PM primarily containing carbon).

- PM include both volatile and non-volatile components. Soot is the most prevalent, non-volatile component. Metals are emitted, but in extremely small amounts.
- Effects on PM emission indices include fuel flow, engine design / operating conditions, altitude, and fuel composition.
- Efforts to predict emission indices, or more specific emission factors, may be characterized into four groups: simple factor, compound factor, grab samples or nearby measurements, and measurement based factors.

The four broad categories of PM estimation methodologies that have been commonly used at airports are directly related to this paper and are discussed here. These are:

- *Simple Factor* multiplied by the number of Landing/TakeOffs (LTOs.)
- The rate of fuel flow multiplied by a *Compound Factor* that includes such variables as the ratio of smoke number (aircraft SN of concern compared to an aircraft SN with a known mass emission rate), mass measurements (when available), thrust, operating pressures and/or temperatures, and other engine parameters.
- *Grab Samples and/or Nearby Deposition* to estimate specific emission rates for aircraft types or facilities and use of rollback models for future estimates.
- Use of actual *Measured Mass* test results (i.e., USEPA Method 5).

The best method at this time, based on available data, was determined to be a variation of the Compound Factor method, validated with measured data. This selection was based on several key considerations. The considerations included:

- The Airport modeling community needs to account for changes in fleet mix and aircraft modes (related to throttle settings). The simple approximation method and the grab-sample / deposition methods do not permit this flexibility. Accordingly, these methods do not meet current requirements and were not considered further.
- The accuracy of each possible method and the availability of data also were heavily weighed when considering this approximation method. It is a foregone conclusion that measured data would be more accurate than estimation techniques. However, insufficient information now exists and additional information development is not expected in the near future to support an entirely new measurement methodology.
- The only comprehensive database now available is the ICAO listing of smoke numbers, which have been shown to correlate to mass emissions.
- The compound factor approach has been used by the airport modeling community and could provide the short-term, first-order approximation that is needed. The largest source of uncertainty in this method is correlation between mass emissions and smoke number. To help reduce the potential error due to the uncertainty of the correlation, the compound factor method uses an adaptation of methodologies that have been derived

based on the limited amount of existing measured data which correlate mass and smoke number. The suggested methodology is a combination of the methodologies put forward by the University of Missouri-Rolla (UMR) and the Deutsches Zentrum fur Luft-und Raumfahrt (DLR). This combined method should allow a more reasonable emission index for PM to be derived for use in the compound factor method.

The largest source of uncertainty in this method is a correlation between mass emissions and smoke number. To help reduce this source of error, validation using the limited data available must be done.

FIRST ORDER APPROXIMATON

The literature review also presented sufficient information to allow a first order approximation method for PM to be suggested for commercial transport operations. It should be remembered that this method is approximate and is only to be considered an interim approach until measured, statistically valid data are available.

The suggested methodology is a combination of the methodologies put forward by UMR and DLR (Dopelheuer, 1997, 1999, 2000; Hagen, 1992, 1996, 1998; Petzold, 1998, 1999; Whitefield, 2001). These reliable researchers have both presented data in a way that is directly useable in a compound factor method. This combined method should allow a more reasonable emission index for PM to be derived for use in the compound factor method.

Consider a compound factor in the general format as shown in Equation 1:

$$EI_i = (SN_i / SN_{ref})(EI_{ref}) \qquad [1]$$

Where:
EI_i = Corrected Emission Index in terms of fuel flow for any aircraft type, i
SN_i = smoke number from ICAO data base for specific aircraft
SN_{ref} = smoke number from a reference aircraft in the ICAO data base
EI_{ref} = known emission Index for reference aircraft

This basic methodology allows an emission index, such as grams of pollutants per kilogram of fuel burn, to be determined beginning with a known, reference emission index, and then corrected by changing smoke numbers (SN). The underlying assumption is that the change in mass emissions is correlated to the change in SN.

However, reference data exist for very few engines. Expanding the previous assumption, curve-fitting techniques from the limited amount of existing measured data could be used to estimate the reference Emission Index (EI) or as done here, the Emission Rate (ER). The work of Champagne (Champagne, 1971) showed a non-linear relationship for the SN to mass concentration for a limited number of engine types. This method was further developed by DLR using the data of Whyte and Hurley to adjust the original curve presented by Champagne. UMR put forward the idea that the overall index could be related to fuel flow. UMR provided further insight by suggesting that only a few categories of aircraft were needed since so many airframes use common engines. This suggests a bias in the fleet toward these engines.

If we combine these ideas, and the measured data available, a curve such as that developed by DLR can be derived, but with the additional step of relating to fuel flow as done by UMR. In other words, a specific emission index or rate could be derived that would be both aircraft specific from the individual smoke numbers and related to fuel flow in the ICAO database. Practitioners needing to predict how mass emissions would be affected by changes in fleet, operations, airfield design, etc. could easily do so by using values available in the ICAO data base for the SN, as well as fuel flow, and when available, mode. This would allow the flexibility needed to determine significant changes in the mass emissions of particulate matter. As such, the objectives of the first order approximation would meet immediate needs.

DERIVED METHODOLOGY

The data of Champagne [Champagne, 1971], Whyte [Whyte, 1982] and Hurley [Hurley, 1993] (as reported by DLR) were used to determine the correlation between smoke number and mass emission. Figure 1 shows this correlation graphically.

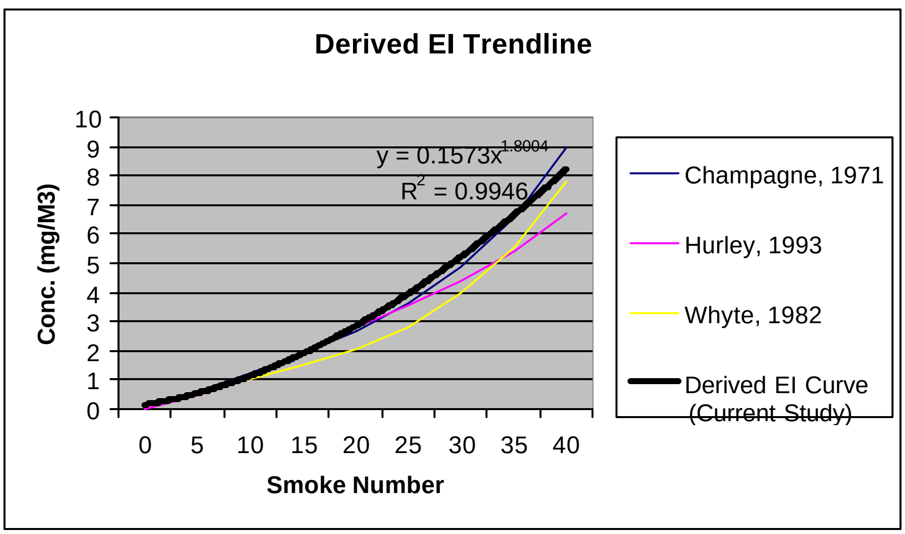

Figure 1. Derived Trend Line

If these data are assumed to be representative of commercial aircraft operations, then a derived trend can be determined as also shown in Figure 1. It should be noted that the trend line was purposely derived to provide an upper limit to the presented data and as such is considered conservative. As shown in the figure when a power law equation is used, an extremely good fit to the data can be determined. By use of the reported ICAO smoke numbers by mode, modal emissions are considered. Then, to relate to fuel flow, one more step is needed.

In the next step, we assume the reported results to be at standard conditions and that the burn conditions are stoichiometric. Based on these considerations, the resulting equation (Equation 2) for predicting the mass of PM for commercial aircraft as follows:

$$ER_{j\text{Mass of PM}} = 0.6\,(SN)^{1.8}\,(FF) \qquad [2]$$

Where:

$ER_{j\text{Mass of PM}}$ = emission rate: mg of PM emitted per second per engine type j
SN = the ICAO reported smoke number
FF = the ICAO reported fuel flow by mode in kilograms/sec

The product of the emission index presented and the time-in-mode would result in a mass based approximation and follow the general method used for other pollutants in the ICAO database. With the derived, aircraft-specific emission factor, the total mass for emission inventories would be derived as:

$$M_{total} = \Sigma_i \Sigma_j (ER_{j\text{Mass of PM}})(N_i)(N_{ei})(t_{\text{mode } i}) \qquad [3]$$

Where:

M_{total} = total mass emitted in mg
N_i = the number of aircraft evaluated
N_{ei} = the number of engines per aircraft type i
$t_{\text{mode } i =}$ the time-in-mode for each aircraft type i

It must be remembered that this model represents a first-order approximation. Small particles are not well represented by the smoke number, the combustion process varies by engine design, and the fuel-to-air ratio will change with each mode. Continual improvements need to be made to this method. Regardless of these limitations, the derived mass-based factor should be more accurate than those that have been used in the past.

It was important to next perform statistical testing (verification) of the FOA to determine the accuracy and uncertainty associated with this approximate method. This task was quite substantial. To complete this work, measurement data was needed that was not used in the model formulation. As such, all work by Champagne, Hurley and Whyte could not be used. This was a difficult task since measured data are very sparse. The known data from the literature review was compiled into a spreadsheet. Additional data was also added to this spreadsheet by searching additional literature, telephone calls, and direct conversations with individuals.

Measured mass data points were identified to compare to the FOA. Requirements to allow a comparison included that the engine type be listed in the ICAO database, that one or more of the four engine modes (idle/taxi, approach, take-off, climbout) used in the vicinity of airports were measured, and that the engine was still used in the overall fleet. This allowed 14 data points to be used for comparison. This comparison is shown in Figure 2.

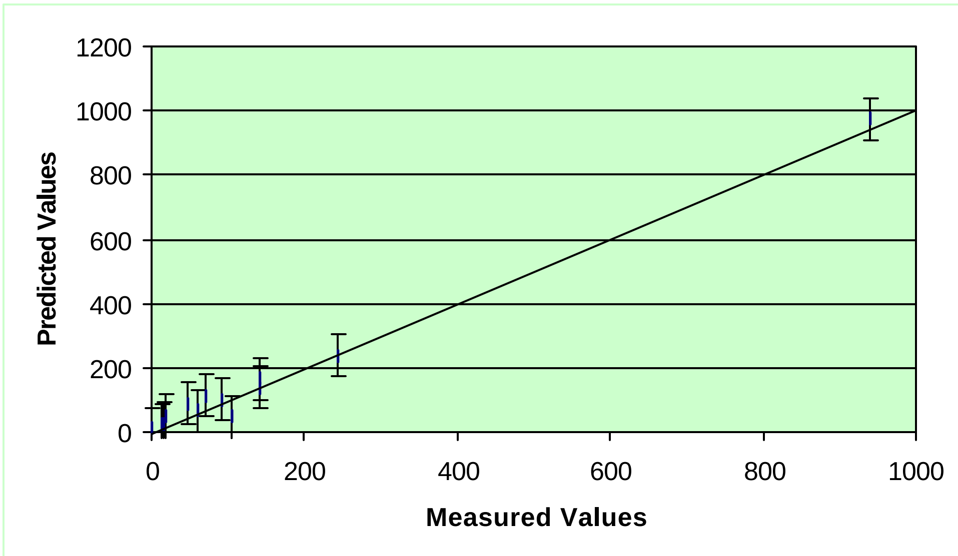

Figure 2. Agreement of FOA and Measured Data Points (Units = mg/s)

It can be seen in Figure 2 that the agreement would seem to be quite acceptable for this FOA. However, the researchers are still exploring to try and find additional data points for comparison to the FOA To this end, researchers that are conducting mass emission measurements from aircraft have been contacted.

The statistical analysis performed to date includes: regression analysis, determination of standard error and standard deviation, and absolute error analysis.

Possible variables that can be included in future versions of the FOA include the air/fuel ratio, sulfur content of the fuel, additives in the fuel, and elevation corrections. As more measured mass data also become available further verification and possible changes in the FOA may also occur. Also begun is exploration into the relative components and mass of volatile emissions.

In the longer term, as more measured data become available the model could be further refined and possibly divided into additional aircraft categories, based on engine design. The scarcity and inconsistency of existing data does not support refinement by specific engine type at this time.

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