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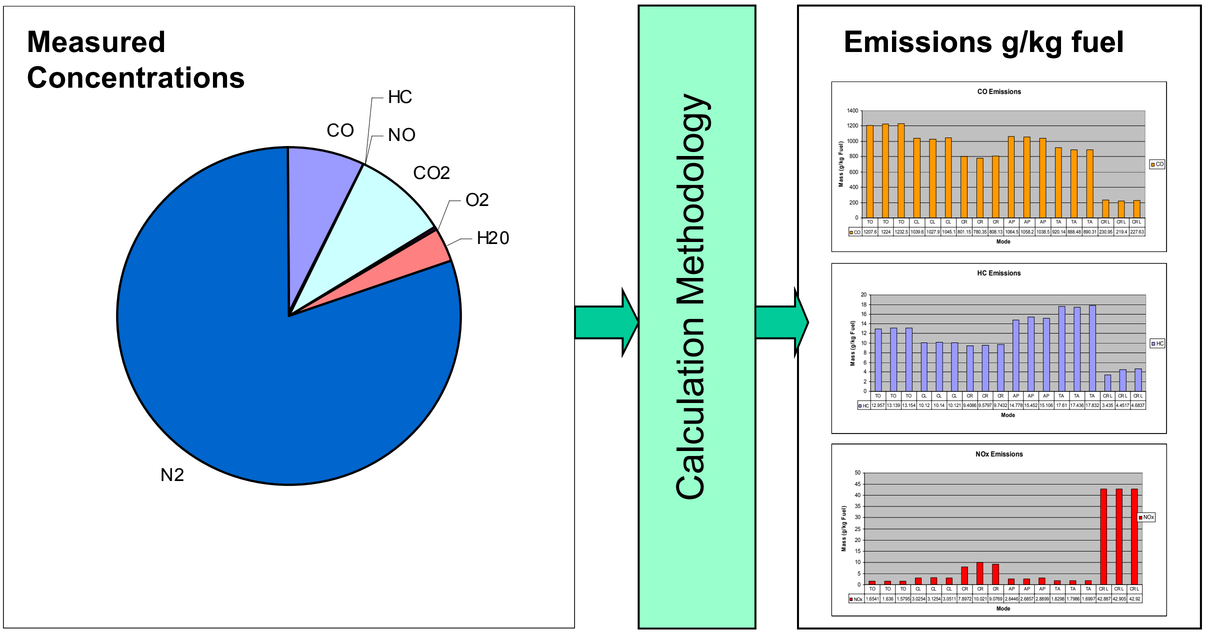
AIRCRAFT PISTON ENGINE EMISSIONS

Appendix 5: Calculation of Emission Factors



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Contents

a) Introduction

Measured concentrations are converted to emission factors (EF) on the basis of molar masses. The fuel flow measurement is necessary for power setting checks (Appendix 3) and to calculate LTO emissions.
The basic calculation is taken from „Advisory Circular“ AC34-1A of the Federal Aviation Administration (FAA). If a low cost gas measurement system is used, as described in appendix 1, some corrections (section d) and the use of equation (5) for the calculation of air/fuel ratio to stoichiometric air/fuel ratio are suggested.

b) List of abbreviations

M_{Air}	Molar mass of dry air	28.966 g/mol
M_{HC}	Molar mass of exhaust-HC, as Methane CH_4	16.040 g/mol
M_{CO}	Molar mass of CO	28.011 g/mol
M_{NO2}	Molar mass of NO_2	46.088 g/mol
M_{NO}	Molar mass of NO	30.010 g/mol
M_{NOx}	Molar mass of NOx, 15% NO_2, 85% NO	32.412 g/mol
M_C	Molar mass of carbon C	12.011 g/mol
M_H	Molar mass of hydrogen H	1.008 g/mol
V_{CO2}	Volume fraction of CO_2 in dry air	0.0003
[HC]	Mean concentration of exhaust-HC	vol/vol
[CO]	Mean concentration of CO	vol/vol wet
[CO_2]	Mean concentration of CO_2	vol/vol wet
[NOx]	Mean concentration of NOx (NO+NO_2)	vol/vol wet [NOx] = 1.18 [NO] [1]
m	Number of C atoms in char. fuel molecule	7 (AVGAS / MOGAS), 12 (JET A1)
n	Number of H atoms in char. fuel molecule	13 (AVGAS / MOGAS), 23 (JET A1)

c) Calculation of EF (Equations used for FOCA ground measurements and data sheets)

$$EF(CO) = \left(\frac{[CO]}{[CO_2]+[CO]+[HC]} \right) \left(\frac{10^3 M_{CO}}{M_C + (n/m) M_H} \right) \left(1 + A \cdot V_{CO2}\right) \qquad (1)$$

$$EF(HC) = \left(\frac{[HC]}{[CO_2]+[CO]+[HC]} \right) \left(\frac{10^3 M_{HC}}{M_C + (n/m) M_H} \right) \left(1 + A \cdot V_{CO2}\right) \qquad (2)$$

$$EF(NOx) = \left(\frac{[NO] \cdot 1.18}{[CO_2]+[CO]+[HC]} \right) \left(\frac{10^3 M_{NOx}}{M_C + (n/m) M_H} \right) \left(1 + A \cdot V_{CO2}\right) \qquad (3)$$

where

$$A = \frac{\lambda \left(M_C + (n/m) M_H\right)}{M_{Air}} \qquad (4)$$

and λ with equation (5) or directly calculated by system.

The calculation of λ (Lambda) is done with the following approximation (5) where CO2, O2 und CO are measured concentrations in volume% and ***HC6NDIR*** **the NDIR HC reading in Hexane ppm.**

[1] Conservative assumption FOCA / DLR

$$\lambda = \frac{CO2 + \frac{CO}{2} + O2 + \left\{ \frac{1.7261}{4} \cdot \frac{3.5}{3.5 + \frac{CO}{CO2}} - 0.0088 \right\} \cdot (CO2 + CO)}{\left(1 + \frac{1.7261}{4} - 0.0088\right) \cdot (CO2 + CO + HC6NDIR \cdot 6 \cdot 10^{-4})} \qquad (5)$$

General definition of λ (Lambda):

$$\lambda = \frac{Airmass : Fuelmass \quad (measured)}{Airmass : Fuelmass \quad (stoichiometric)}$$

$$\lambda > 1 : lean \qquad \lambda < 1 : rich$$

d) Equations for "low cost" measurement system described in Appendix 1 for AVGAS/MOGAS engines (used for FOCA in-flight measurements and comparative ground measurements)

EF(HC)

Many NDIR HC analyzers (like the one that FOCA uses for in-flight tests) read HC concentrations in hexane equivalents. Please note that in the standard calculation formulas for EF(CO), (HC) and (NOx) above, the HC concentrations have to be methane based. Parallel measurements with a hot FID HC analyzer have shown that correction factors for the NDIR HC values can be derived. The HC correction factor counts for hexane to methane conversion and for partial to total HC measurement. Because of fuel, engine and power dependent HC composition, the factor is not a constant:

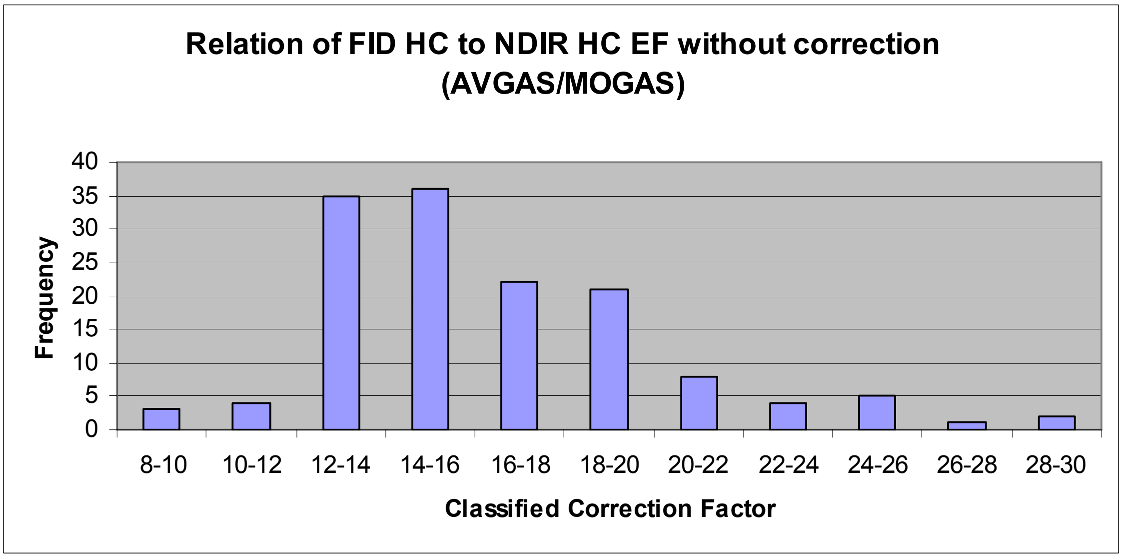

Figure 1: Distribution of the HC correction factor, based on 141 measurements with 8 different engines and all power modes. The derived mean correction factor for EF(HC) is **16.3.** Depending on the engine, the engine power condition and the fuel, the error band of the NDIR HC measurement compared to the total HC measurement with FID will be +- 25%.

The magnitude of possible errors in EF(HC), when using NDIR HC measurement systems can be considered acceptable for the purpose of emission inventories, but it is significant. Therefore, FOCA uses an additional hot FID for all ground measurements and FOCA engine datasheets are all based on hot FID measurements where no estimations and HC correction factors are necessary.

EF(CO)

The effect on EF(CO) when using NDIR HC values instead of FID HC values is small. On the basis of 90 measurements with 5 different engines, the resulting correction factor is **0.9839**. When using this correction and NDIR HC values, the error band is +- 1% compared to FID HC.

EF(NOx)

The effect on EF(NOx) when using NDIR HC values instead of FID HC values is small. On the basis of 90 measurements with 5 different engines, the correction factor is **0.9839**, equal to E(CO) correction. The error band - when using this correction and NDIR HC values - is +- 1% compared to FID HC. The electrochemical NOx sensor which is used in the FOCA low cost measurement system (Appendix 1) is in fact a NO sensor and does not account for NO2. After comparative measurements the correction factor for NO to NOx conversion was set to **1.18** together with an assumption for M_{NOx} (as defined in section b). The possible error band is assumed +- 10%.

Equations:

$$EF(CO) = 0.9839 \cdot \left(\frac{[CO]}{[CO_2]+[CO]+[HC6NDIR]} \right) \left(\frac{10^3 M_{CO}}{M_C + (n/m) M_H} \right) (1 + A \cdot V_{CO2}) \qquad (6)$$

$$EF(HC) = 16.3 \cdot \left(\frac{[HC6NDIR]}{[CO_2]+[CO]+[HC6NDIR]} \right) \left(\frac{10^3 M_{HC}}{M_C + (n/m) M_H} \right) (1 + A \cdot V_{CO2}) \qquad (7)$$

$$EF(NOx) = 0.9839 \cdot \left(\frac{[NO] \cdot 1.18}{[CO_2]+[CO]+[HC6NDIR]} \right) \left(\frac{10^3 M_{NOx}}{M_C + (n/m) M_H} \right) (1 + A \cdot V_{CO2}) \qquad (8)$$

used together with equations (4) and (5).

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e) Equations for "low cost" measurement system described in Appendix 1 for DIESEL engines

Similarly to what has been said in section d), correction factors for HC have been derived for diesel engines:

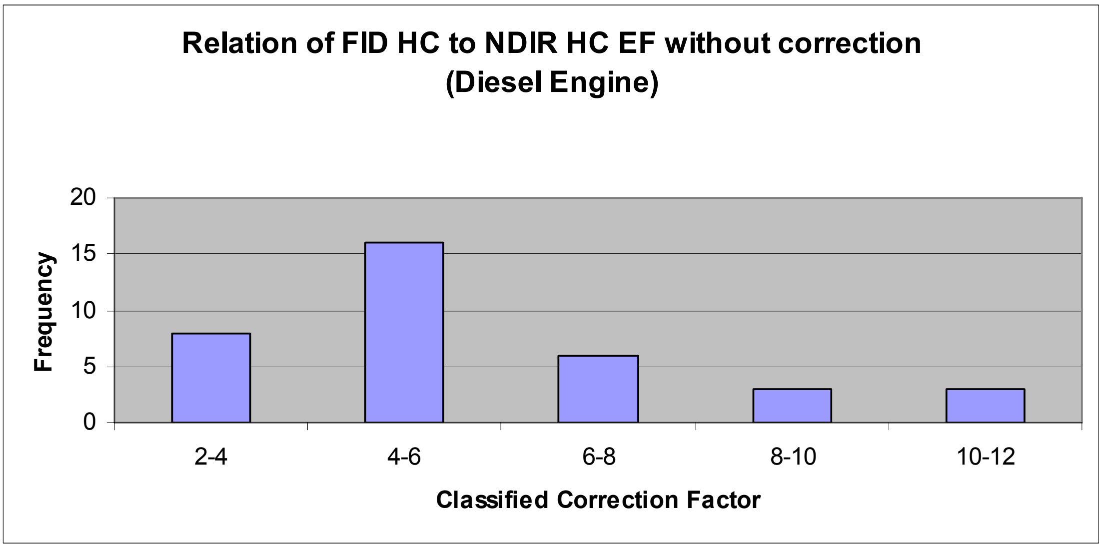

Figure 2: Distribution of the HC correction factor, based on 36 measurements with 2 different engines and all power modes. The derived mean correction factor for EI(HC) is **5.8.** Depending on the engine, the engine power condition and the fuel, the error band of the NDIR HC measurement compared to the total HC measurement with FID can be +- 40%.

EF(CO)

The effect on EI(CO) when using NDIR HC values instead of FID HC values is very small. On the basis of 36 measurements with 2 different engines, the correction factor is **0.9976**. When using this correction and NDIR HC values the error band is +- 0.3% compared to FID HC.

EF(NOx)

The effect on EI(NOx) when using NDIR HC values instead of FID HC values is small. On the basis of 36 measurements with 2 different engines, the correction factor is **0.9976**, equal to EI(CO) correction. When using this correction and NDIR HC values the error band is +- 0.3% compared to FID HC.
The electrochemical NOx sensor which is used in the FOCA low cost measurement system (Appendix 1) is in fact a NO sensor and does not account for NO2. After comparative measurements the correction factor for NO to NOx conversion was set to **1.18** together with an assumption for M_{NOx} (as defined in section b). The possible error band is assumed +- 10%.

Equations (next page):

$$EF(CO) = 0.9976 \cdot \left(\frac{[CO]}{[CO_2] + [CO] + [HC6NDIR]} \right) \left(\frac{10^3 M_{CO}}{M_C + (n/m) M_H} \right) (1 + A \cdot V_{CO2}) \qquad (9)$$

$$EF(HC) = 5.8 \cdot \left(\frac{[HC6NDIR]}{[CO_2] + [CO] + [HC6NDIR]} \right) \left(\frac{10^3 M_{HC}}{M_C + (n/m) M_H} \right) (1 + A \cdot V_{CO2}) \qquad (10)$$

$$EF(NOx) = 0.9976 \cdot \left(\frac{[NO] \cdot 1.18}{[CO_2] + [CO] + [HC6NDIR]} \right) \left(\frac{10^3 M_{NOx}}{M_C + (n/m) M_H} \right) (1 + A \cdot V_{CO2}) \qquad (11)$$

used together with equations (4) and (5).

f) Correction of ambient air temperature influence on normally aspirated piston engines

HC and CO emission factors for normally aspirated piston engines have been shown to be significantly temperature dependent, mainly because of air density variations and its influence on the air/fuel mixture. To correct the emission factors to 15°C, the following equations are suggested:

CO Measurement :EF CO(15°C) = 3.1259*(15 - T) + EF CO(T) (12)
HC Measurement: EF HC(15°C) = 0.0164*(15 - T) + EF HC(T) (13)

Ambient air humidity primarily seems to have an effect on NOx emissions. However, these emissions are very low at “full rich” conditions and therefore no significant correction could be established.

g) Statistical checks

For each engine and power mode, a minimum of three valid measurements has been defined. The confidence interval (90% Conf. Level) is determined with a T-Test and assumed normal distributed values.

h) Fuel flow

The fuel flow is normally measured in liters/hour or US gallons/hour. The standard calculation of the fuel flow in kg/s is done with a mean fuel density of 0.72 kg / liter for AVGAS/MOGAS and of 0.80 kg / liter for DIESEL/JETA1.