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AIRCRAFT PISTON ENGINE EMISSIONS

Appendix 3: Power Settings and Procedures for Static Ground Measurements

Picture 1: Ground measurement (HB-KIA)

FOCA, CH-3003 Bern

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Contents

1. The problem of piston engine power definitions

The term „horse power“ is not very well defined. Generally, quite a variety of definitions and measurement methodologies are used which cause (at least) slight variations in the final numbers. As far as aircraft piston engines and propeller aircraft are concerned, the following terms could be identified:

- **Brake horsepower** (BHP): Strictly speaking, BHP is the measure of an engine's horsepower without the loss in power caused by the gearbox, generator, water pump and other auxiliaries. The prefix "brake" refers to where the power is measured: at the engine's output shaft, as on an engine dynamometer. In aircraft piston engine manuals, power is often given in brake horsepower.

- **Propeller horsepower**: The horsepower that is delivered to the propeller. Most of the tested aircraft piston engines do not have a reduction gear or other auxiliaries that might cause a significant loss of power through e.g. friction. Therefore, propeller horsepower is considered very near brake horse power under these circumstances.

- **Rated horsepower**: The normal maximum allowable power output of the aircraft piston engine. In power charts of aircraft piston engine manuals, this number is often equal to maximum brake horse power.

2. Theoretical power calculation (scientific SI-system[1])

The power (*P*) which is delivered to the propeller is calculated by multiplying the torque (*M*) by the angular velocity (ω) of the propeller shaft.

$$P = M \cdot \omega \qquad (1)$$

Angular velocity and RPM (n) have the following relationship:

$$\omega = 2\pi \cdot n \qquad (2)$$

where n is the number of revolutions per second.

Equation (2) in (1):

$$P = M \cdot 2\pi \cdot n \qquad (3)$$

At 2400 RPM (= 40.00 per second) and a torque of 400 Newtonmeter, the power equals about 100 Kilowatt (around 135 HP, depending on the definition).

This simple example shows that when knowing RPM and torque at the propeller shaft, engine propeller power is defined and can be determined exactly. Piston engine aircraft cockpits give information about engine RPM but do not usually have a torque indicator. It would have been very costly to install a torque meter between engine shaft and propeller and to make this design airworthy for the in-flight tests. So, this straightforward way of determining propeller power for the emission measurements could not be followed.

3. Engine manifold pressure (MAP) and RPM for power determination

MAP indicates the absolute pressure of the air/fuel mixture between the throttle and the cylinder inlet valve. The measuring gauge has a sealed capsule and a capsule that is exposed to manifold pressure. It is normally calibrated to inches of mercury, where 29.92 In Hg is the standard pressure. At full throttle, and in the case of a normally aspirated engine, the MAP will indicate nearly the value of the absolute pressure of the ambient air. For such engines, at full throttle, MAP is always a little bit lower

[1] SI = système international, kg, meter, second,…

than ambient air pressure due to losses in the induction system. If the throttle is reduced, the MAP decreases. If the engine has stopped, the MAP shows ambient absolute air pressure. A turbocharged engine achieves MAP above ambient pressure.

BHP (and propeller horsepower as described in a)) are almost directly related to MAP and engine RPM. The power output from a piston engine depends on both, engine RPM and the difference in pressure between the inside of the cylinders and the atmosphere outside the engine.

But one has to be careful: When climbing at constant MAP and RPM, since the pressure in the manifold is constant, the reduction in ambient temperature increases the density of air in the manifold, resulting in a gradual increase in power. Constant MAP is maintained by opening the throttle during climb until the throttle is fully open. In other words: 23 In Hg is more power at 10 000 feet than it is at sea level. This has to be taken into account for ground measurement power settings, if they are based on MAP.

4. Correlation of fuel flow and propeller power

First of all, it must be noted, that for a given thrust, the fuel flow is NOT constant. The problem with piston engine thrust is that we get less thrust for the same fuel flow, as velocity is increased. (This is completely different from what happens in a jet). But:

Piston engine fuel flow is constant for a given amount of power. This was the starting point to look for the correlation between fuel flow and propeller power.

Table 1: Determination of propeller horsepower with HBEYS. Example sheet (source: “In flight Abgasmessung BAZL/CCUW”, R = rich, L = lean, FT = full throttle)

Aircraft	HBEYS (DR400-180R)
Engine	O-360-A3A
Propeller	Sensenich 76EM8S5-0-58
Silencer	Gomolzig
Fuel	AVGAS100LL
Measurement System	Stargas 898

Flights from 30.04.03, 13.08.03 and 21.08.03:

Flight Altitude QNH (ft)	Date	Nr.	Ambient Air Pressure (hPa)	Pressure Altitude (ft)	Relative Humidity (%) (rounded)	OAT (°C)	"Power-setting"	RPM (1/min)	MAP (In Hg)	Fuel Mixt.	T Zyl. (°C)	T Oil (°C)	Fuel Flow (l/h)
4000	30.4.						cruise	2400	20	R	200	80	35
4000							cruise	2500	23	R	205	80	49
2000	13.8.	2	952	1647	40	24	FT, acceler.	2410	27	R	210	80	56
2000		3	923	2430	40	23	FT, vy	2500	27	R	200	80	58
2000		5	905	2916	40	23	Reduced	2050	18	R	210	85	26
2000		7	928	2295	40	23	Approach	1580	14	R	180	80	14
2000		9	924	2403	40	23	FT, vy	2510	28	R	200	80	59
2000		11	907	2862	40	23	Reduced	2080	17	R	200	85	26
2000		13	928	2295	40	23	Approach	1520	12	R	170	80	10
4000	13.8.	3	855	4266	30	22	FT, vy	2500	25	R	210	92	57
4000		5	841	4644	30	21	Reduced	2070	17	R	200	95	28
4000		7	863	4050	30	21	Approach	1580	12	R	180	95	15
4000		9	859	4158	30	22	FT, vy	2530	25	L	210	85	40
4000		11	842	4617	30	21	Reduced	2050	16	L	220	98	20
4000		13	863	4050	30	21	Approach	1410	11	L	190	92	10
6000	13.8.	3	799	5778	30	20	FT, vy	2510	24	R	210	95	55
6000		5	781	6264	30	18	Reduced	2060	15	R	200	92	25
6000		7	803	5670	30	18	Approach	1440	10	R	180	85	8
6000		9	795	5886	30	20	FT, vy	2570	24	L	210	82	44
6000		11	780	6291	30	18	Reduced	2070	16	L	210	90	20
6000		13	801	5724	30	18	Approach	1490	10	L	180	82	11
4000	21.8.	2	866	3969	50	16	cruise	2440	20	R	210	75	38
4000		3	868	3915	50	16	cruise	2330	20	lambda =1	200	80	29

Propeller horsepower calculations were based on ambient air pressure values and hand written power curves from Textron/Lycoming. Figure 1 shows an example for the engine model O-360 A series, marvel carburettor and an engine cylinder compression ratio of 8.5 : 1.

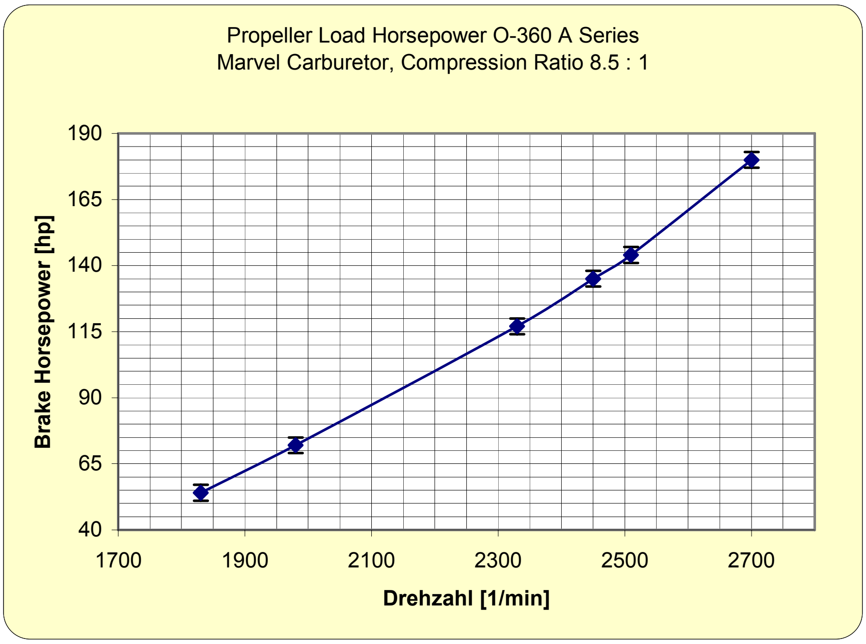


Figure 1: Power Curve Lycoming Model O-360 A Series, Curve No. 10350-A (Textron/Lycoming) digitalized.

Propeller horsepower was assumed very near brake horsepower (see section a)). The calculated values for propeller horsepower, the measured fuel flow, MAP, ambient air pressure and flight mode were normalized and plotted together (figures 2 and 3).

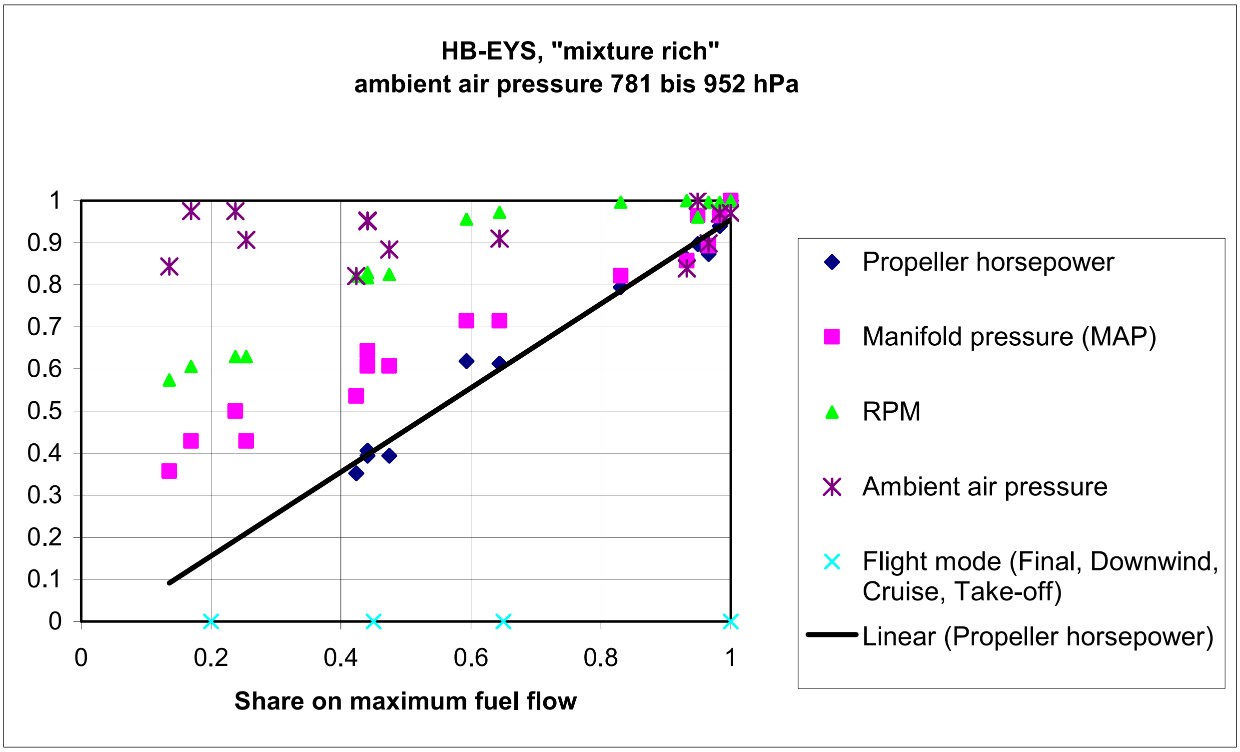


Figure 2: Normalized selected engine parameters in function of fuel flow (mixture rich). Example: At 45% (=0.45) of maximum fuel flow, propeller power is at 40% (=0.4), manifold pressure at 60% (=0.6) and engine RPM at 82% (=0.82) of the maximum value.

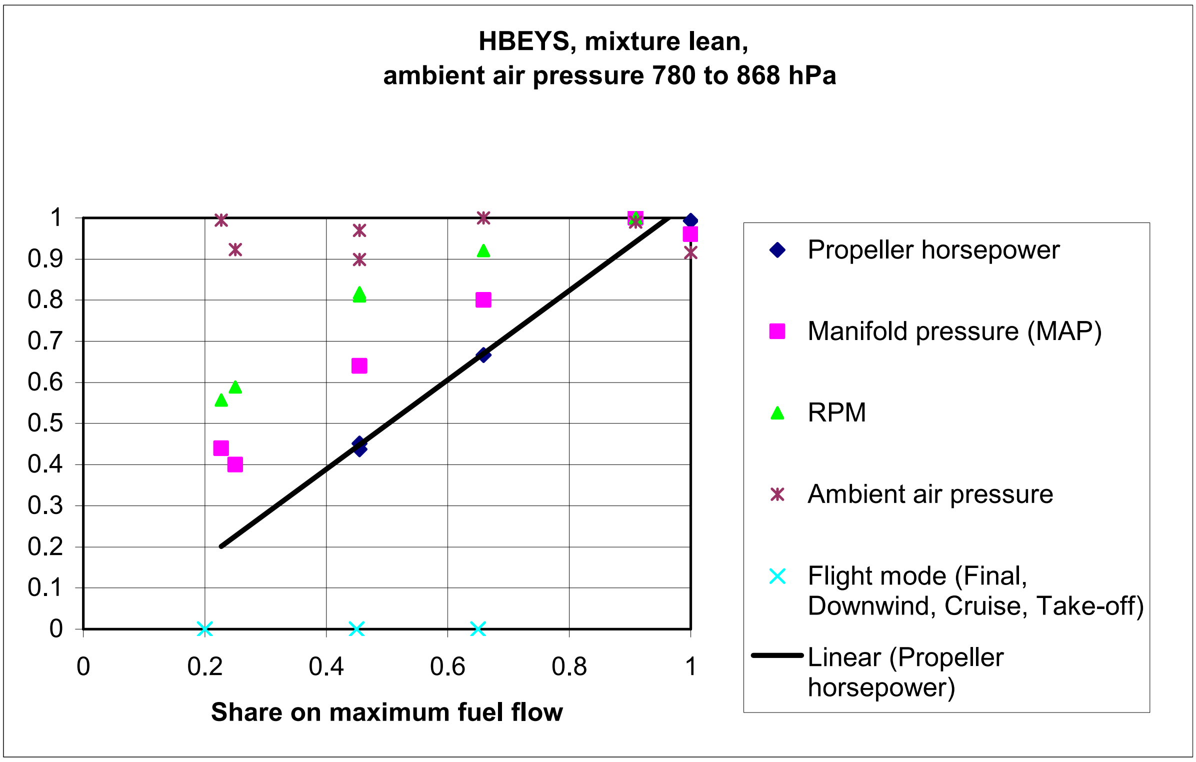


Figure 3: Normalized selected engine parameters in function of fuel flow (mixture lean)

It can be seen from figures 2 and 3 that for the investigated engine, propeller horsepower and fuel flow correlate quite nicely (R^2 = 0.98), better than MAP or RPM.
MAP is also directly related to ambient pressure and figure 2 shows that for a certain propeller power, the MAP is varying, although fuel flow and propeller horsepower are kept constant.

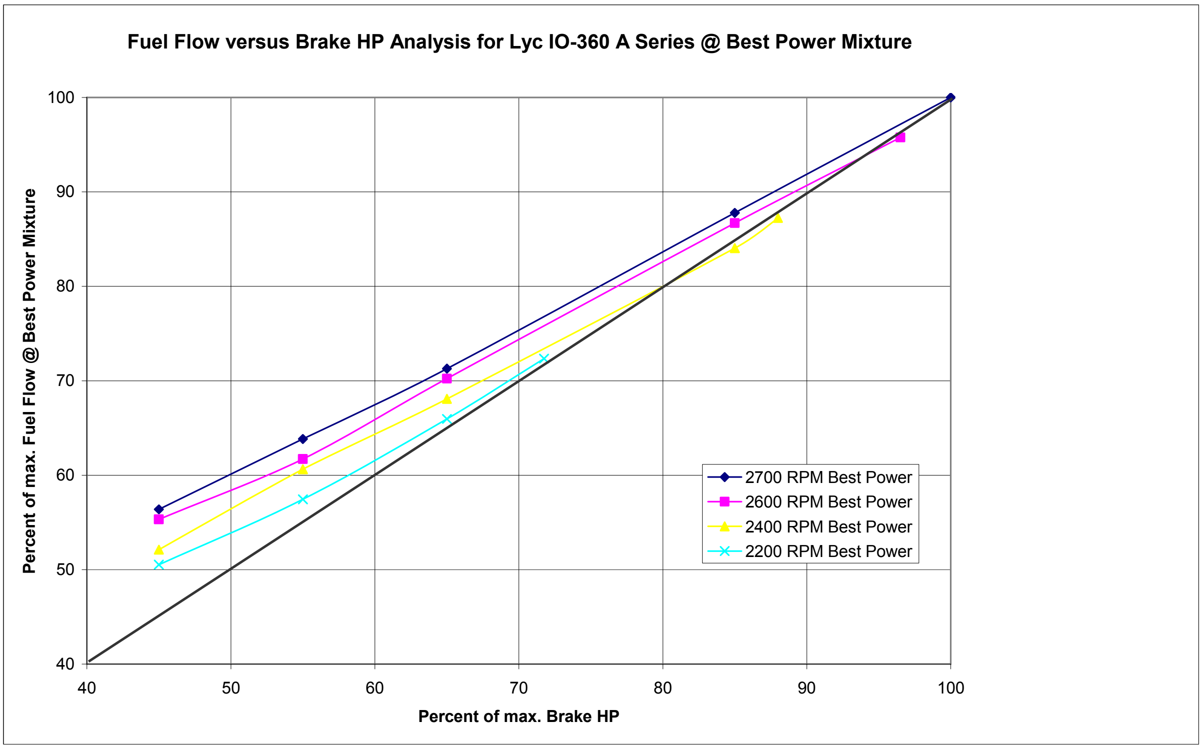


Figure 4: In-flight fuel flow versus brake horsepower for different propeller adjustments (HBKEZ). Restrictions: Especially for low power settings below 40% of maximum fuel flow, significant deviations from the linear relationship can occur, because the piston engine efficiency is not a constant over the full power range. This can be seen in this figure, which shows an analysis for an injected aircraft piston engine with variable pitch propeller at best power mixture (HBKEZ, Appendix 2).

Generally, the linear relationship between propeller horsepower and fuel flow at higher power settings could be reproduced, also for other engine-propeller combinations. Fuel flow was equally found useful to account for changes in ambient conditions. As ambient air pressure and air density decrease[2], engine power decreases which is well translated into fuel flow decrease (at constant mixture setting). Therefore it is considered sufficiently accurate for those emission measurements, which are not intended for certification, to use fuel flow as the major parameter for engine propeller horsepower settings.

The FOCA low cost emission measurement system (see Appendix 1 and 5) requires a direct fuel flow measurement. The fuel flow transducer, which has to be installed and calibrated on the aircraft, can therefore serve as propeller horsepower setting device at the same time.

5. Adjustment of ground measurement power settings (Fuel Flow Method)

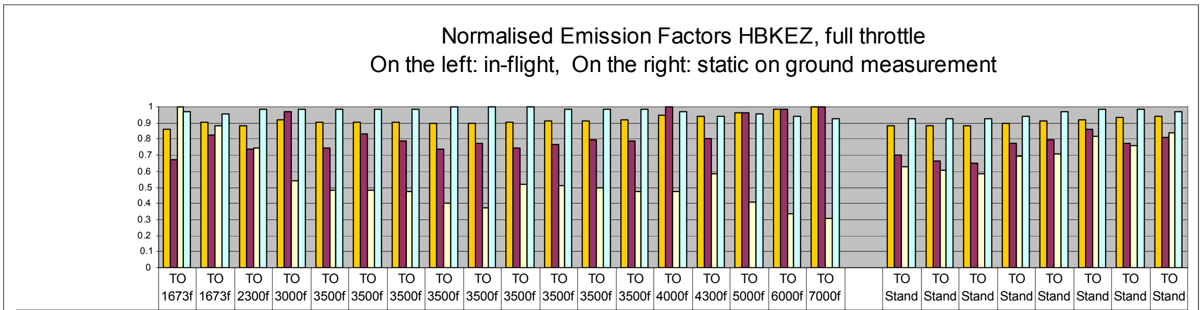
FOCA tries to produce emission factors and fuel flow data for emission inventory purposes at the highest possible cost efficiency. Therefore, besides a low-cost measurement system with sufficient accuracy (as described in Appendix 1), a methodology for static ground measurements is needed.

Primary goal: Find ground power settings that are representative of typical in-flight modes and emissions.

Results from in-flight emission tests (see Appendix 2) were used to select appropriate settings for ground measurements.

- Step 1: Take in-flight measurement results and try to reproduce them at static ground measurements.
- Step 2: Derive power setting methodology for static ground measurements
- Step 3: Take an aircraft that has not been measured in-flight, apply the power setting methodology (step 2) for static ground measurements, followed by in-flight measurements to validate the methodology.

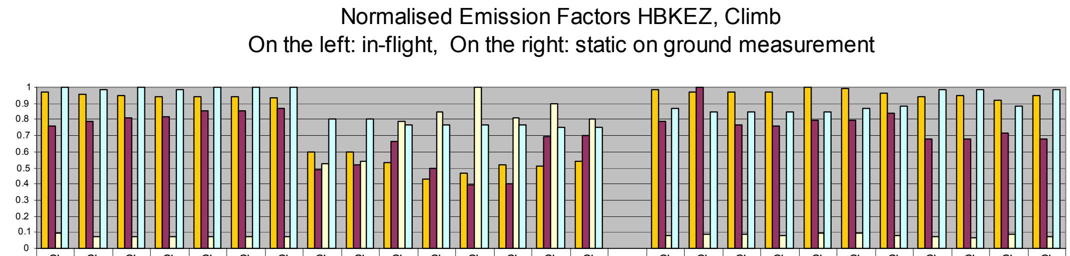
5.1 Step 1: Comparison of in-flight and static ground measurements of HBKEZ (example)



	TO 1673f	TO 1673f	TO 2300f	TO 3000f	TO 3500f	TO 3500f	TO 3500f	TO 3500f	TO 3500f	TO 3500f	TO 3500f	TO 3500f	TO 3500f	TO 4000f	TO 4300f	TO 5000f	TO 6000f	TO 7000f		TO Stand	TO Stand	TO Stand	TO Stand	TO Stand	TO Stand	TO Stand	TO Stand
Rel. EF CO	0.864	0.907	0.884	0.923	0.903	0.905	0.904	0.895	0.898	0.902	0.912	0.914	0.916	0.946	0.94	0.967	0.985	1		0.88	0.88	0.88	0.897	0.914	0.922	0.933	0.945
Rel. EF HC	0.669	0.827	0.74	0.972	0.743	0.83	0.788	0.738	0.771	0.745	0.767	0.796	0.791	1	0.802	0.964	0.987	0.997		0.7	0.662	0.649	0.774	0.799	0.859	0.775	0.808
Rel. EF NOx	1	0.882	0.745	0.537	0.482	0.482	0.472	0.399	0.369	0.519	0.514	0.495	0.474	0.478	0.582	0.412	0.333	0.304		0.628	0.609	0.587	0.69	0.706	0.817	0.761	0.837
Normalised Fuel Flow	0.972	0.958	0.986	0.986	0.986	0.986	0.986	1	1	1	0.986	0.986	0.986	0.972	0.944	0.958	0.944	0.93		0.93	0.93	0.93	0.944	0.972	0.986	0.986	0.972

Figure 5: Comparison of emission factors for CO, HC and NO_x from in-flight and static on ground tests at full throttle. Flights were performed up to a pressure altitude of 7000ft and different ambient conditions. NO_x is highest at ground level, CO and HC are highest at high altitude (mixture full rich). Please note that all HC measurements were based on NDIR, not on FID.

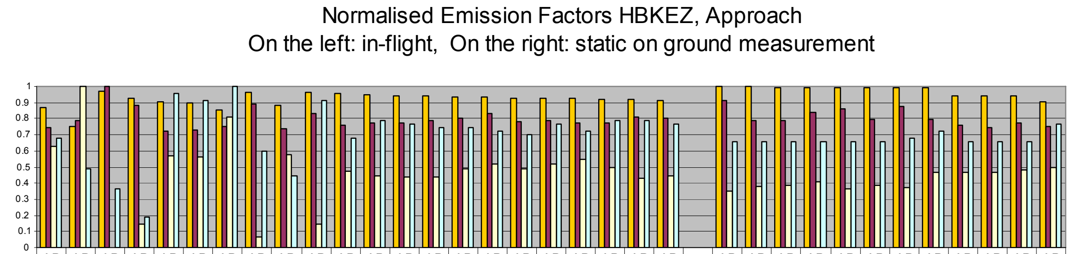
[2] Air density decrease: Mainly through increase of ambient air temperature. Humidity increase had little effect



	CL 3000f	CL 3500f	CL 3500f	CL 3500f	CL 3500f	CL 3500f	CL 3500f	CL 3500f	CL 3500f	CL 3500f	CL 3500f	CL 3600	CL 4500	CL 4500f	CL 5500f
Rel. EF CO	0.973	0.953	0.949	0.945	0.942	0.94	0.937	0.601	0.596	0.531	0.429	0.47	0.521	0.509	0.542
Rel. EF HC	0.759	0.787	0.813	0.814	0.852	0.857	0.865	0.492	0.518	0.664	0.498	0.392	0.4	0.692	0.701
Rel. EF NOx	0.091	0.07	0.07	0.072	0.07	0.071	0.071	0.526	0.54	0.787	0.849	1	0.807	0.896	0.799
Normalised Fuel Flow	1	0.983	1	0.983	1	1	1	0.8	0.8	0.767	0.767	0.767	0.767	0.75	0.75

	CL Stand	CL Stand	CL Stand	CL Stand	CL Stand	CL Stand	CL Stand	CL Stand	CL Stand	CL Stand	CL Stand
Rel. EF CO	0.985	0.971	0.972	0.972	1	0.994	0.962	0.942	0.951	0.918	0.952
Rel. EF HC	0.79	1	0.768	0.76	0.792	0.794	0.838	0.682	0.678	0.714	0.68
Rel. EF NOx	0.078	0.088	0.086	0.083	0.095	0.095	0.084	0.074	0.068	0.085	0.07
Normalised Fuel Flow	0.867	0.85	0.85	0.85	0.85	0.867	0.883	0.983	0.983	0.883	0.983

Figure 6: Comparison of emission factors for CO, HC and NO_x from in-flight and static on ground tests at climb. Flights were performed up to a pressure altitude of 5500ft and different ambient conditions. The second set of in-flight measurements starting from 3500ft to 5500ft (in the middle of the figure) has been measured with fuel mixture adjustment during climb (as described in Appendix 2, section 4.f)). All ground measurements were performed with mixture full rich, with fuel flow guided power setting (suffix “alt”) and MAP guided power setting (“v3”). Please note that all HC measurements were based on NDIR, not on FID.



	AP 160	AP 200	AP 250	AP 260	AP 320	AP 320	AP 320	AP 320	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350	AP 350
Rel. EF CO	0.87	0.75	0.97	0.93	0.9	0.9	0.85	0.97	0.88	0.96	0.96	0.95	0.94	0.94	0.94	0.93	0.93	0.92	0.93	0.92	0.92	0.92
Rel. EF HC	0.75	0.79	1	0.88	0.72	0.73	0.75	0.89	0.74	0.83	0.76	0.78	0.78	0.79	0.8	0.83	0.78	0.79	0.77	0.77	0.81	0.8
Rel. EF NOx	0.63	1	0	0.15	0.57	0.56	0.81	0.06	0.57	0.14	0.48	0.45	0.44	0.44	0.49	0.52	0.49	0.52	0.55	0.5	0.43	0.44
Normalised Fuel Flow	0.68	0.49	0.36	0.19	0.96	0.91	1	0.6	0.45	0.91	0.68	0.79	0.77	0.74	0.74	0.72	0.7	0.77	0.72	0.79	0.79	0.77

	AP Sta	AP Sta	AP Sta	AP Sta	AP Sta	AP Sta	AP Sta	AP Sta	AP Sta	AP Sta	AP Sta	AP Sta
Rel. EF CO	1	1	0.99	0.99	0.99	0.99	0.99	1	0.94	0.94	0.94	0.9
Rel. EF HC	0.91	0.79	0.79	0.84	0.86	0.8	0.88	0.79	0.76	0.74	0.77	0.75
Rel. EF NOx	0.35	0.38	0.39	0.41	0.37	0.39	0.37	0.47	0.46	0.46	0.48	0.5
Normalised Fuel Flow	0.66	0.66	0.66	0.66	0.66	0.66	0.68	0.72	0.66	0.66	0.66	0.77

Figure 7: Comparison of emission factors for CO, HC and NO_x from in-flight and static on ground tests at approach. Flights were performed from a pressure altitude of 3500ft and different ambient conditions. Flight measurements show significant variations coming from different approach power settings. All ground measurements were performed with mixture full rich, with fuel flow guided power setting (suffix “alt”) and MAP guided power setting (suffix “v3”). Please note that all HC measurements were based on NDIR, not on FID.

5.2 Step 2: Power setting methodology for static ground measurements

The first version of the methodology is solely based on fuel flow measurements for power settings at ground level.

5.2.1 Determination of maximum fuel flow

Generally, in order to get measurement results that are near standard sea level conditions, it is helpful if the test location is situated at low altitude airports. Many airports in the Swiss Midlands are at about 1500ft AMSL. If measurements are performed during cold days in winter and high ambient air pressure, the density altitude can be reduced to around 0ft AMSL. Under these conditions a normally aspirated piston engine can produce its maximum rated propeller power and its maximum fuel flow. Moreover, measurements at low ambient temperatures have the advantage of better engine cooling and better prevention of “hot spots” inside the engine cowling during the static tests.

For practical reasons, it was not possible for FOCA to do all the ground static tests at density altitudes around 0ft AMSL.

However, the maximum fuel flow at different ambient conditions between winter and summer showed relatively small differences. Although, high humidity also reduces air density, the significant portion of difference is generated by ambient air temperature variations (see also section 5.3.3). Additionally, part of the variation has to be attributed to the fuel flow transducers limited accuracy.

Examples for total variations (all flights, take-off and all ground measurements, full throttle, high RPM):

HBEYS 57 < max. fuel flow < 60 liters/hour
HBKEZ 68 < max. fuel flow < 71 liters/hour

Keeping in mind that the emission measurements were primarily designed for inventory purposes, reflecting operational conditions, the variation seemed acceptable. However, when ever possible, FOCA tried to measure normally aspirated piston engines at low density altitude, giving highest possible propeller power and fuel flow at full throttle. Of course, influence of ambient air pressure was not an issue for ground level static tests in the case of turbocharged engines. And:

There was no significant difference in maximum fuel flow at full throttle with the aircraft standing or with the aircraft accelerating on the runway.

For details of the measurement procedure, see section 6.

5.2.2 Power settings other than maximum propeller power

Table 2 was generated from in-flight and ground measurement comparisons in order to match fuel flow and emissions obtained with ground measurements as good as possible to in-flight conditions. (Examples are given in figures 5 to 7 of section 5.1)

Table 2: Percent of maximum fuel flow for all selected aircraft modes (mixture “full rich”)

Mode	% of maximum fuel flow
Take off	100
Climb out	85
Cruise	65
Approach	45
Taxi	AFM

The power setting for the different modes is established by adjusting the throttle to bring the indicated fuel flow to the corresponding % fuel flow calculated value. The taxi mode is treated differently: The engine is running at the recommended RPM for warm up according to AFM/engine operation manual. (Details in section 6)

Example: Max. fuel flow 70 liter / hour -> Climb out setting 70 liter /hour * 0.85 = 60 liter / hour

5.3 Step 3: Application of the power setting methodology (step 2) for static ground measurements with an aircraft that has not been measured in-flight, followed by in-flight measurements

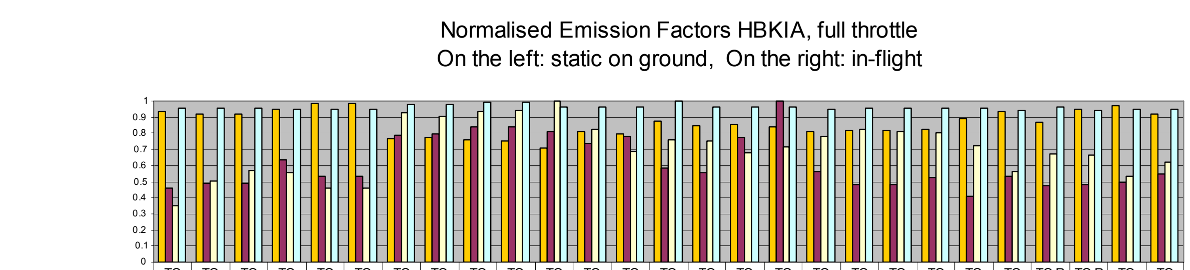
The fuel flow methodology developed in step 2 was applied to the high performance piston engine aircraft HBKIA. It was considered demanding to match static ground and in-flight measurements of such an aircraft, because of variable pitch propeller and an automatic air/fuel mixture adjustment of the engine (Appendix 2, Section 5). Therefore, this aircraft was considered an interesting choice to test the fuel flow method.

Picture 2: Preparations for ground static emission measurements of HB-KIA

Picture 3: Preparations for ground static emission measurements of HB-KIA

5.3.1 Comparison of ground and later in-flight measurements

General remark: The in-flight tests following the ground static tests have been flown in very different ambient conditions, pressure altitudes and sometimes including individual operational behaviour of different pilots (Appendix 2). It could not be the aim to match a certain flight exactly with a certain ground measurement. The main goal was, to develop the methodology so far that emission factors (resulting from ground measurements) were in the range of values occurring in-flight. The following figures show emission factors and fuel flow in relation to their maximum values obtained within all the measurements. If the engine and the measurement system would perform absolutely identical at each flight, all in-flight pillars in the figure would be equal to 1. In reality, there are already significant differences within a certain flight mode. We consider the methodology useful, if it is able to produce the same pillar height range as compared to the in-flight pillars for the different species and the fuel flow (see figures below).



	TO 0000	TO 0000	TO 0000	TO 0000	TO 0000	TO 0000	TO LSZG	TO LSZG	TO LSZG	TO LSZG	TO LSZG	TO LSZG	TO LSZG	TO 1700	TO 1700	TO LSZB	TO LSZB	TO 2300	TO 3000	TO 3000	TO 3000	TO 3000	TO 3000	TO R 3000	TO R 3500	TO 4000	TO 4000
Rel. EF CO	0.932	0.922	0.922	0.952	0.985	0.985	0.764	0.772	0.757	0.753	0.707	0.812	0.795	0.878	0.85	0.858	0.836	0.808	0.817	0.82	0.824	0.894	0.931	0.87	0.949	0.973	0.917
Rel. EF HC	0.461	0.491	0.491	0.637	0.53	0.53	0.791	0.797	0.836	0.837	0.807	0.74	0.782	0.584	0.557	0.77	1	0.563	0.484	0.484	0.529	0.412	0.534	0.478	0.484	0.5	0.546
Rel. EF NOx	0.354	0.504	0.569	0.558	0.463	0.463	0.927	0.907	0.932	0.943	1	0.823	0.686	0.756	0.753	0.676	0.719	0.778	0.824	0.812	0.805	0.724	0.565	0.675	0.662	0.531	0.624
Normalised Fuel Flow	0.96	0.96	0.96	0.952	0.952	0.952	0.98	0.98	0.993	0.993	0.962	0.962	0.962	1	0.962	0.962	0.962	0.951	0.96	0.96	0.96	0.96	0.941	0.962	0.941	0.952	0.952

Figure 8: Comparison of normalized emission factors for take-off power settings of all ground and in-flight measurements of HBKIA. The ground static results are represented by the first six sets of columns on the left. HC emissions were measured with NDIR (Appendix 1).

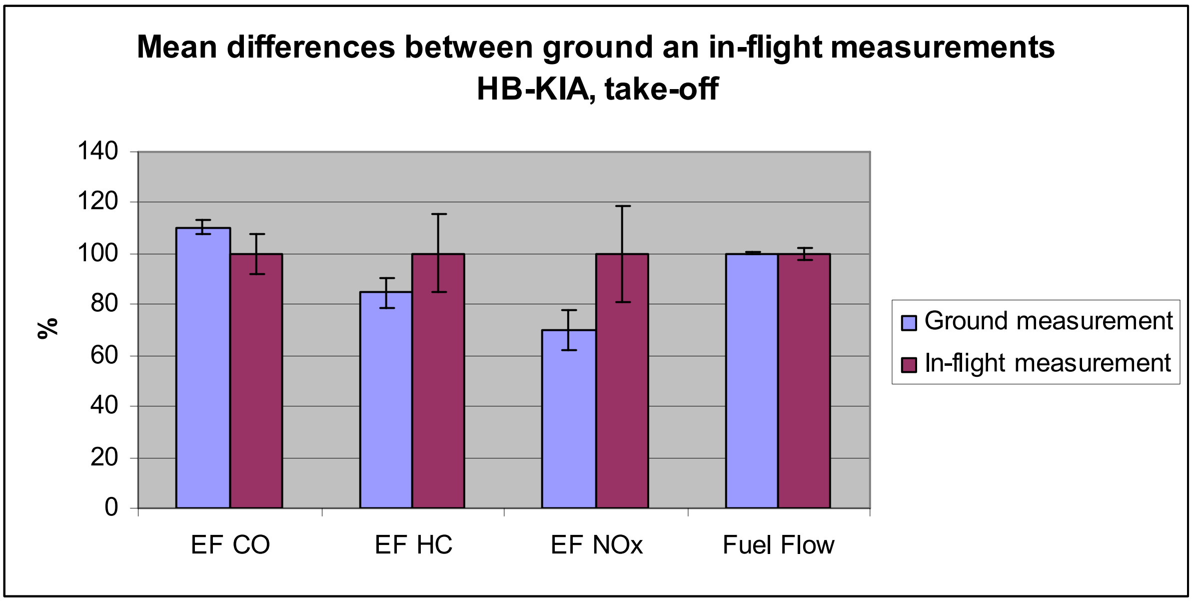
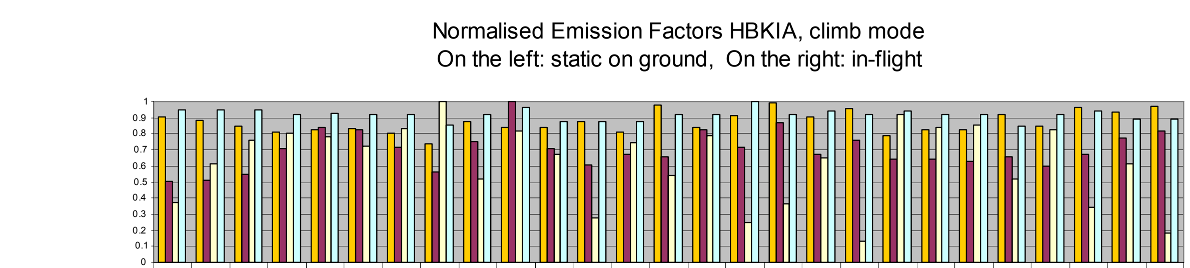


Figure 9: Relative difference in mean emission factors between ground and in-flight measurements with indicated standard deviation for HB-KIA, take-off.

Discussion of take-off mode: The take-off fuel flow is stable within 5% for all measurements. CO emission factors tend to be higher at static conditions by around 10% with the exception of high altitude take-offs. NO_x emission factors seem to be around 30% lower at static conditions. However, in absolute terms, the difference is in the order of grams / kg fuel. HC emission factors have a tendency to be lower than in-flight at low altitudes.



	CL 0000	CL 0000	CL 0000	CL LSZG	CL LSZG	CL LSZG	CL LSZG	CL LSZG	CL LSZG	CL R	CL LSZG	CL LSZG	CL LSZG	CL 0000	CL R	CL 2300	CL R	CL 2300	CL 3000	CL 3000	CL 3000	CL 3000	CL R 3000	CL 3000	CL 3000	CL 3300	CL 4000
Rel. EF CO	0.904	0.882	0.847	0.812	0.821	0.831	0.801	0.737	0.879	0.838	0.837	0.878	0.814	0.977	0.837	0.911	0.995	0.906	0.956	0.787	0.827	0.827	0.918	0.843	0.961	0.933	0.968
Rel. EF HC	0.501	0.511	0.548	0.709	0.838	0.823	0.712	0.562	0.749	1	0.71	0.603	0.674	0.66	0.828	0.715	0.865	0.671	0.759	0.642	0.641	0.627	0.654	0.597	0.67	0.775	0.815
Rel. EF NOx	0.374	0.614	0.757	0.806	0.782	0.722	0.831	1	0.521	0.816	0.668	0.278	0.746	0.542	0.786	0.245	0.368	0.651	0.13	0.921	0.841	0.856	0.521	0.826	0.342	0.61	0.182
Normalised Fuel Flow	0.948	0.948	0.948	0.921	0.928	0.921	0.92	0.856	0.921	0.962	0.877	0.877	0.877	0.921	0.92	1	0.92	0.941	0.921	0.941	0.921	0.921	0.846	0.921	0.941	0.888	0.892

Figure 10: Comparison of normalized emission factors for climb mode of all ground and in-flight measurements of HBKIA. The ground static results are represented by the first three sets of columns on the left. HC emissions were measured with NDIR (Appendix 1).

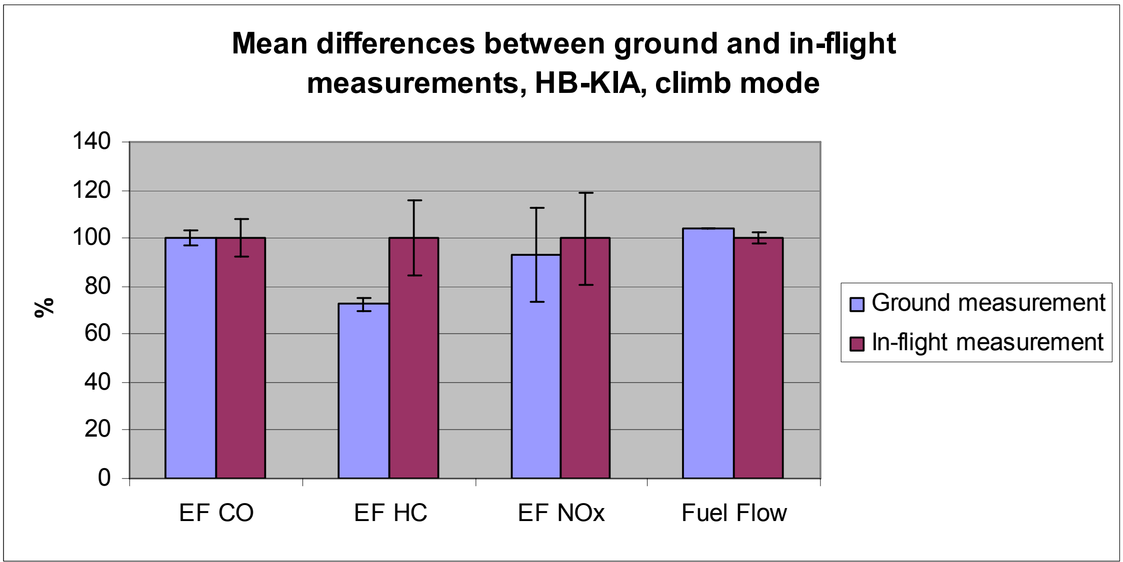
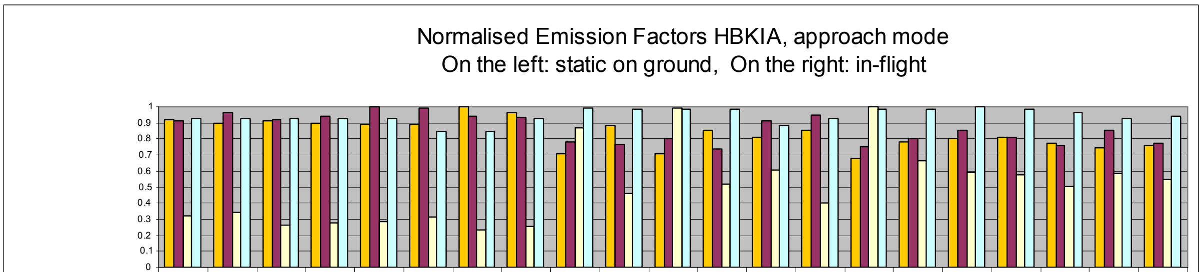


Figure 11: Relative difference in mean emission factors between ground and in-flight measurements with indicated standard deviation for HB-KIA, climb mode.

Discussion of climb mode: The variation of in-flight emission factors can be rather significant. In this example, this is especially the case for NO_x emission factors. Nevertheless, matching of mean values for all in-flight emission factors to the ground measurement values is considered acceptable with the exception of EF HC. It must be noted, that HC emissions had been measured with NDIR instead of FID (Appendix 1) only. Therefore, the composition of HC had an influence on the total value and this could be part of the difference.



	AP 0000	AP 0000	AP 0000	AP 0000	AP 0000	AP 0000	AP 2400	AP 3000	AP 3000	AP 3000	AP 3000	AP 3000	AP 3200	AP 3200	AP 4000	AP 4000	AP 4000	AP 4000	AP 4500	AP 5000	AP 5000
Rel. EF CO	0.9225	0.8976	0.9133	0.9002	0.8941	0.8887	1	0.9614	0.7058	0.882	0.7082	0.854	0.8084	0.855	0.6775	0.7779	0.8039	0.8074	0.7743	0.7446	0.7591
Rel. EF HC	0.9157	0.9601	0.9228	0.9441	1	0.9962	0.9409	0.933	0.7817	0.7652	0.8024	0.74	0.9145	0.9502	0.7552	0.8021	0.8505	0.8075	0.7592	0.8507	0.7715
Rel. EF NOx	0.3176	0.3438	0.2592	0.2755	0.2857	0.3128	0.2315	0.2546	0.8716	0.4581	0.9936	0.5168	0.6037	0.404	1	0.6615	0.5878	0.5793	0.5062	0.5854	0.5489
Normalised Fuel Flow	0.9283	0.9283	0.9283	0.9283	0.9283	0.8491	0.8491	0.9245	0.9925	0.9849	0.9849	0.9849	0.8868	0.9245	0.9849	0.9849	1	0.9849	0.9623	0.9245	0.9434

Figure 12: Comparison of normalized emission factors for approach mode of ground and in-flight measurements of HBKIA. The ground static results are represented by the first six sets of columns on the left.

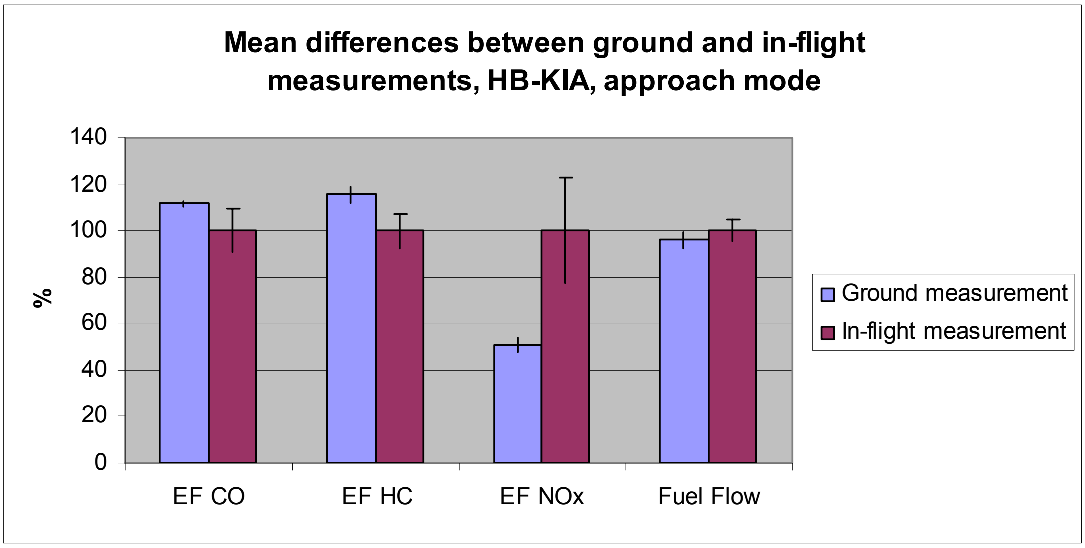
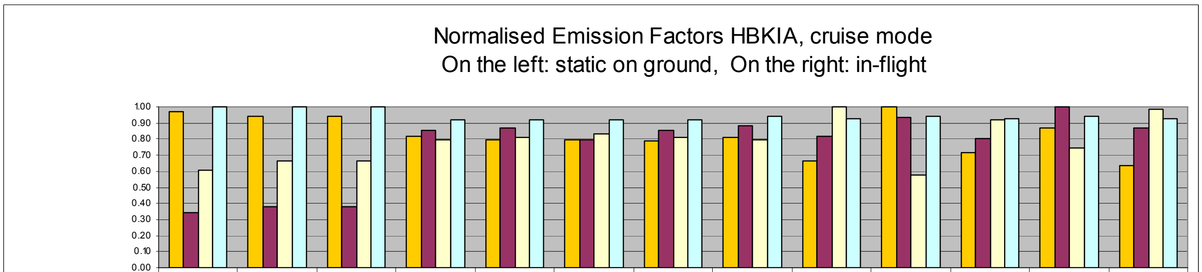


Figure 13: Relative difference in mean emission factors between ground and in-flight measurements with indicated standard deviation for HB-KIA, approach mode.

Discussion of approach mode: NO_x emission factors have the tendency to be significantly lower at ground tests than in flight. The contrary is true for CO and HC. This can be explained by the fact that the engine is running at a less rich air/fuel mixture during flight, most probably due to the automatic mixture adjustment in the engine (Appendix 2, section 5).



	0 CR LR GND	0 CR LR GND	0 CR LR GND	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500
Rel. EF CO	0.97	0.94	0.94	0.81	0.80	0.79	0.79	0.81	0.66	1.00	0.71	0.87	0.64
Rel. EF HC	0.34	0.38	0.38	0.86	0.87	0.80	0.86	0.88	0.82	0.93	0.80	1.00	0.87
Rel. EF NOx	0.60	0.67	0.67	0.80	0.81	0.83	0.81	0.80	1.00	0.57	0.92	0.74	0.99
Normalised Fuel Flow	1.00	1.00	1.00	0.92	0.92	0.92	0.92	0.94	0.93	0.94	0.93	0.94	0.93

Figure 14: Comparison of normalized emission factors for cruise mode of ground and in-flight measurements of HBKIA. The ground static results are represented by the first three sets of columns on the left. HC emissions were measured with NDIR (Appendix 1). Mixture was set “rich of EGT peak”. (For details see section 6)

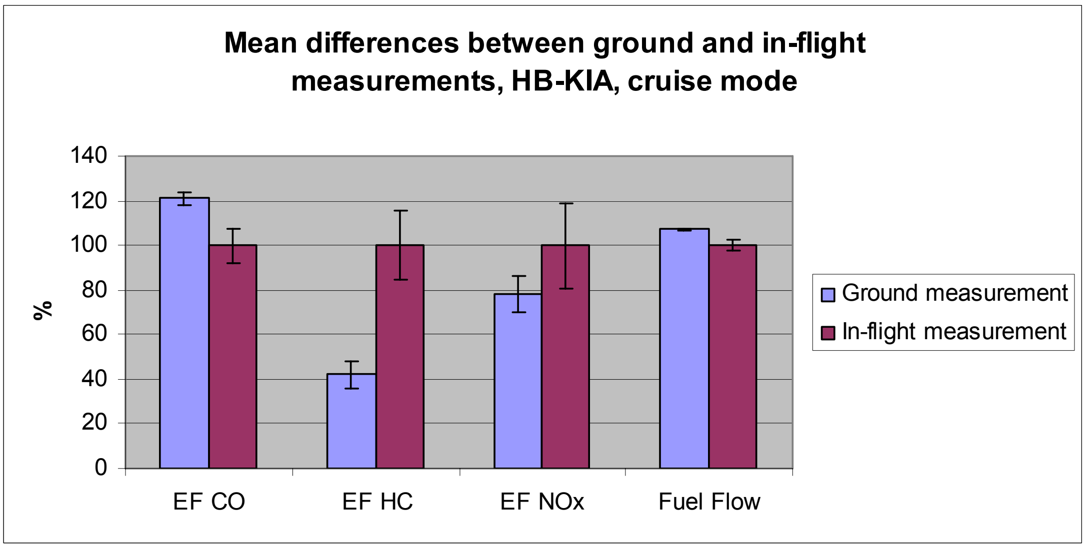


Figure 15: Relative difference in mean emission factors between ground and in-flight measurements with indicated standard deviation for HB-KIA, approach mode.

Discussion of cruise mode: Cruise mode emission factors are extremely dependent on pilot's choice for the mixture setting (Appendix 2). In-flight results show the variation between settings of different pilots. It was found that the mean value for lambda (Appendix 5, section c)) for the standard mixture setting condition "rich of EGT peak" was around 0.93 to 0.95. In ground tests, after setting the power reference, the mixture setting was adjusted to this range of lambda (see section 6 for details). It is interesting to see, that although CO emission factors seem to be higher and NO_x emission factors lower for the ground measurement, the HC emission factors are significantly lower. A similar situation can be seen in climb mode (figure 11). No logical explanation could be found, because HC emission factors should normally correlate with CO. However, as mentioned before, HC emissions had been measured with NDIR instead of FID (Appendix 1) only.

5.3.2 Adjustments to the fuel flow method for complex aircraft/engines

For aircraft equipped with manifold pressure gauge, the fuel flow method was combined with manifold pressure preset values (section 6.4). This procedure further improved matching between ground and in-flight data. For the engine Teledyne/Continental IO-550-B of HB-KIA, the following ground based emission factors were obtained with this method:

Table 3: Fuel flow and mean emission factors for TCM IO-550-B (times are not relevant here)

MODE	POWER SETTING (%)	TIME (minutes)	FUEL FLOW (kg/s)	EI HC (g/kg)	EI CO (g/kg)	EI NOx (g/kg)
TAKE-OFF	100	0.3	0.0182	12.7	818	6
CLIMB OUT	85	2.5	0.018	12.3	787	6
CRUISE	65	60	0.0152	6.9	750	8
APPROACH	45	3	0.0098	11.5	1055	2
TAXI	12	12	0.0038	42.6	1123	0
CRUISE LEAN	65	60	0.0138	5.4	473	23

The data presented in table 3 have been checked against the flights ECERT 57 and 64 (Appendix 2, sections 5.o) and 5.p)) in order to show a better match with in-flight measured emission inventories.

Table 4: Comparison of emission results from in-flight full mission measurements (ECERT 57 and 64) and emission results based on the ground measurement data sheet (Table 3). For the calculation based on the data sheet, the average pilot 1 and pilot 2 times were used, as indicated on the bottom of the table.

HBKIA	Pilot 1	Pilot 2	Average Pilot 1 and 2	Based on Data Sheet
LTO Fuel (kg)	11.1	11.2	11.1	11.8
LTO CO (g)	9159	10932	10046	11337
LTO HC (g)	384	382	382	218
LTO NOx (g)	57	30	43	40
CR Fuel (Mission kg)	17	18	17.5	19.1
CR CO (Mission g)	7325	10108	8716.5	9008
CR HC (Mission g)	180	173	176.5	103
CR NOx (Mission g)	476	342	409	438
CR Fuel (kg/h)	49	43	46	49.7
CR CO (g/(h)	20929	24259	22594	23498
CR HC (g/h)	514	415	464.5	268
CR NOx (g/h)	1360	822	1091	1142
Taxi Time (Min.)	11	11	11	11
Take-off Time (Min.)	1	1	1	1
Climb Time (Min.)	3.5	3.5	3.5	3.5
Cruise Time (Min.)	21	25	23	23
Approach Time (Min.)	7.5	7.5	7.5	7.5

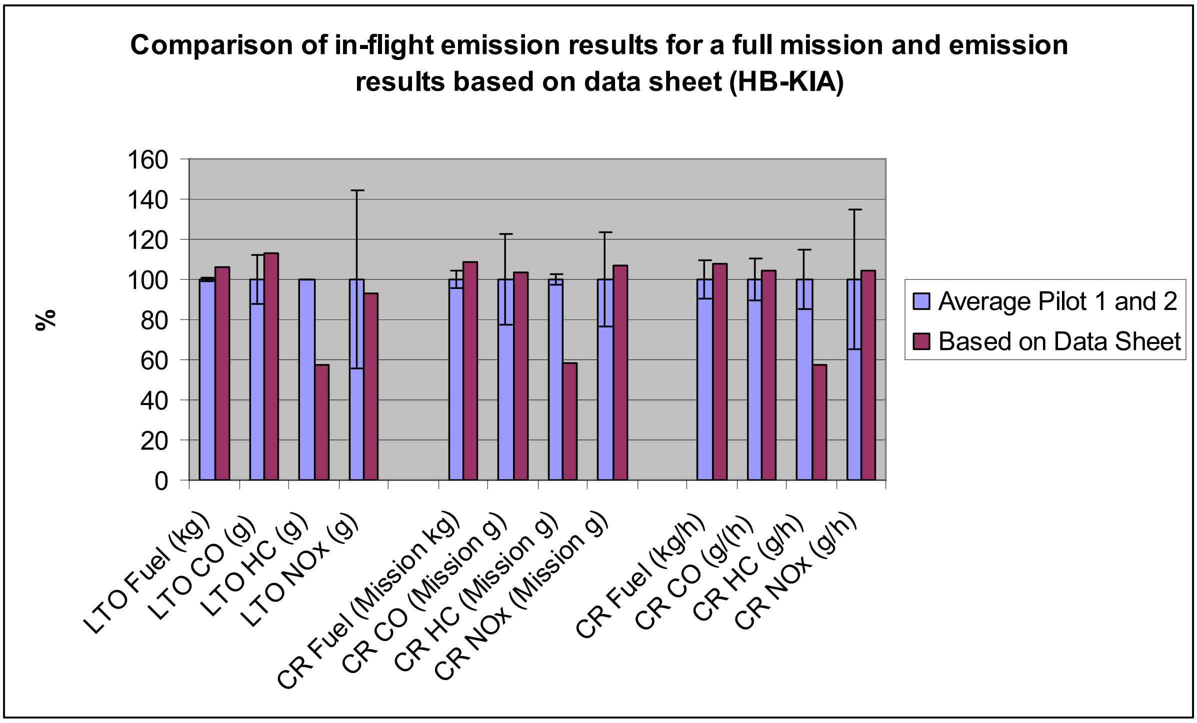


Figure 16: Relative comparison of in-flight emission results for a full mission and emission results based on the data sheet of table 3. Emission results based on ground measured data for fuel, CO and NO_x match the emissions of the selected flights by 3 to 8% difference. HC emissions, based on the data sheet, are significantly lower (by 42%). It looks as if the differences in HC emissions between in-flight and ground measurements are systematic. It must be noted that the HC emission factors presented in table 3 were measured with a FID for total HC. In-flight measurement of HC could only be done with the NDIR sensor and total HC had to be estimated (see Appendix 5). Standard deviations for in-flight emissions are only based on the two flights and are therefore not statistically robust.

5.3.3 Temperature corrections for normally aspirated carburetted aircraft piston engines

The value of ambient air density (which is a function of ambient air temperature) can influence the air/fuel ratio in the carburettor significantly, much more than ambient humidity. Changing air/fuel ratio (and therefore changing lambda) changes the value of emission factors (even with all other factors remaining constant).

To compensate for temperature effects on emission factors for normally aspirated carburetted engines, two simple correction formulas are suggested, shifting the values to approximately 15°C outside air temperature (see Appendix 5). The correction represents present state of investigation and has not been developed any further.

Table 5: Generally, lambda gets lower at higher temperatures (the engine runs „richer“). The taxi mode of this particular engine is behaving differently and is not representative for this class of engines. (Example from HB-EYS, LycO-360, Marvel carburettor).

Mode	lambda 10.03.04 /1°C	lambda 17.03.04 / 20°C	cold minus warm
TO	0.708	0.704	0.004
TO	0.704	0.692	0.012
TO	0.701	0.689	0.012
CL	0.759	0.747	0.012
CL	0.762	0.743	0.019
CL	0.757	0.732	0.025
CR	0.827	0.813	0.014
CR	0.834	0.811	0.023
CR	0.827	0.806	0.021
AP	0.763	0.746	0.017
AP	0.766	0.748	0.018

AP	0.772	0.75	0.022
TA	1.338	1.371	-0.033
TA	1.333	1.359	-0.026
TA	1.343	1.386	-0.043
CR L	0.994	0.96	0.034
CR L	1.001	0.973	0.028
CR L	0.996	0.966	0.03

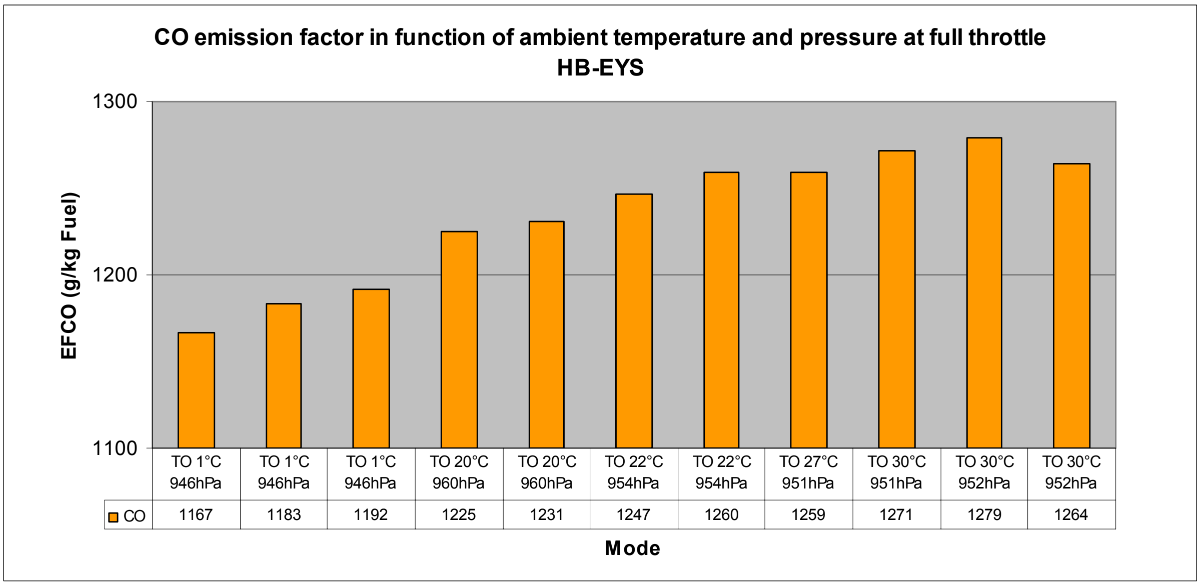


Figure 17: Example for temperature dominated EF CO increase. Ambient pressure is QFE. Several measurements at the same temperature and QFE also show statistical differences resulting from measurement inaccuracies and engine performance fluctuations.

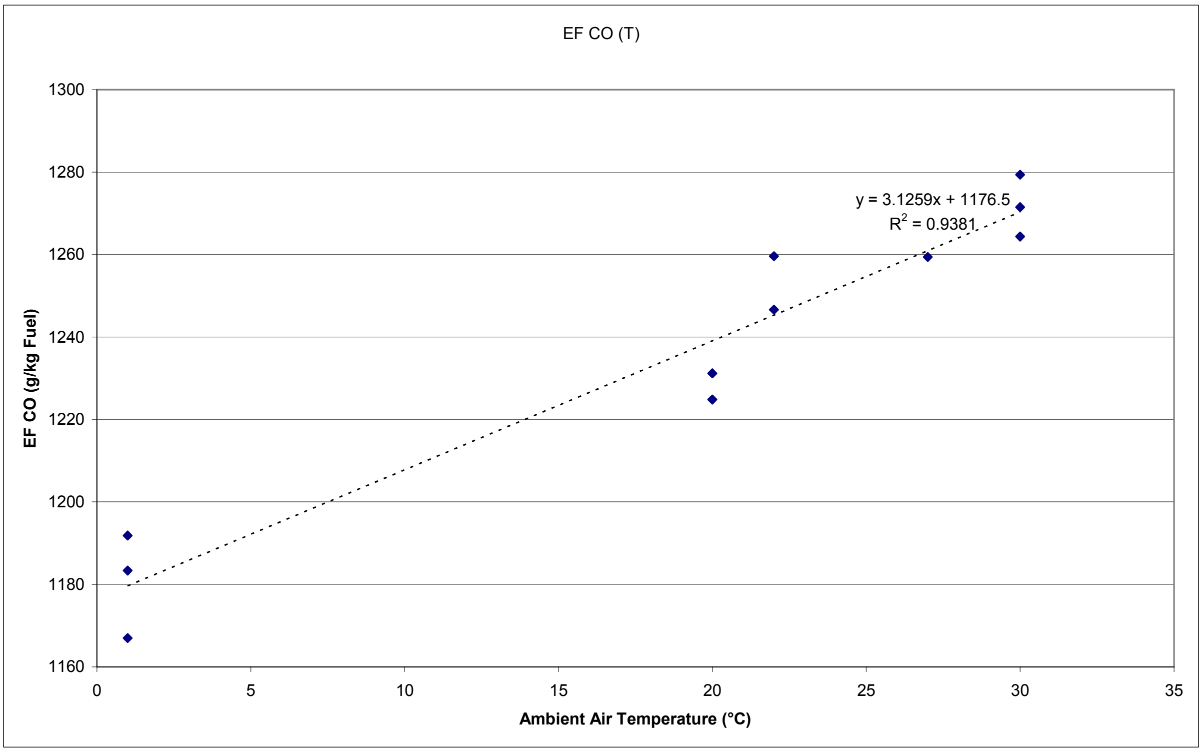


Figure 18: Example of linear correction of EF CO in function of ambient air temperature. At 15°C, the EF CO is assumed to be 1223 g/kg fuel (HB-EYS). See Appendix 5, section f) for first order approximation formulas.

6. Recommended ground measurement power setting procedures for emission tests

6.1 Selection of methodology

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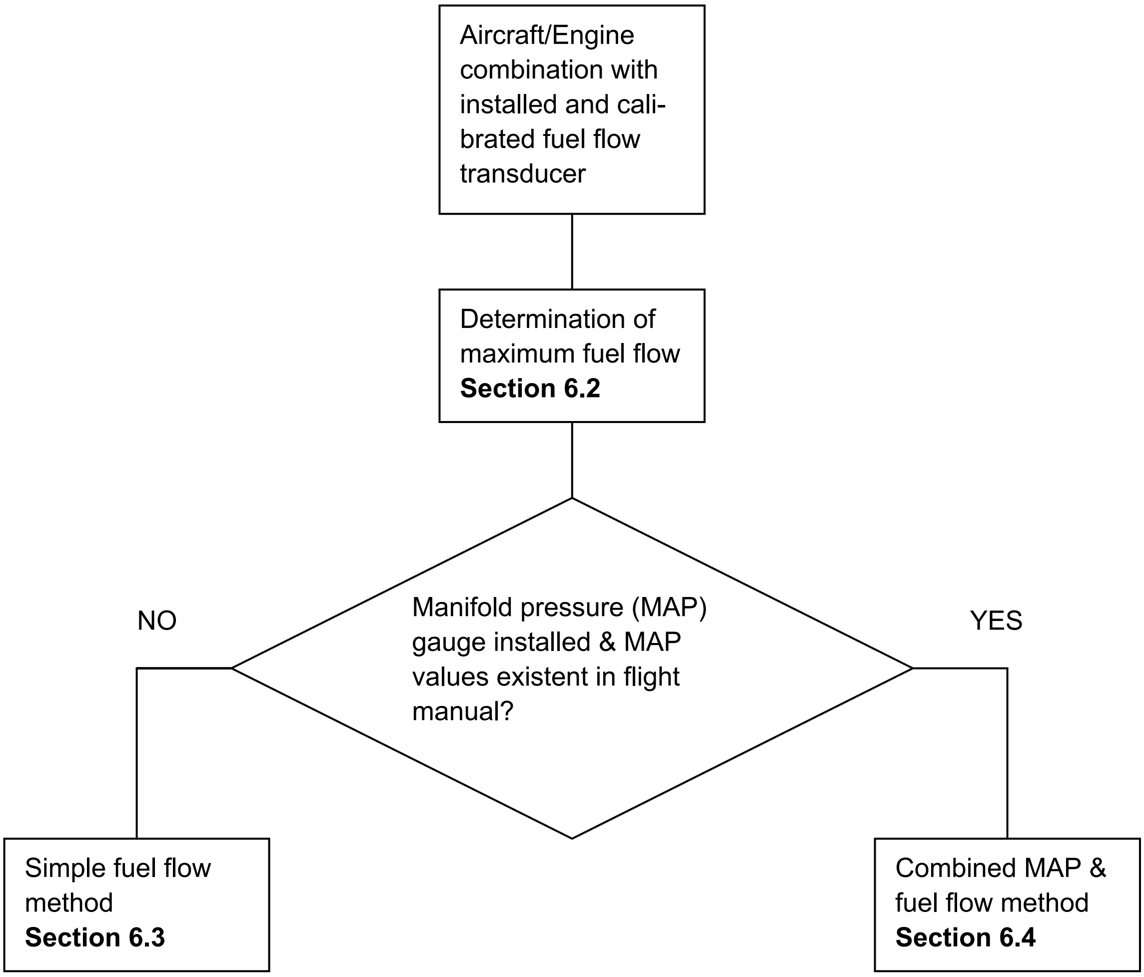


6.2 Procedure for determination of maximum fuel flow

6.2.1 Fuel flow calibration

The fuel flow measurement system, either already existing in the aircraft or installed for the measurements only, should be calibrated. This can normally only be done with flight testing, which requires to certify the installation. The fuel flow transducer used by FOCA (Appendix 1) is a certified design and can be installed in terms of a major aircraft modification. Calibration of the transducer was achieved by

- Marking the position of the aircraft wheels before first refuelling.
- Refuelling the aircraft with the fuel reaching a clearly defined optical reference.
- Running the fuel flow system during flights, which last several hours.
- Noting the time integrated fuel consumption indicated by the fuel flow system until next refuelling.
- Parking the aircraft with the same balance exactly at the position where the previous refuelling took place.
- Refuelling the aircraft to the previously defined optical reference.
- Noting the relation between tanked amount of fuel and fuel flow system indicated fuel consumption.
- Correcting the calibration factor according to the fuel flow transducer manual.

After installation in the aircraft, the factory pre-calibration value of the fuel flow transducer was often within 5% of the determined calibration value.

6.2.2 Preparing the aircraft for a maximum fuel flow (and emission) measurement

As mentioned before, determination of maximum fuel flow (maximum propeller horsepower) of normally aspirated piston engines should be made at low density altitudes (low ambient air temperature and high ambient air pressure conditions). At a density altitude of 0 ft, the engine will behave similar to sea level due to a similar "weight of charge" in the inlet. Practical recommendations:

- Wheels are secured with wheel chocks and fully braked by the pilot
- The measurement car is placed behind the main wing and in a sufficient distance to the tail wing, outside the propeller stream and without obstructing the aircraft, should the aircraft move forward.
- If the engine is equipped with a variable pitch propeller, the pitch setting is "high RPM".
- The engine has to be perfectly warmed up.
- When going to full throttle, the aircraft is observed from outside with permanent radio contact between observer and pilot.
- Full throttle static conditions should generally not last more than one minute. Engine temperatures have to be observed carefully.
- This configuration can be used for the whole emission measurement

Picture 4: Determination of maximum fuel flow (static measurement). The aircraft brakes are fully applied and the wheels secured by wheel chocks.

After determination of maximum fuel flow, the engine is idling at the RPM which is suggested according to the aircraft flight manual (AFM), in order to cool down. During this time, the corresponding fuel flows, belonging to Climb out, Cruise (mixture rich) and Approach can be calculated, as described in section 6.3 and 6.4 respectively.

Picture 5: Emission measurement of a Microlight (Swiss Ecolight) aircraft, normally used for glider towing. The power to weight ratio of this aircraft is such that the towing rope is necessary to hold the aircraft in position during full throttle operation.

6.3 Simple fuel flow method

6.3.1 Fuel flow for all modes

All power settings are derived from the following table:

Table 6: Percent of maximum fuel flow for all selected aircraft modes (mixture “full rich”)

Mode	% of maximum fuel flow
Take off	100
Climb out	85
Cruise	65
Approach	45
Taxi	AFM

The power setting for the different modes is established by adjusting the throttle to bring the indicated fuel flow to the corresponding % that has been calculated out of the maximum fuel flow.

Important:

- If the engine has manual mixture adjustments, all settings from table 6 correspond to mixture “full rich”.
- The taxi mode is treated differently: The engine is running at the recommended RPM for warm up according to the AFM/engine operation manual. Therefore, in order to measure taxi mode, the engine power is set by the recommended engine RPM and the resulting fuel flow is measured.

- Cruise power for engines with manual mixture control: The initial power setting is adjusted with "mixture full rich" at 65% of maximum fuel flow, according to table 6. The final cruise setting (CRUISE LEAN) for the measurement will be obtained by leaning the mixture to **lambda = 0.93** (see 5.3.1), while maintaining the RPM from the initial power setting. (It is recommended to use an exhaust emission measurement system, which is capable of computing the lambda values from measured concentrations instantly, see more details in 6.3.2.)

Example: Max. fuel flow = 70 liter / hour

- ➔ Climb out setting = 70 liter /hour * 0.85 = <u>60 liter / hour</u>
- ➔ Cruise **initial** setting with mixture full rich = <u>46 liter / hour</u>
- ➔ Cruise lean setting by leaning to lambda = 0.93 and maintaining RPM. Now, the fuel flow and emission concentrations are measured. Fuel flow is usually between 50 and 55% of maximum fuel flow and would result in around 37 liter / hour for this example
- ➔ Approach setting = 32 liter / hour
- ➔ Taxi setting = Taxi RPM according engine/aircraft manual, usually around 7 liters / hour.

6.3.2 Recommended procedure

- We recommend going from high power to low power measurements, at least three measurements per power mode and a VHF radio communication between pilot and measurement team.
- The first measurement would be again the maximum fuel flow (max. power) measurement. At this occasion, the repetition of maximum fuel flow is a check for the first maximum fuel flow measurement.
- As soon as measured concentrations are stable, data are recorded. The pilot should note at least fuel flow, RPM and engine temperatures during the measurements. (This can be a demanding task, with the airframe vibrating and having to hold the throttle lever in its position.)
- After the measurements, the engine power is reduced to the recommended Taxi/Idle setting for cooling down.
- The measurement for climb out mode is prepared and if necessary, measurement equipment is checked again for calibration and zero points.
- The pilot is then asked to set the throttle to reach the climb out fuel flow value, calculated as described above. As soon as the fuel flow reading is reported to be stable and measured concentrations are stable, the next data recording begins. The pilot should note at least fuel flow, RPM and engine temperatures during the measurements, as above.
- After measurement, the engine power is again reduced to the recommended Taxi/Idle setting for cooling down.
- This procedure is repeated down to taxi mode.

Cruise mode:

- As described in the example above, **the measurement of the cruise mode is special, if the engine is equipped with a manual mixture adjustment.** The pilot is asked to set the throttle to reach the cruise fuel flow value at mixture "full rich", calculated as described above. As soon as the fuel flow reading is reported to be stable, the mixture is slowly leaned to lambda = 0.93. The corrections ("a bit richer, a bit leaner") are transmitted from the measurement team to the pilot. The pilot has to make sure that RPM remain constant. If not, a throttle adjustment is necessary, followed by a mixture adjustment. At stable conditions, the data recording begins. The pilot should again note at least fuel flow, RPM and engine temperatures after stable conditions have been established, as mentioned above. The adjustment of static cruise power can take more than one minute and therefore it is vital to observe engine temperatures carefully. Engine cylinder head temperatures are rising and there is less engine cooling, because the aircraft is not moving forward.

6.4 Combined MAP & fuel flow method

More complex aircraft, especially those fitted with a variable pitch propeller or even constant speed propeller need a MAP gauge, which is generally a reasonable power indicator (see section 3). Engine parameter comparison of in-flight and ground measurements showed a potential for improvements by use of MAP. **This method is referred as "V5" in FOCA piston engine emissions data sheets.**

6.4.1 Preparations

From Airplane Operations Manual (AFM), typical MAP values for **climb and cruise mode** are recorded. We suggest a reference pressure altitude of sea level for climb mode and 5000ft for cruise mode.

Normally, no MAP values are given in the AFM for **approach mode**. From in-flight test we recommend a pre-selected mean value of **18 InHg and minimum 44% of maximum fuel flow at mixture "full rich"** (Appendix 2).

The MAP values are input to the measurements, as shown with the orange fields in figure 19.

For **take-off mode**, no pre-selected MAP value is necessary. However, at full power with a normally aspirated engine, the value is an indication for ambient air pressure. Near sea level it can read around 29 InHg (Because of some inefficiencies in the engine induction system it does not fully reach the value of ambient air pressure with the engine running at full power). However, it is possible to get nearly 100% of rated maximum propeller horsepower at 27 InHg too, if the air is cold and therefore dense enough. That is one reason, why we recommend doing the measurements at low altitude airports and cold ambient temperatures (low density altitudes). With the variable pitch propeller, a pre-selected RPM value, normally the maximum allowed RPM for take-off, is necessary. This is indicated in the dark blue fields in figure 19. For all static ground measurements we recommend to leave propeller pitch at "high RPM".

Taxi mode power is selected by RPM, according to AFM, as with the simple fuel flow method. RPM input is indicated in light blue in figure 19. MAP and fuel flow for taxi mode will result from measurements.

	US gal/h	JS gal/h or l/h			1/min.	1/min.		
Max. FF R			(AFM/Test)	RPM TA			RPM TO	(AFM)
	In HG	ft			In HG	ft		
MAP 65%CR			(AFM)	MAP 85% CL				(AFM)
	In HG	ft			In HG	ft		
MAP AP			(Test)	MAP TA				(Test)

Meas. Nr.	Mode/Mixt.	MAP	FF	FF/ MFF (%)	FF Check	MAP	RPM input	RPM	λ input	λ
1	TO	F.T.			min. 95					
2	TO	F.T.			min. 95					
3	TO	F.T.			min. 95					
4	CL	0.0			min.77					
5	CL	0.0			min.77					
6	CL	0.0			min.77					
7	CR R	0.0			min. 51					
8	CR R	0.0			min. 51					
9	CR R	0.0			min. 51					
10	CR L	0.0			min. 45				0.93	
11	CR L	0.0			min. 45				0.93	
12	CR L	0.0			min. 45				0.93	
13	AP	0.0			min. 44					
14	AP	0.0			min. 44					
15	AP	0.0			min. 44					
16	TA	0.0			min. 09					
17	TA	0.0			min. 09					
18	TA	0.0			min. 09					

Figure 19: Engine data input and recording sheet used by FOCA. All entries from measurements go into the yellow coloured fields, brown fields are MAP predefined values, red fields the calculated relations of measured fuel flow to maximum fuel flow and green fields contain minimum percentage of maximum fuel flow that should be achieved in the power setting (fuel flow check).

6.4.2 Recommended procedure

- We recommend going from high power to low power measurements with at least three measurements per power mode
- There should be a VHF radio communication between the pilot and the measurement team.
- All measurements should be done with propeller pitch “high RPM”.
- The first measurement would be again the maximum fuel flow (max. power) measurement. At this occasion, the repetition of maximum fuel flow is a check for the first maximum fuel flow measurement.
- As soon as measured concentrations are stable, data are recorded. The pilot should note at least fuel flow, RPM and engine temperatures during the measurements. (This can be a demanding task, with the airframe vibrating and having to hold the throttle lever in its position.)
- After the measurements, the engine power is reduced to the recommended Taxi/Idle setting for cooling down.
- The measurement for climb out mode is prepared and if necessary, measurement equipment is checked again for calibration and zero points.
- The pilot is then asked to set the throttle to reach the climb out MAP value. As soon as the MAP reading is reported to be stable and measured concentrations are stable, the next data recording begins. The pilot should note at least fuel flow, RPM and engine temperatures during the measurements, as above. The fuel flow is transmitted to the measurement team and it is checked that the value fulfills the minimum requirement (E.g. minimum 77% of the maximum fuel flow for climb, see figure 17, green column). If the minimum fuel flow is not reached, throttle should be increased accordingly.
- After measurement, the engine power is again reduced to the recommended Taxi/Idle setting for cooling down.
- This procedure is repeated down to taxi mode.

Cruise mode:

- As described in the simple fuel flow method, **the measurement of cruise mode** following the climb mode **is special, if the engine is equipped with a manual mixture adjustment.** The pilot is asked to set the throttle to reach the cruise MAP value at mixture “full rich”. As soon as the MAP, RPM and fuel flow reading are reported to be stable, the mixture is slowly leaned to lambda = 0.93. The corrections (“a bit richer, a bit leaner”) are transmitted from the measurement team to the pilot. The pilot has to make sure that RPM remain constant. If not, a throttle adjustment is necessary, followed by a mixture adjustment. At stable conditions, the data recording begins. The pilot should again note at least fuel flow, RPM and engine temperatures after stable conditions have been established, as mentioned above. Again, the adjustment of static cruise power can take more than one minute and therefore it is vital to observe engine temperatures carefully. Engine cylinder head temperatures are usually rising and there is less engine cooling, because the aircraft is not moving forward.

7. Example for measurement documentation

FOCA Groundmeasurement	VERSION I.V5	Injected Eng./CS Prop.	Meas. Nr.	78	A/C Reg.	HB	NCO

Aircraft	Commander 114		Full Cycle
Engine	Lyc IO-540-T4A5D	Engine Hours	1817
Prop	HC-C2YR-1	Fuel Injector	standard
Silencer	standard	Rated P. (HP)	260
Fuel	AVGAS 100LL		
Equipment	Stargas 898, Mexa-1150 HFID		

Crew	
PIC	G. Staude
Expert	rit
Warm up	
Block Time	Flight Time
13:20	
14:05	
Check Oil Temp.> 60°C	

Day	13. Dez 06	Wind (° / kn)	calm	Dewpoint (°C)	NIL	Airport (ft)	1575
						PA	1071
Begin LT	14.57 Uhr	Air T (°C)	3	QNH (hPa)	1031	DA	9

	US gal/h	US gal/h or l/h			1/min.	1/min.		
Max. FF R		85	(AFM/Test)	RPM TA	1000	2700	RPM TO	(AFM)
	In HG	ft			In HG	ft		
MP 65% CR	22.5	SL	(AFM)	MP 85% CL	25	SL		(AFM)
	In HG	ft			In HG	ft		
MP AP	17.9	SL	(Test)	MP TA	11.8			(Test)

Meas. Nr.	Mode/Mixt.	% Power	FF	FF/ MFF (%)	FF Check	MP	RPM input	RPM	λ input	λ
1	TO	F.T.	84	99	min. 95	27.2	2700	2620		0.749
2	TO	F.T.	83	98	min. 95	27.2	2700	2620		0.749
3	TO	F.T.	83	98	min. 95	27.2	2700	2620		0.749
4	CL	25.0	74	87	min.77	25		2590		0.76
5	CL	25.0	74	87	min.77	25		2590		0.759
6	CL	25.0	74	87	min.77	25		2590		0.757
7	CR R	22.5	61	72	min. 51	22.5		2480		0.773
8	CR R	22.5	61	72	min. 51	22.5		2480		0.773
9	CR R	22.5	61	72	min. 51	22.5		2480		0.771
10	CR L	22.5	49	58	min. 45	22.5		2350	0.93	0.947
11	CR L	22.5	49	58	min. 45	22.5		2350	0.93	0.95
12	CR L	22.5	49	58	min. 45	22.5		2350	0.93	0.943
13	AP	17.9	37	44	min. 44	18		2120		0.809
14	AP	17.9	37	44	min. 44	18		2120		0.811
15	AP	17.9	37	44	min. 44	18		2120		0.812
16	TA	11.8	12	14	min. 09	11.8	1000	1000		0.8
17	TA	11.8	12	14	min. 09	11.8	1000	990		0.794
18	TA	11.8	13	15	min. 09	11.8	1000	980		0.781

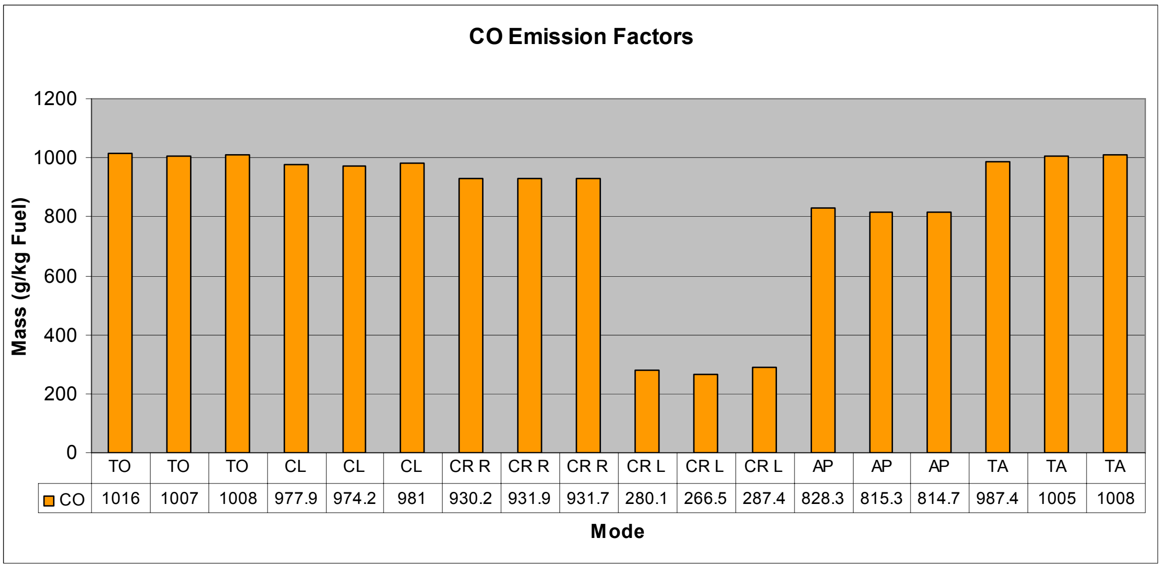
Figure 20: Practical example of the engine data input file for a Lyc IO-540 measurement (Aircraft HB-NCO). The file contains relevant aircraft and engine data, ambient conditions and (in this case) predefined MAP values from AFM, measured fuel flow, MAP, RPM and lambda (compare to figure 19).

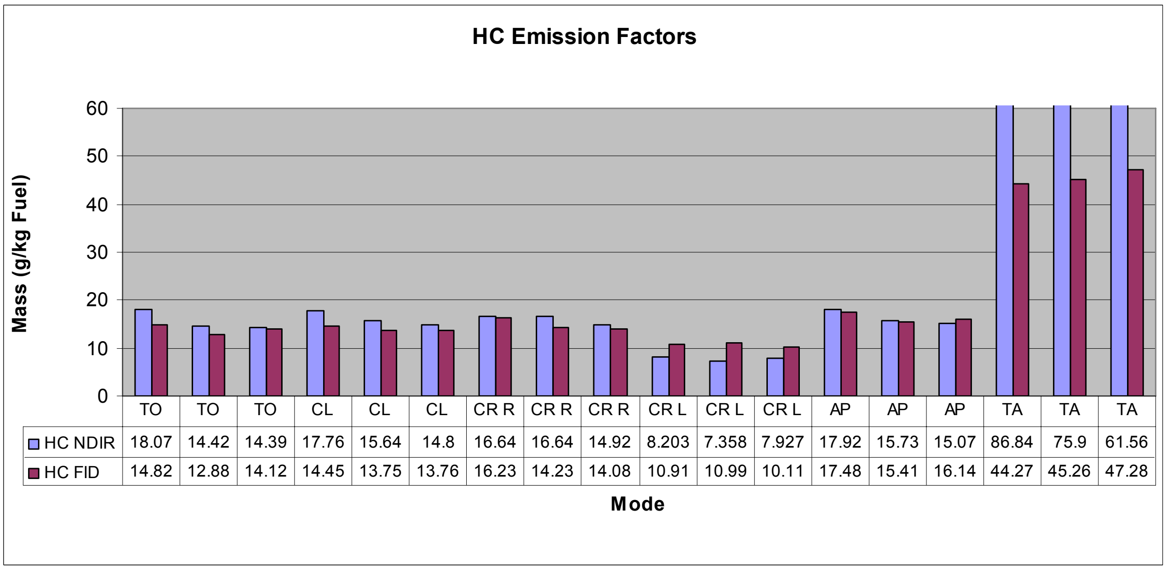
					Stargas NDI	Horiba FID						
Meas. Nr.	Mode/Mixture	FF	CO (Vol. %)	CO2 (Vol. %)	HC (ppm)	HC (ppmC)	O2 (Vol. %)	NO (ppm)	Lambda	Airpr. (hPa)	Humidity	Air T (°C)
1	TO	84	9.027	8.68	170	2300	0.16	198	0.749	964		3
2	TO	83	8.954	8.79	136	2000	0.09	165	0.749	964		3
3	TO	83	8.994	8.79	136	2200	0.09	127	0.749	964		3
4	CL	74	8.528	8.85	164	2200	0.17	226	0.76	964		3
5	CL	74	8.522	8.92	145	2100	0.11	180	0.759	964		3
6	CL	74	8.571	8.85	137	2100	0.1	137	0.757	964		3
7	CR R	61	7.877	8.97	149	2400	0.15	251	0.773	964		3
8	CR R	61	7.877	8.97	149	2100	0.15	251	0.773	964		3
9	CR R	61	7.96	9.07	135	2100	0.1	216	0.771	964		3
10	CR L	49	2.058	12.63	64	1400	0.25	2191	0.947	964		3
11	CR L	49	1.945	12.64	57	1400	0.24	2296	0.95	964		3
12	CR L	49	2.116	12.61	62	1300	0.2	2066	0.943	964		3
13	AP	37	6.782	9.49	155	2500	0.35	364	0.809	964		3
14	AP	37	6.664	9.61	136	2200	0.3	389	0.811	964		3
15	AP	37	6.649	9.59	130	2300	0.31	389	0.812	964		3
16	TA	12	8.173	7.89	744	6400	1.77	42	0.8	964		3
17	TA	12	8.389	7.8	655	6600	1.7	39	0.794	964		3
18	TA	13	8.547	7.86	538	7000	1.34	40	0.781	964		3

Figure 21: Measured exhaust concentrations (Measurement HB-NCO). Data entries are checked for plausibility and variation (First measurement quality check).

		NDIR	FID		
Meas Nr.	EI CO [g/kg]	EI HC [g/kg]	EI HC [g/kg]	EI NOx [g/kg]	LTO
1	1015.51348	18.0651925	14.8165072	3.041351843	TO
2	1006.90822	14.4248084	12.8788933	2.53347117	TO
3	1008.03576	14.3923887	14.1195705	1.94350651	TO
4	977.859871	17.7578546	14.4453432	3.538319905	CL
5	974.182434	15.6446866	13.746553	2.809509427	CL
6	980.950534	14.8000098	13.7629223	2.140895179	CL
7	930.226235	16.6431938	16.2298584	4.047256074	CR R
8	931.862325	16.6431938	14.2261031	4.054374423	CR R
9	931.68529	14.9187271	14.0750912	3.451986958	CR R
10	280.070402	8.20343786	10.9100221	40.71209449	CR L
11	266.544	7.35811704	10.9863414	42.96159664	CR L
12	287.420635	7.92668518	10.111635	38.31702853	CR L
13	828.306316	17.9240617	17.4843281	6.070071338	AP
14	815.276508	15.7268266	15.4123325	6.497985909	AP
15	814.676326	15.0659279	16.1373549	6.50785081	AP
16	987.375305	86.835632	44.2747876	0.692802229	TA
17	1004.68735	75.897227	45.2626966	0.637741339	TA
18	1008.17031	61.5586021	47.281799	0.644227734	TA

Figure 22: Calculated emission factors (according Appendix 5)





Figures 23 and 24: Visualization of CO and HC emission factors for the measured engine modes.

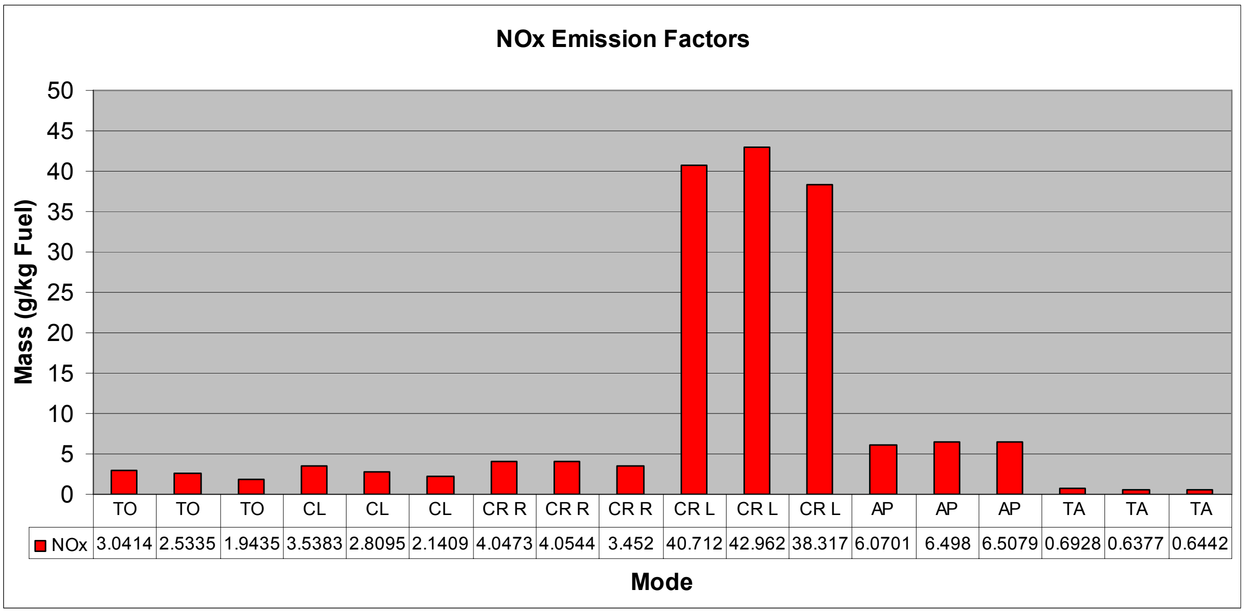
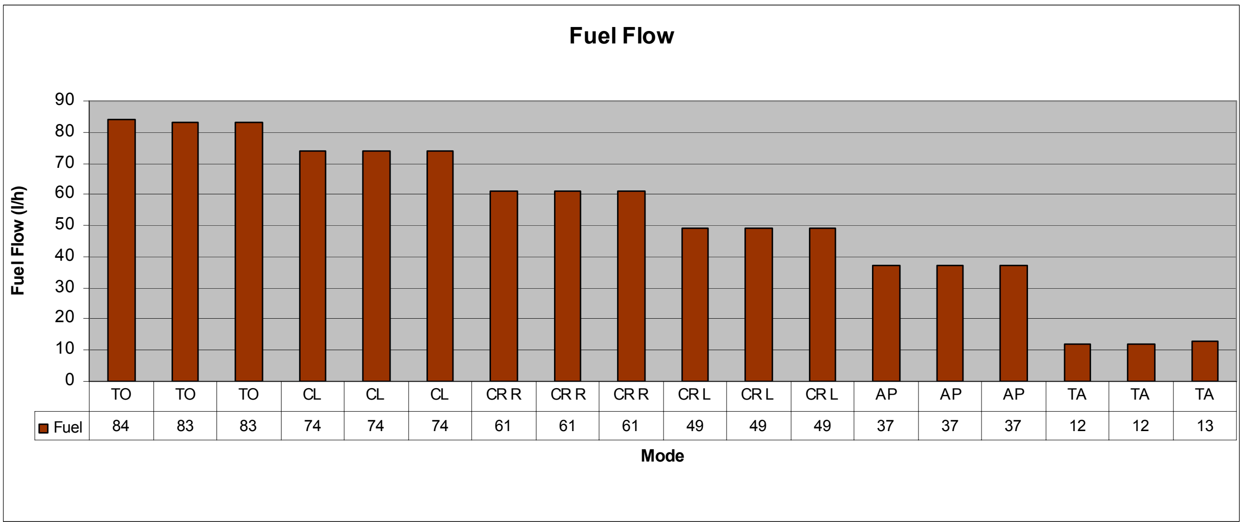
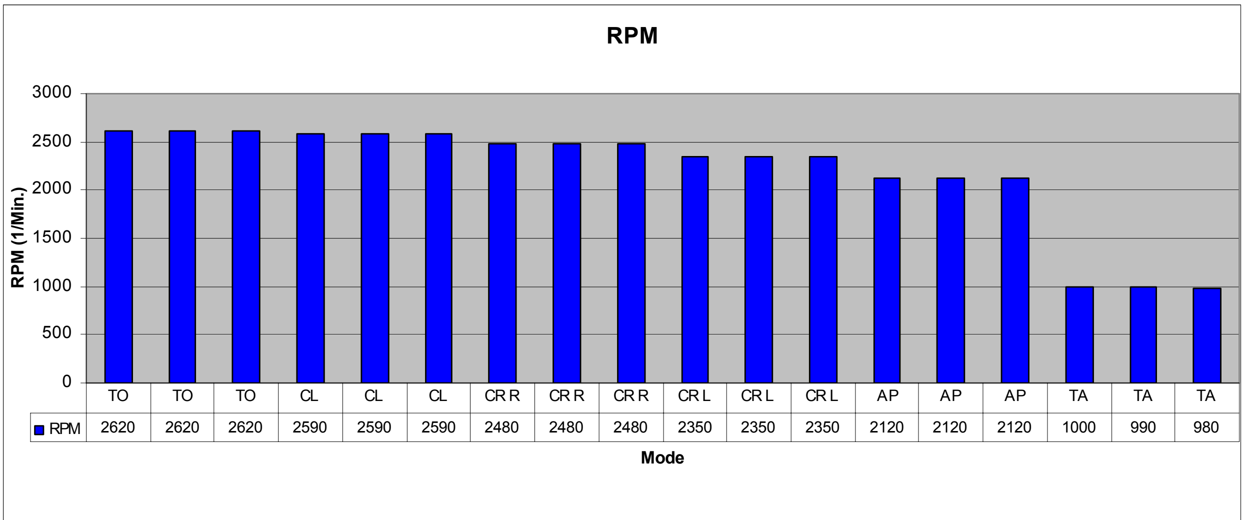
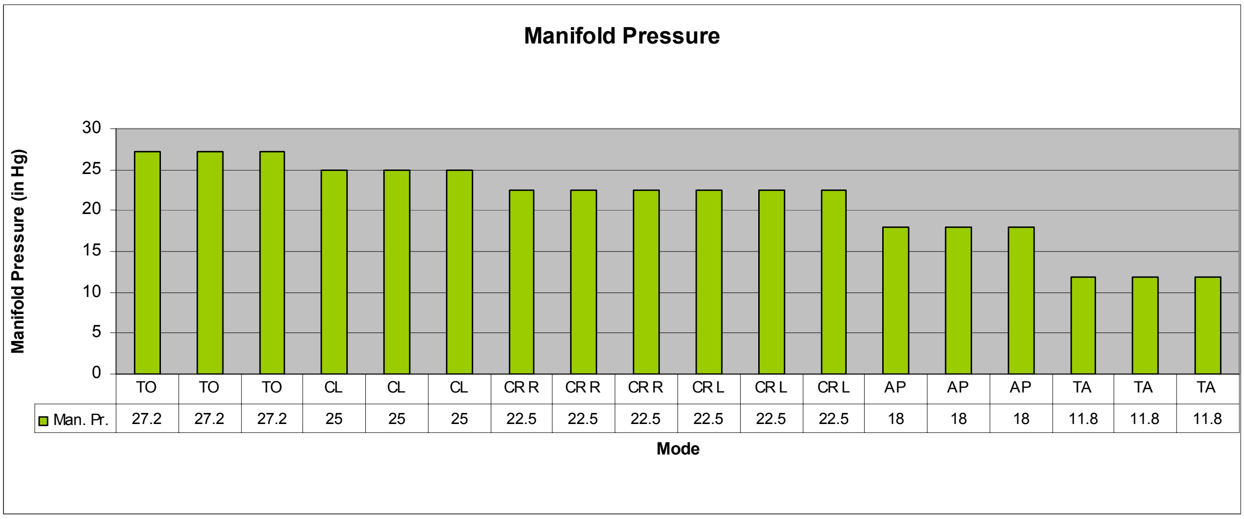


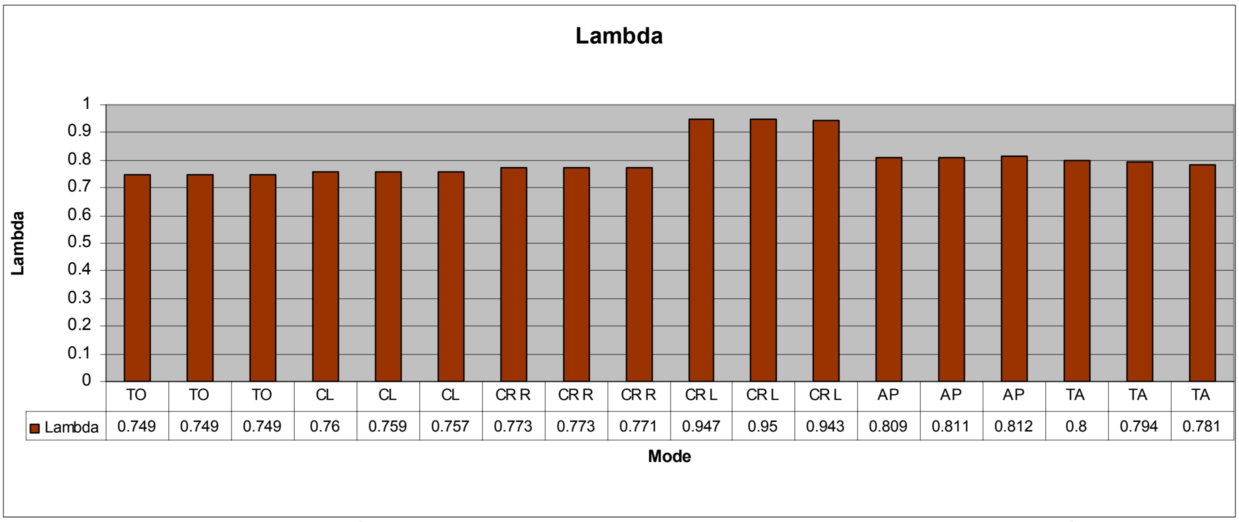
Figure 25: Visualization of NO_x emission factors for the measured engine modes. Visualization is used for a second measurement quality check.





Figures 26 and 27: Visualization of measured fuel flow and RPM. During subsequent measurements of one particular power mode, fuel flow and RPM should be maintained constant.





Figures 28 and 29: Visualization of measured MAP and lambda. During subsequent measurements of one particular power mode, MAP should be maintained constant and lambda should result in practically constant values. (Third check for measurement quality). For engines with manual air/fuel mixture adjustment, like the engine measured in this example, the CR L (cruise leaned) lambda value should be kept constant as well, with a value around 0.93, as described in 6.3.1, 6.3.2 and 6.4.2. In this example, the CR L lambda values vary between 0.943 and 0.95.

Statistical Basis for Calculation
Number of Measurements per powersetting
3
Factor for 90% Confidence Level (T-Test, Assumption: Normal Distribution)
2.92

Figure 30: Before computing mean values per power mode, the statistical functions for determining a 90% confidence interval are defined. For this very small sample of only three measurements per power mode, a T-test is suggested.

TO	Emp. Mean	Emp. St.Dev.	Mean stat. Error	90% CI	Fuel Flow (kg/s)
EI CO [g/kg]	1010.15	4.68	2.70	4.47	0.0167
EI HC [g/kg]	13.94	0.98	0.57	2.05	
EI NOx [g/kg]	2.51	0.55	0.32	1.53	

CL	Emp. Mean	Emp. St.Dev.	Mean stat. Error	90% CI	Fuel Flow (kg/s)
EI CO [g/kg]	977.66	3.39	1.96	3.80	0.0148
EI HC [g/kg]	13.98	0.40	0.23	1.30	
EI NOx [g/kg]	2.83	0.70	0.40	1.73	

CR	Emp. Mean	Emp. St.Dev.	Mean stat. Error	90% CI	Fuel Flow (kg/s)
EI CO [g/kg]	931.26	0.90	0.52	1.96	0.0122
EI HC [g/kg]	14.84	1.20	0.69	2.26	
EI NOx [g/kg]	3.85	0.35	0.20	1.21	

AP	Emp. Mean	Emp. St.Dev.	Mean stat. Error	90% CI	Fuel Flow (kg/s)
EI CO [g/kg]	819.42	7.70	4.45	5.73	0.0074
EI HC [g/kg]	16.34	1.05	0.61	2.12	
EI NOx [g/kg]	6.36	0.25	0.14	1.03	

TA	Emp. Mean	Emp. St.Dev.	Mean stat. Error	90% CI	Fuel Flow (kg/s)
EI CO [g/kg]	1000.08	11.14	6.43	6.89	0.0025
EI HC [g/kg]	45.61	1.53	0.88	2.56	
EI NOx [g/kg]	0.66	0.03	0.02	0.36	

CR L	Emp. Mean	Emp. St.Dev.	Mean stat. Error	90% CI	Fuel Flow (kg/s)
EI CO [g/kg]	278.01	10.59	6.11	6.72	0.0098
EI HC [g/kg]	10.67	0.48	0.28	1.44	
EI NOx [g/kg]	40.66	2.32	1.34	3.15	

Figure 31: Calculation of empirical mean, empirical standard deviation, mean statistical error and 90% confidence interval based on T-test. Mean HC emission factors are only based on the FID values. The fuel flow in kg/s is calculated from fuel flow in litres/hour by using a fuel density of 0.72 kg/litre, if actual density at 15°C is not known.

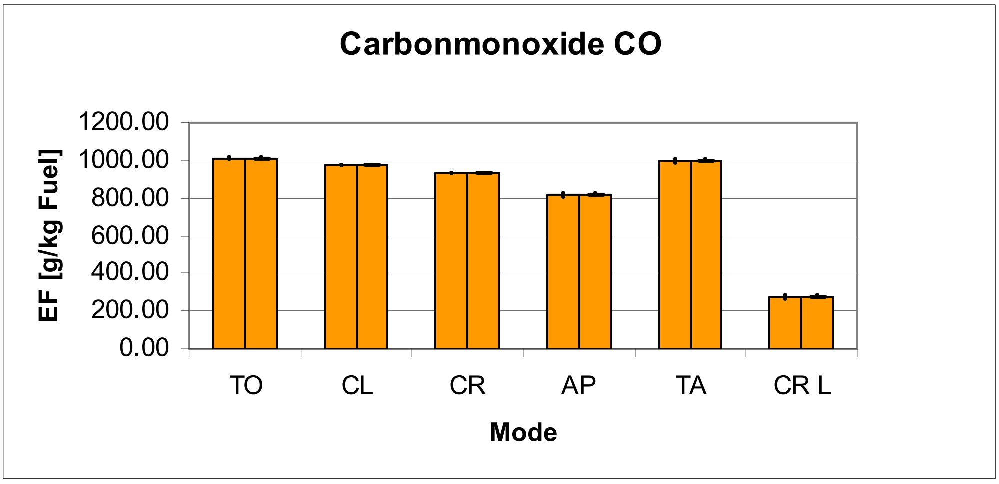


Figure 32: Visualization of mean statistical error and 90% confidence interval (two bars with emission factor value for each power mode) for EF CO.

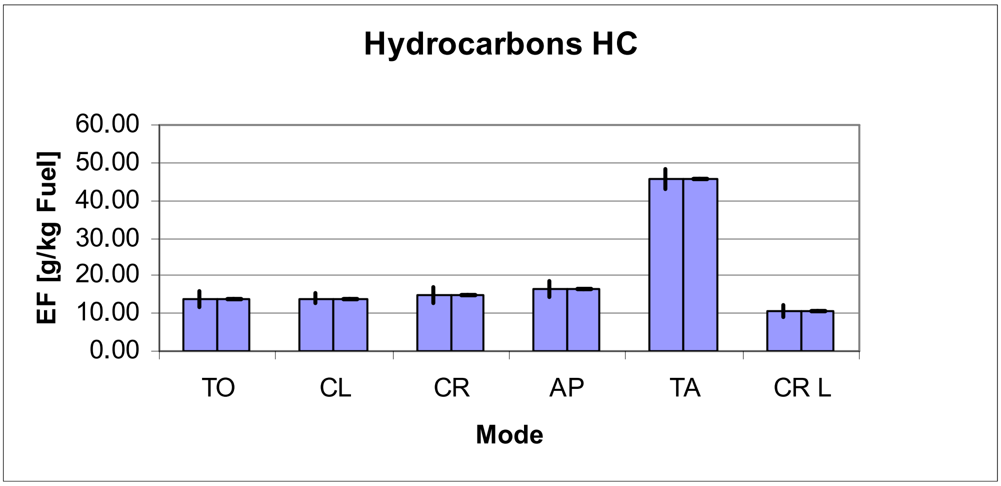


Figure 33: Visualization of mean statistical error and 90% confidence interval (two bars with emission factor value for each power mode) for EF HC (based on FID).

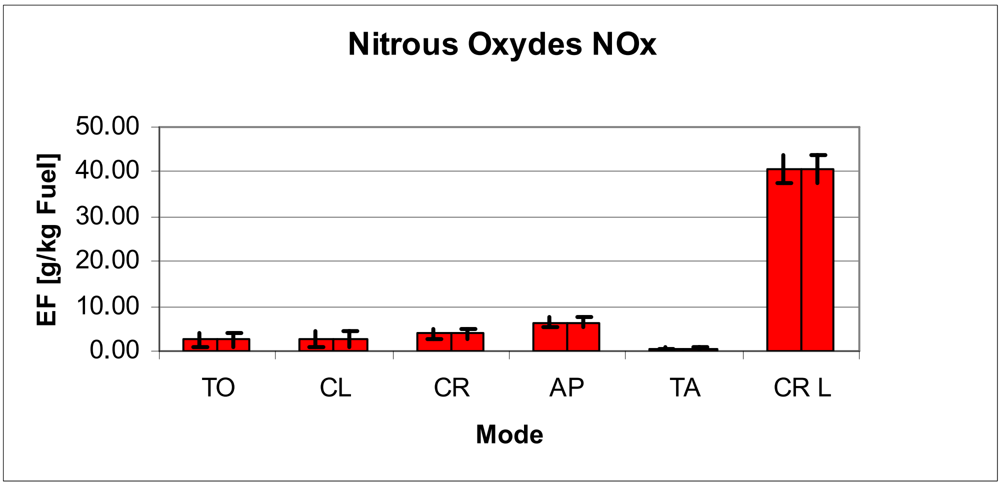
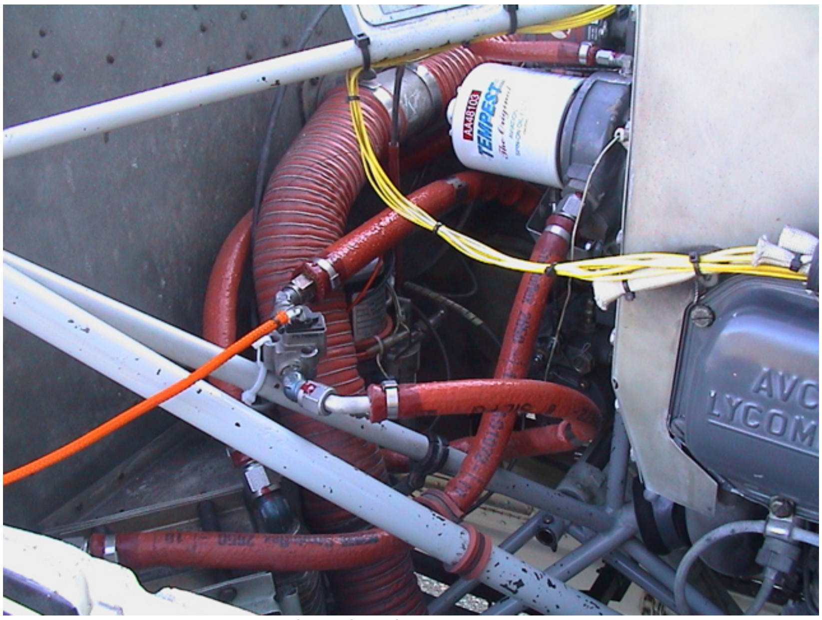


Figure 34: Visualization of mean statistical error and 90% confidence interval (two bars with emission factor value for each power mode) for EF NO_x. Please note the limitations for NO_x measurements with the FOCA low-cost measurement system, as described in Appendix 1 and 5. Systematic errors are not included in this statistical analysis.



Picture 6: Documentation of the fuel flow transducer installation (in the middle of the picture). The orange wire leaving to the left is carrying the pulses from the transducer to the fuel flow indicator in the cockpit. This installation is NOT certified for in-flight operation.

Schweizerische Eidgenossenschaft
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Confederaziun svizra

Federal Office of Civil Aviation, Environmental Affairs
ENGINE EXHAUST EMISSIONS MEASUREMENT
PISTON ENGINES

ENGINE IDENT	Lyc IO-540-T4A5D	INJECTOR	standard
UNIQUE ID NUMBER	PF12	INJECTION NOZZLE	-
ENGINE TYPE	6Cyl. 4Stroke Air cooled	RATED POWER (Poo) (HP)	260
PROPELLER TYPE	HC-C2YR-1		

DATA STATUS

x	EMISSION INVENTORY
	PRE-REGULATION
	CERTIFICATION
	REVISED

TEST ENGINE STATUS

	NEWLY MANUFACTURED ENG.
x	USED ENGINE
	DEDICATED TO PRODUCTION
	OTHER (SEE REMARKS)

MEASUREMET STATUS

	GROUND BASED FIXED PITCH PROP
x	GROUND BASED VARIABLE PITCH PROP

CURRENT ENGINE STATUS

x	IN PRODUCTION
	OUT OF PRODUCTION
	OUT OF SERVICE

EMISSIONS STATUS

	DATA CORRECTED TO REFERENCE TEMPERATURE
	DATA CORRECTED TO REFERENCE (ANNEX 16 VOLUME II)
IV5	CALCULATION METHODOLOGY VERSION NUMBER

MEASURED DATA

MODE	POWER SETTING (%)	TIME (minutes)	FUEL FLOW (kg/s)	EI HC (g/kg)	EI CO (g/kg)	EI NOx (g/kg)	PM (…) (…)
TAKE-OFF	100	0.3	0.0167	13.9	1010	3	
CLIMB OUT	85	2.5	0.0148	14.0	978	3	
CRUISE	65	60	0.0122	14.8	931	4	
APPROACH	45	3	0.0074	16.3	819	6	
TAXI	12	12	0.0025	45.6	1000	1	
CRUISE LEAN	65	60	0.0098	10.7	278	41	
LTO TOTAL FUEL (kg) or EMISSIONS (g)			5.63	138	5341	17	
CRUISE 1HOUR FUEL (kg) or EMISSIONS (g)			35.3	376	9808	1435	
NUMBER OF TESTED ENGINES			1	1	1	1	
NUMBER OF TESTS			3	3	3	3	

ATMOSPHERIC CONDITIONS

BAROMETER QNH (hPa)	1031
TEMPERATURE (°C))	3
DEW POINT (°C)	-
DENSITY ALTITUDE (ft)	9

FUEL

SPEC	AVGAS 100LL
HC	C7H13

MANUFACTURER:

TEST ORGANIZATION:	FOCA
TEST LOCATION:	LSPL
TEST DATES:	13. Dez 06

REFERENCE:
33-05-003.001 groundmeasurement78.injected.
constantspeed.IV5.1.HBNCO_061213_rit
Expert: T. Rindlisbacher

REMARKS:

Figure 35: Final data sheet for Lyc IO-540-T4A5D as provided by FOCA for download.