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Aviation Policy and Strategy
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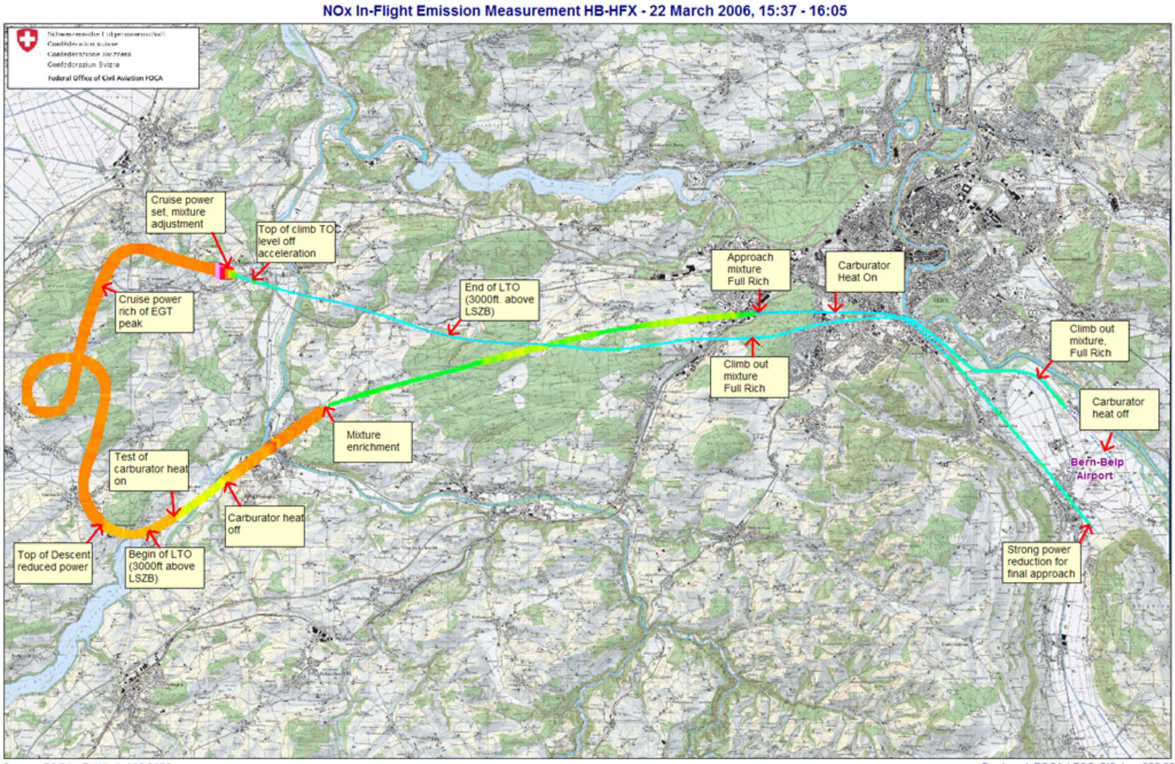
FOCA DATA BASE FOR AIRCRAFT PISTON ENGINE EMISSION FACTORS

Appendix 2: In-flight Measurements

NOx In-Flight Emission Measurement HB-HFX - 22 March 2006, 15:37 - 16:05



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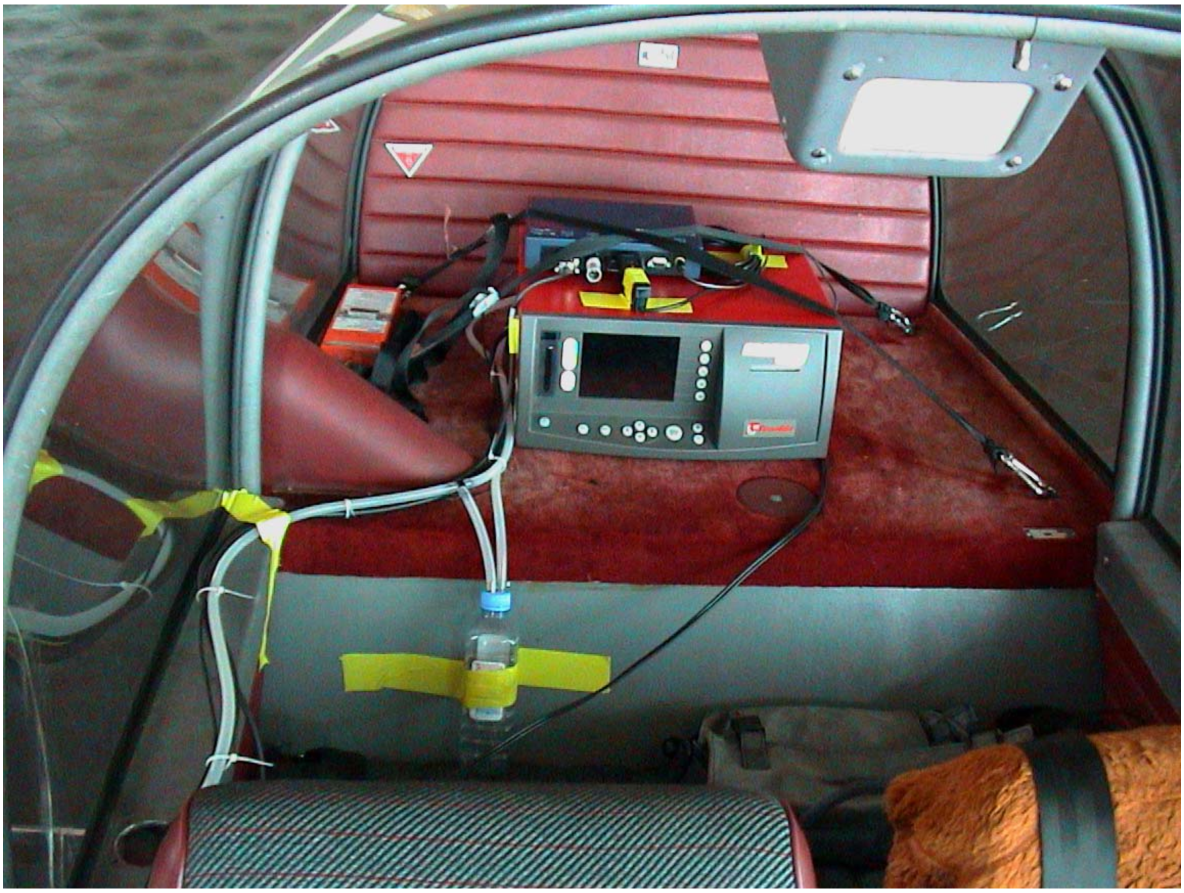
Contents

1.a) HB-EYS: Preparation for the first in-flight tests

July 2003: The FOCA measurement system was installed in HBEYS for the first time. After successful ground testing, documentation for airworthiness validation of such a major aircraft modification (aircraft category “restricted”) was completed.


Picture 1: Electronic RPM and fuel flow installation

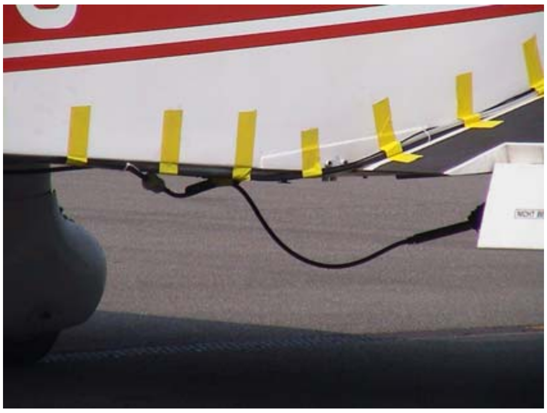

Picture 2: Sampling lines in and out


Picture 3: Installation of the remote controlled gas analyzer in the luggage compartment of HBEYS. The exhaust sample flows through the black line to the analyzer. Because of high CO concentrations in the exhaust, all sample gas has to be pumped outside the cabin (white line). Water condensate is separated from the sample and trapped in a small bottle at the bottom. To check cabin CO concentration level, a CO detector is installed, which is independent from the analyzer.
The fuel scan box, which indicates the fuel flow, is placed on the knees of the copilot.
The exhaust probe installation has been tested during many hours of ground operation prior to the first flight.

Picture 4: Exhaust probe

Picture 5: Cockpit of HBEYS with 12VDC/70W power supply for the gas analyzer on the right.

Picture 6: Taxiing for the first flight



Picture 7: Those tapes have proven reliable…

Installation steps HBEYS

1. Mount exhaust probe
2. Mount RPM detector (Engine cowling, electric line)
3. Connect Fuel Scan
4. Remove back seat, ELT OFF during work
5. Fix Stargas in baggage compartment, install H_2O line
6. ELT ON
7. Install 12DC lines and extern TV-screen
8. Install exhaust sample lines IN and OUT (via fresh air vents on starboard, which are removed)
9. Install lines for thermocouple
10. Scotch all lines (exhaust sampling lines, PET, 12VDC and RPM detector lines)

Operational Changes

Installation moves the centre of gravity aft, which has to be considered in „Weight and Balance“

At engine start up there is an additional checklist for measurement system start up.

If one of the cockpit CO detectors changes the colour to green or even blue, the canopy must be immediately opened by about 10 cm.

Maximum continuous vertical acceleration is limited to +2g. Avoid negative vertical accelerations.

Maximum pressure altitude is limited to 7000 ft AMSL.

Checklist Stargas 898

Preparing for operation

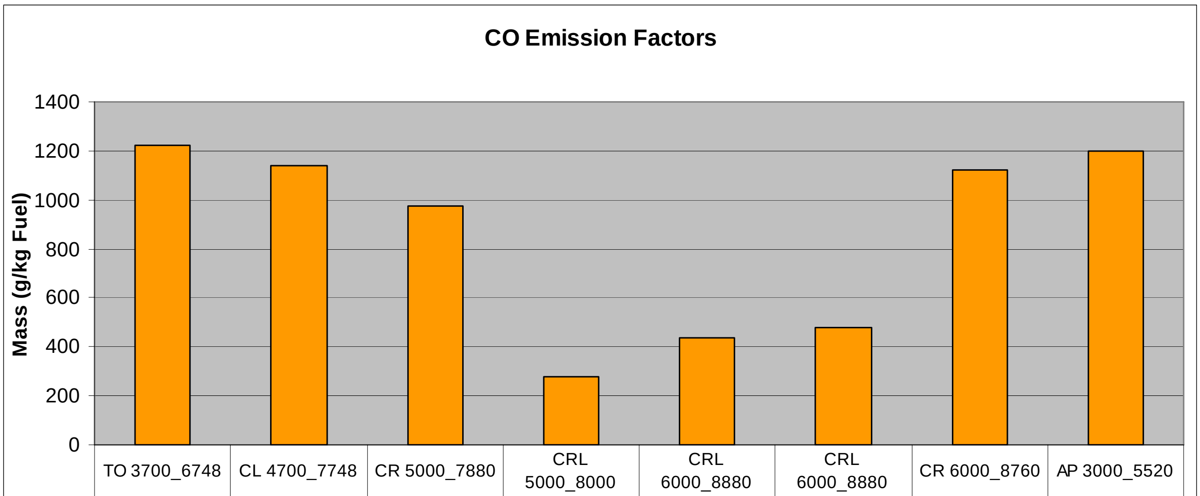
Paper roll	Check
Operation supply switch	Chose „Battery“
Robin Checklist	Engine in warming up phase
Robin Checklist Radio Master	ON
Main switch Stargas	ON
External monitor	ON
Revolution counter	Red LED ON
Pump	In function
Menu Pump	OFF
Revolution counter	Green LED ON, if negative: Vary Engine revolutions betw. taxi idle and 2000 RPM
Clock Stargas	Check
Menu Exhaust measurement	Standard

Before measurement

Warming phase	> 30 seconds
Pump	ON
Automatic calibration	in function
Value for O2 (with probe pipe disconnected)	21%
Other values (with probe pipe disconnected)	0 (HC few ppm)
Fuel Flow	in function

1.b) Calculated emission factors for first test flight with HBEYS

All calculations are done according Appendix 5. Abbreviations used in the figures:
TO = Take off roll, CL = Climb, CR = Cruise, AP = Approach, L = air fuel mixture manually leaned
3700_6748 = Altitude 3700ft QNH and Density Altitude 6748ft etc.



	TO 3700_6748	CL 4700_7748	CR 5000_7880	CRL 5000_8000	CRL 6000_8880	CRL 6000_8880	CR 6000_8760	AP 3000_5520
CO	1224	1137	975	279	436	479	1124	1199

Figure 1: CO emission factors for take-off, climb, cruise and approach. TO, CL, CR5000_7748, CR6000_8760 and AP have been flown with air-fuel mixture “full rich”. CRL has been flown with manually adjusted engine air-fuel mixture.

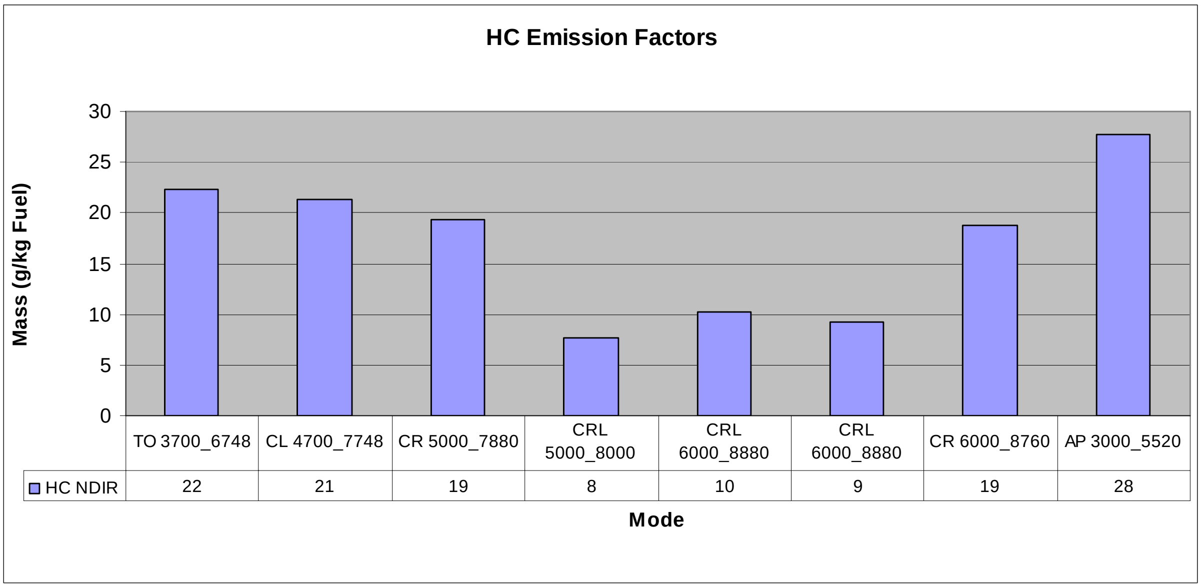


Figure 2: HC emission factors for take-off, climb, cruise and approach. TO, CL, CR5000_7748, CR6000_8760 and AP have been flown with air-fuel mixture "full rich". CRL has been flown with manually adjusted air-fuel mixture.

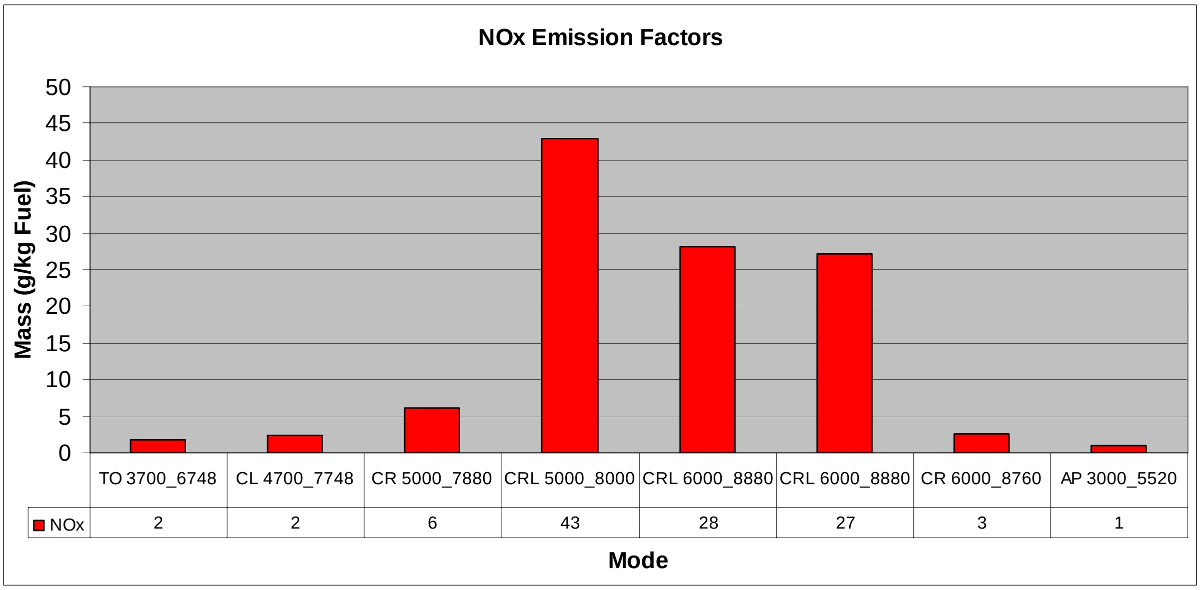


Figure 3: NO_x emission factors for take-off, climb, cruise and approach. TO, CL, CR5000_7748, CR6000_8760 and AP have been flown with air-fuel mixture "full rich". CRL has been flown with manually adjusted air-fuel mixture.

1.c) Discussion and general explanations

The engine tested (like the majority of existing aircraft piston engines) is air cooled. Cooling requirements are best met in cruise, when the air flow is rather high and the power is reduced.

Take-off and Climb: At full power and climb power, such engines would overheat, if they were operated at high combustion efficiency (at high combustion temperatures). For that reason, the standard air-fuel mixture ratio is set far on the rich side. This means that in the combustion chamber, too much fuel is mixed to the air. The excess fuel takes heat in the process of vaporization and combustion temperatures in the combustion chamber remain low, although the engine produces high power. The system can be described as "internal combustion chamber cooling by using excess fuel". In that operating condition, the air-fuel mixture setting is normally described as "full rich". The actual air-fuel mixture compared to the stoichiometric mixture (when oxygen meats exactly the demand for complete combustion) is described with the term "lambda" (see Appendix 5). It is clear that "full rich" conditions result in very low fuel efficiency and very incomplete combustion. This can be seen in the extraordinary high CO and rather high HC emission factors for take-off and climb power settings.

Manual air/fuel mixture control: Most of these engines do not have an automatic mixture control. For reduced power (normally below 75% maximum brake horse power), the mixture has to be manually set to less rich conditions, according to the flight altitude (density altitude) as described in the engine and aircraft operating manual. In many cases of normal aspirated engines (as with the tested aircraft), the manual mixture adjustment to less richer conditions should start during climb at about 5000ft pressure altitude, because the engine maximum power has fallen to around 75% of maximum sea level brake horse power.

Cruise: During cruise, below 75% of maximum brake horse power, the manual mixture adjustment should normally be done for every flight altitude. During the first test flight, when reaching 5000ft, the pilot established cruise configuration. First, the mixture has been left at “full rich” position (CR 5000_7880). Then, the pilot adjusted the mixture to less rich conditions:

Setting the air/fuel mixture: This test aircraft (like many others) does not have exhaust gas temperature gauges, therefore no information about peak exhaust gas (and internal combustion) temperatures (EGT) is available. Therefore the pilot adjusts the mixture with a "rule of thumb": Normally the pilot pulls the mixture lever and leans the mixture until a slight RPM drop of the fixed pitch propeller is recognized. At this condition, the engine is running slightly lean. After that, the pilot pushes the mixture lever slightly back (about 1 cm) and the engine is running slightly rich. After a while, the pilot checks cylinder head and oil temperature. The result on emission factors of the described setting can be seen in CRL 5000_8000. Because of higher combustion efficiency, CO and HC emission factors are significantly lower. However, with increasing combustion temperatures, the NO_x emission factors drastically increase. This is the classical trade-off, (fuel efficiency versus NO_x) also known from rich burn jet engines.

The same mixture adjustment has been repeated at 6000ft cruising altitude. From this first test we had the impression that the "rule of thumb" resulted in a richer mixture than at 5000ft. (CRL 6000_8800) which was confirmed later.

Descent and approach:

During descent, the air/fuel mixture should be enriched gradually. For simplicity - and to make sure pilots do not forget – the AFM of the test aircraft (and of many similar aircrafts) suggests pushing the mixture lever directly to the “full rich” position. The effect of this operation can be seen in CR 6000_8760, where the mixture has been set to full rich just before descent and during approach (AP 3000_5520). Again, we see very high CO and HC emission factors, resulting from much too rich air/fuel mixture, causing very incomplete combustion.

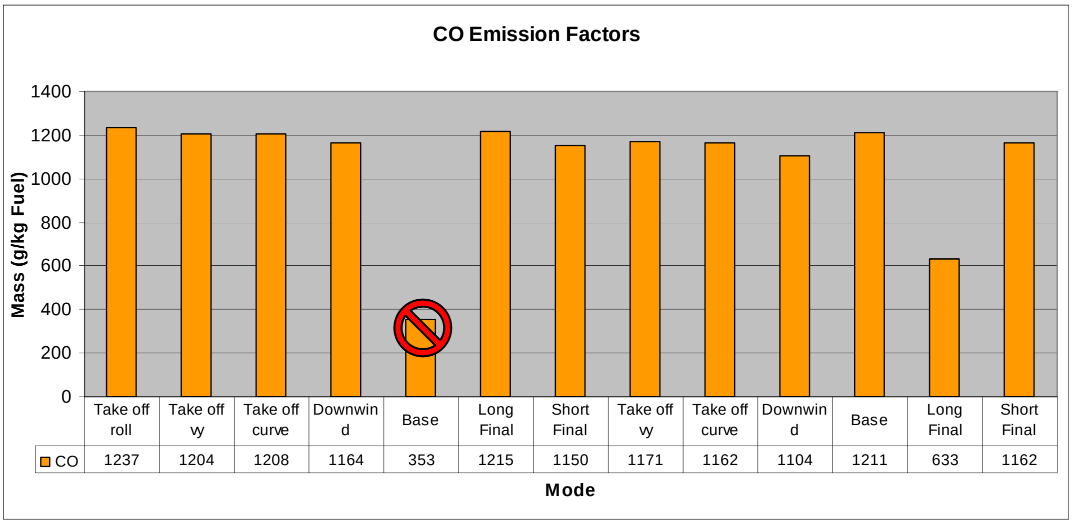
2) Standard flight test programme

The first flight test had shown the tremendous influence of pilot operations on emission factors. A lot of in – flight data would be needed for the development of ground based static tests. For the purpose of calculating emission inventories, the measurement of aerodrome circuits and the study of flight altitude on emissions were necessary.

- Aerodrome circuits (VFR traffic departure and arrival pattern) simulated outside aerodrome airspace, starting at 2000, 4000 and 6000ft. Mixture full rich and leaned (standard leaning procedure as described in 1.c)).
- Climb at full power (within permitted engine limits) with measurements at 3000, 4000, 5000, 6000 and 7000ft. Descent (Approach) at around 45% engine load with measurements at 7000, 6000, 5000, 4000 and 3000ft. Mixture full rich and leaned (standard leaning procedure as described in 1.c)).
- Climb at reduced power (at around 85% engine load) with measurements at 3000, 4000, 5000, 6000 und 7000f. Mixture full rich and leaned (standard leaning procedure as described in 1.c)).
- Cruise at 3000, 4000, 5000, 6000 und 7000ft between 65 and 75% engine load. Controlled leaning (via emission measurements) and standard leaning procedure as described in 1.c).
- Predefined flight profiles.

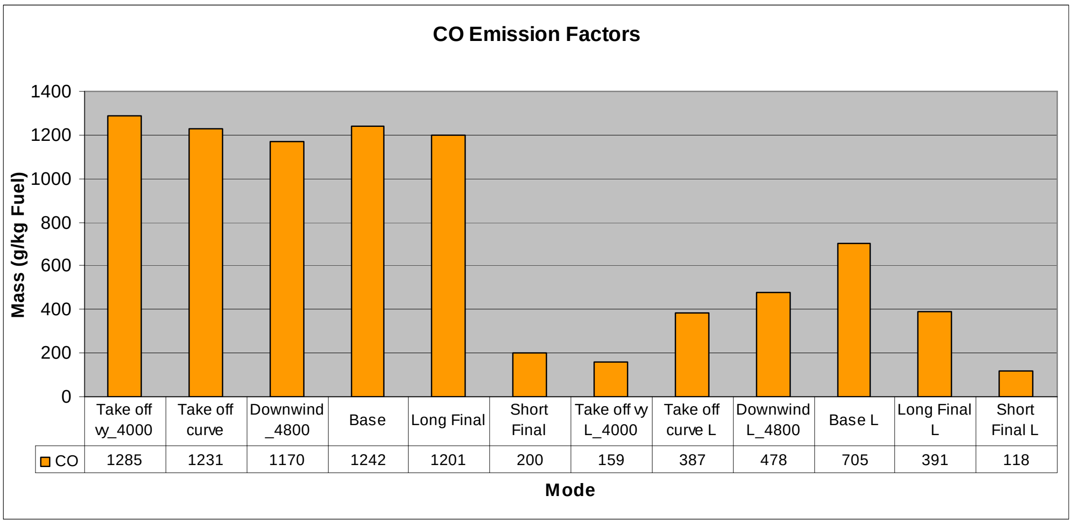
3) HBEYS (Carburated Engine Lyc O-360 Series)

3.a) Results for simulated aerodrome circuits, flown at 2000 to 6000ft



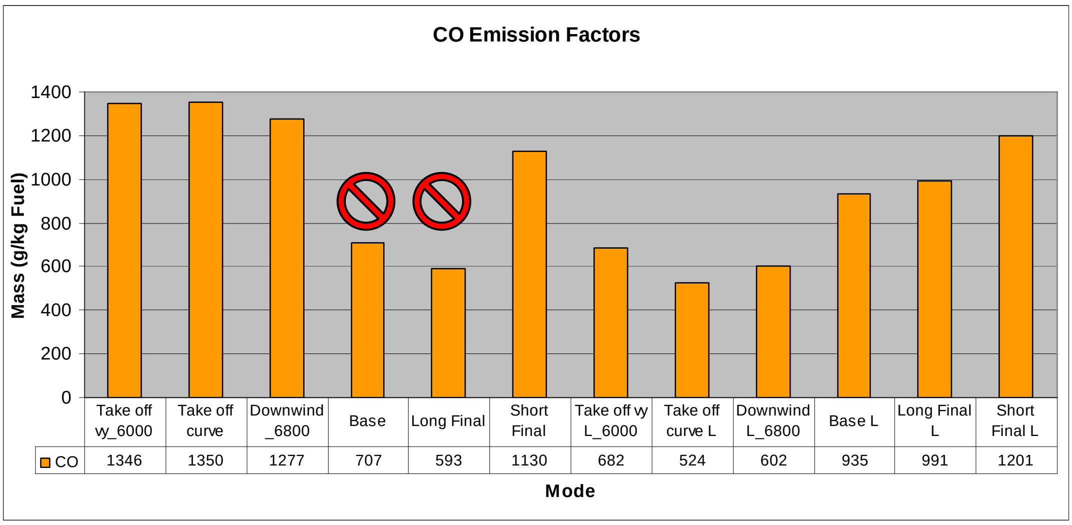
	Take off roll	Take off vy	Take off curve	Downwind	Base	Long Final	Short Final	Take off vy	Take off curve	Downwind	Base	Long Final	Short Final
CO	1237	1204	1208	1164	353	1215	1150	1171	1162	1104	1211	633	1162

Figure 4: CO emission factors during two aerodrome circuits, starting at 2000ft, downwind at 2800ft. (ECERT 4, HBEYS). The first base leg was measured during power adjustments and is not considered valid.



	Take off vy_4000	Take off curve	Downwind _4800	Base	Long Final	Short Final	Take off vy L_4000	Take off curve L	Downwind L_4800	Base L	Long Final L	Short Final L
CO	1285	1231	1170	1242	1201	200	159	387	478	705	391	118

Figure 5: CO emission factors during two aerodrome circuits, starting at 4000ft, downwind at 4800ft. The second circuit has been flown with leaned mixture as described in 1.c. (ECERT 4.2 HBEYS)



	Take off vy_6000	Take off curve	Downwind _6800	Base	Long Final	Short Final	Take off vy L_6000	Take off curve L	Downwind L_6800	Base L	Long Final L	Short Final L
CO	1346	1350	1277	707	593	1130	682	524	602	935	991	1201

Figure 6: CO emission factors during two aerodrome circuits, starting at 6000ft, downwind at 6800ft. The second circuit has been flown with leaned mixture as described in 1.c. (ECERT 4.3 HBEYS) The first base leg was measured during power adjustments and is not considered valid.

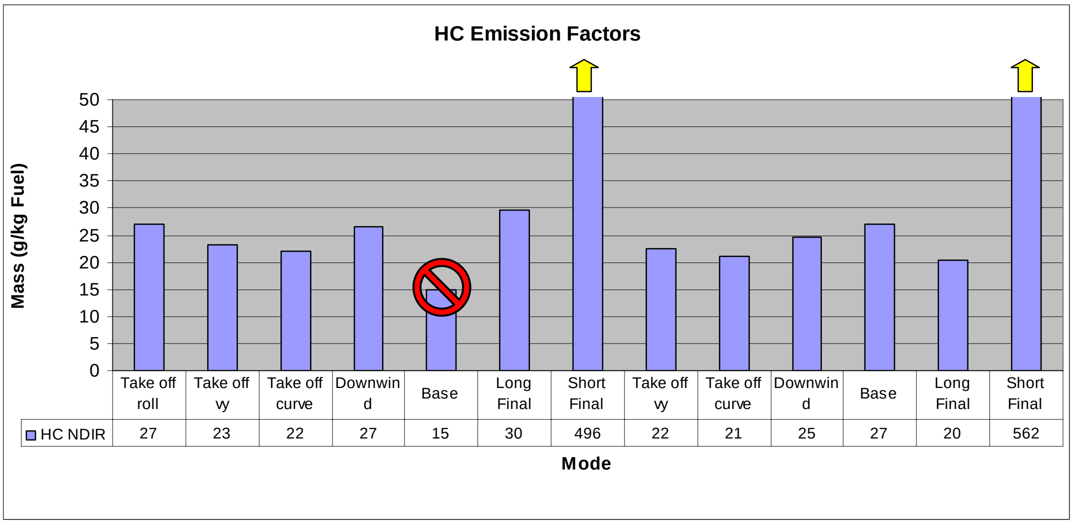


Figure 7: HC emission factors during two aerodrome circuits, starting at 2000ft, downwind at 2800ft. (ECERT 4, HBEYS). The first base leg was measured during power adjustments and is not considered valid.

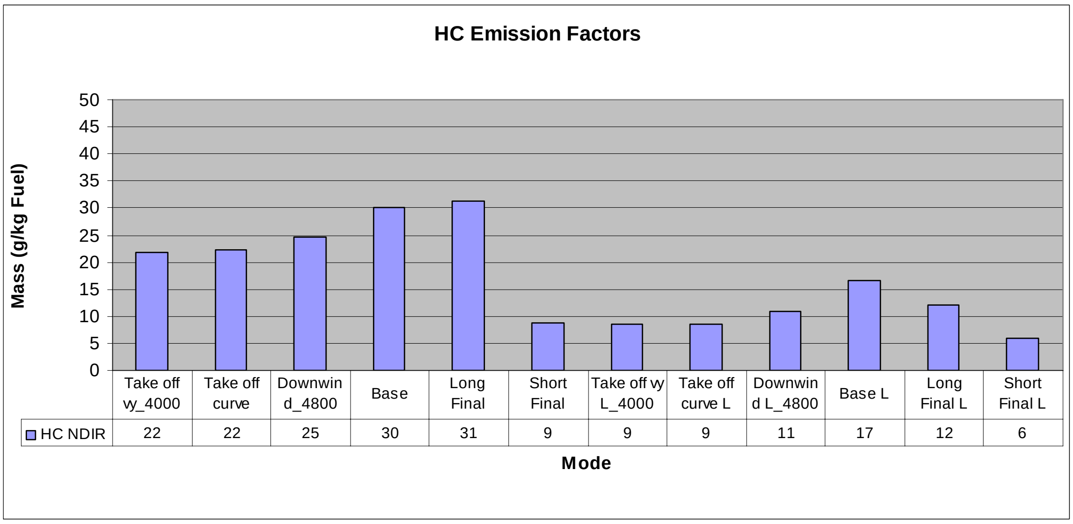


Figure 8: HC emission factors during two aerodrome circuits, starting at 4000ft, downwind at 4800ft. The second circuit has been flown with leaned mixture as described in 1.c. (ECERT 4.2, HBEYS)

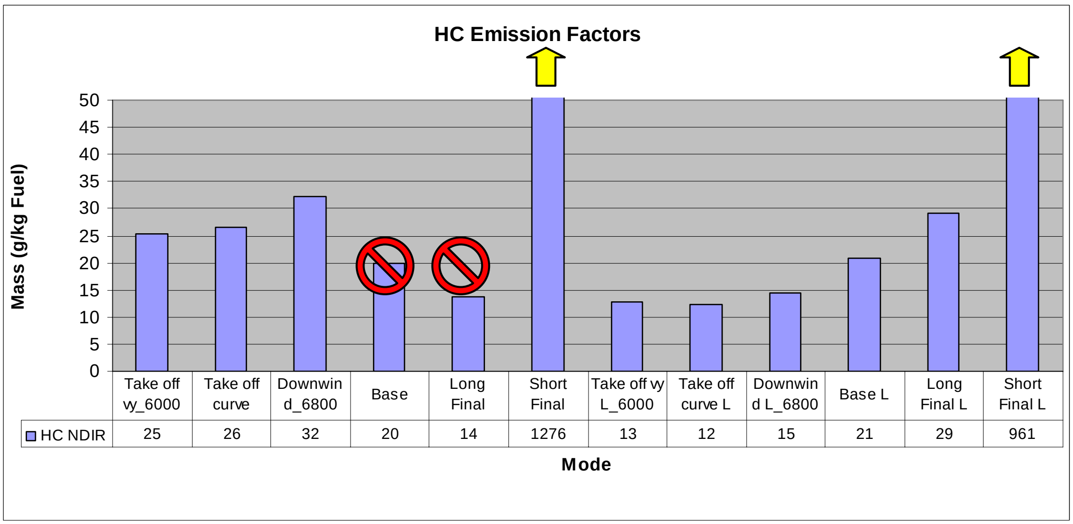


Figure 9: HC emission factors during two aerodrome circuits, starting at 6000ft, downwind at 6800ft. The second circuit has been flown with leaned mixture as described in 1.c. (ECERT 4.3, HBEYS). The first base leg was measured during power adjustments and is not considered valid.

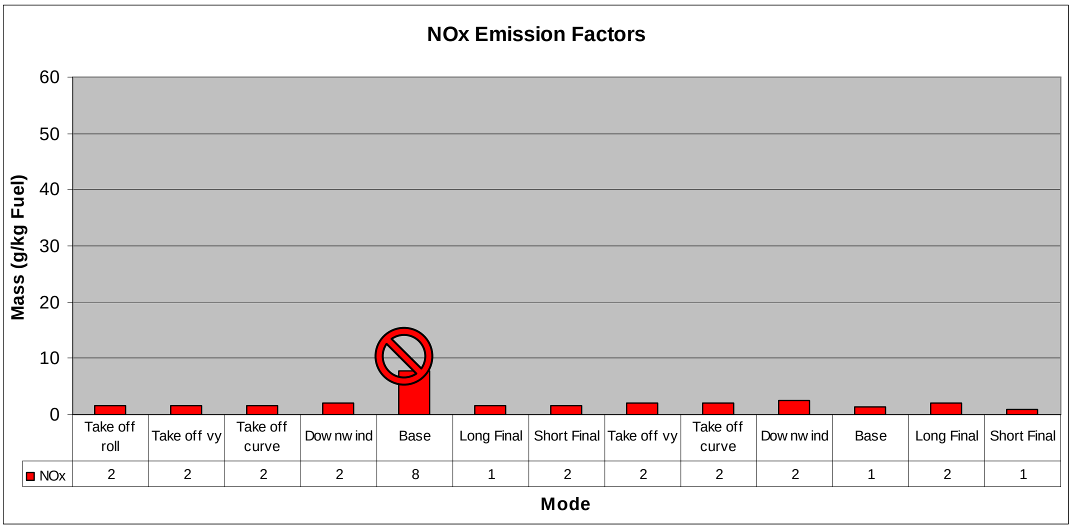


Figure 10: NO_x emission factors during two aerodrome circuits, starting at 2000ft, downwind at 2800ft. (ECERT 4, HBEYS). The first base leg was measured during power adjustments and is not considered valid.

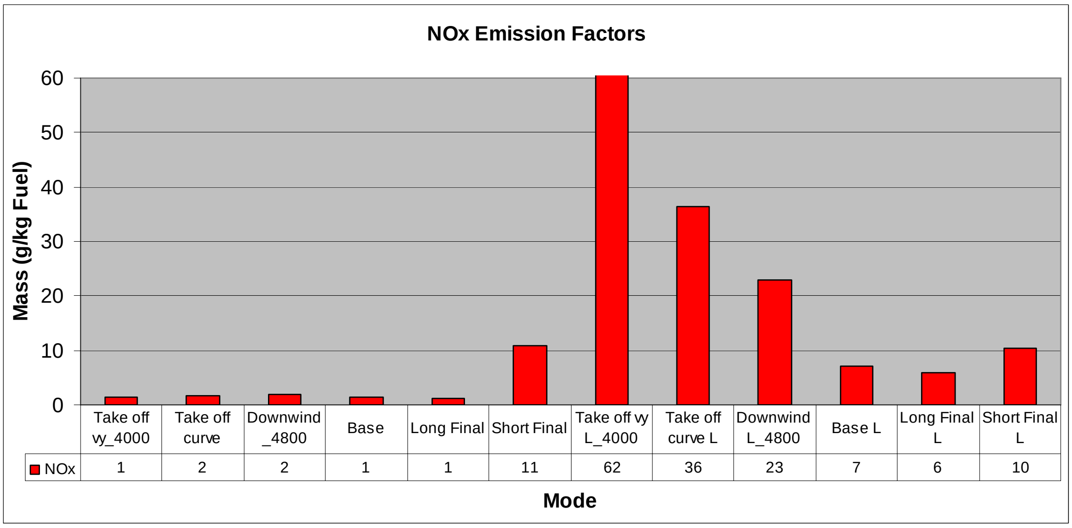


Figure 11: NO_x emission factors during two aerodrome circuits, starting at 4000ft, downwind at 4800ft. The second circuit has been flown with leaned mixture as described in 1.c. (ECERT 4.2, HBEYS)

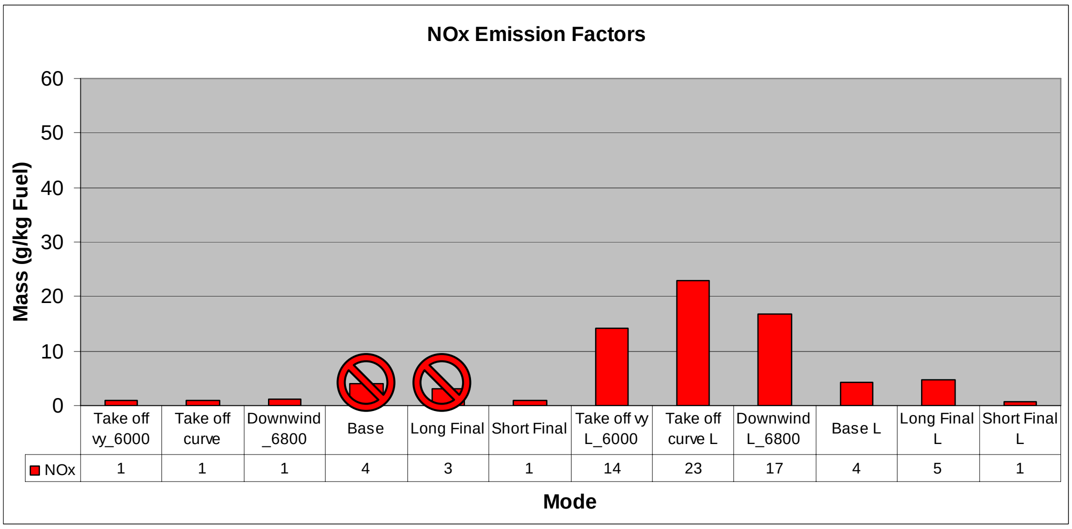


Figure 12: NO_x emission factors during two aerodrome circuits, starting at 6000ft, downwind at 6800ft. The second circuit has been flown with leaned mixture as described in 1.c. (ECERT 4.3, HBEYS). The first base leg was measured during power adjustments and is not considered valid.

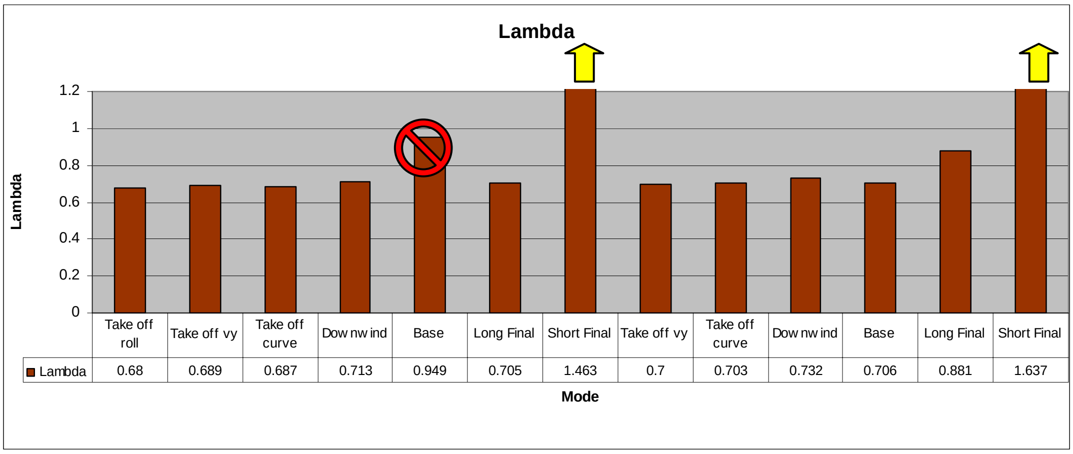


Figure 13: Lambda (=actual air/fuel ratio to stoichiometric air/fuel ratio) during two circuits, starting at 2000ft, downwind at 2800ft. (ECERT 4, HBEYS). The first base leg was measured during power adjustments and is not considered valid.

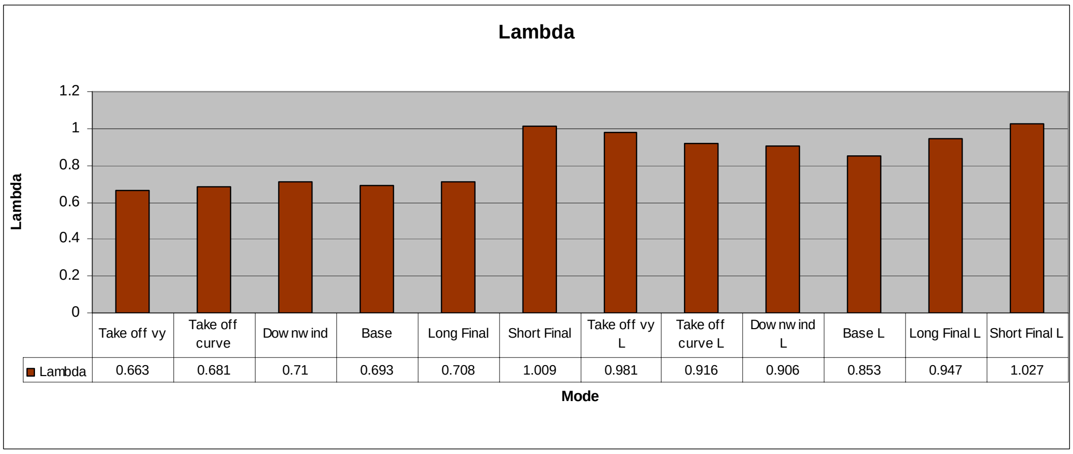


Figure 14: Lambda during two circuits, starting at 4000ft, downwind at 4800ft. The second circuit has been flown with leaned mixture as described in 1.c) (ECERT 4.2, HBEYS).

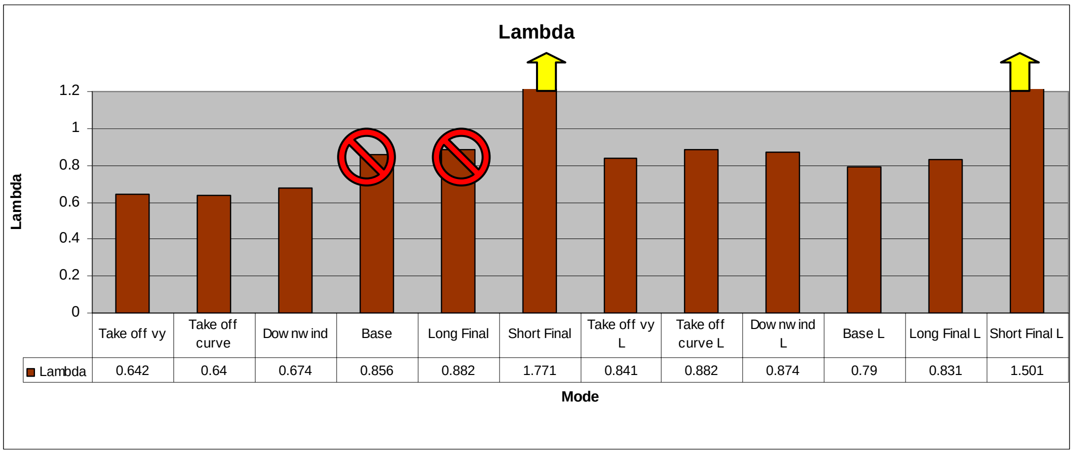


Figure 15: Lambda during two circuits, starting at 6000ft, downwind at 6800ft. The second circuit has been flown with leaned mixture as described in 1.c) (ECERT 4.3, HBEYS). The first base leg was measured during power adjustments and is not considered valid.

3.b) Discussion

CO emission factors remain rather constant at an extremely high value of around 1200 g/kg fuel, if the engine is operated at standard "full rich" mixture setting (figure 4). If the circuit is flown at higher altitude, the CO emission factors gets even worse at "full rich" condition. This can also be seen in the lambda value, which drops, the higher the aircraft flies (minimum lambda at around 0.64, figure 15). At this condition the engine swallows around 36% more fuel mass than necessary for efficient combus-

tion. The additional enrichment of the air/fuel mixture with higher altitude can be explained by the fact that the air density becomes smaller with increasing altitude, thus the carburetor mixes even less air mass to the fuel than with higher air density at lower altitude.
Below 5000ft and at full throttle, the engine air-fuel mixture is generally not adjusted to leaner conditions. For the circuit flying with moderate outside air temperature, we decided to start leaning at 4000ft and did not see any engine temperature problems with that particular aircraft. The effect of the mixture adjustment can be clearly seen in figure 5. CO emission factors drop by a factor of 2 to 8. However, at a fixed mixture lever setting, the air/fuel mixture seems to become richer again, as power is reduced (see CO emission factor increase on the right of figure 5 between take-off L (=lean) and base L, and lambda drop in figure 14, from take-off L to base L).
Comparison of figure 5 and figure 6 shows that the standard “rule of thumb” leaning procedure seems to lead to higher CO emission factors at higher altitude, thus to richer air/fuel mixture than at 4000ft. This can also be seen in figures 14 and 15, right hand side, with lower values for lambda at 6000ft.

Similar findings result for HC emission factors (figures 7 to 9) with values around 25 g/kg fuel at “full rich” mixture setting and half the value at less rich conditions. However, a dramatic increase in HC emission factors can be seen in short final measurements (figures 7 and 9) when the engine throttle is in idle position just before simulated touch down. In figure 8, this effect does not occur. A comparison between fuel flows and RPM in the measurements of figures 7, 8 and 9 showed that the engine was not really at idle setting in the short final at 4000ft (figure 8). So in fact, this difference between figure 8 and figures 7 and 9 can be explained. The remaining question about the reason for the high HC emission factors at “flight idle”[1] remained unsolved and we decided to investigate this in a separate flight test (see section 3.c).

NO_x emission factors behave vice versa to CO and HC as can be seen in figures 10, 11 and 12. At “full rich” mixture, hardly any NO_x can build up. Values are around 1 to 2 g / kg fuel. At less rich conditions, NO_x emission factors grow. The highest factor of 62 g/kg fuel was measured during take-off at 4000ft (figure 11). At this high power and hot condition, the engine was running nearly stoichiometric (figure 14, take-off L, lambda = 0.981).

From FOCA experience it is well known that aerodrome circuits are mostly flown at mixture setting “full rich”. Exceptions are high (density) altitude airports, like Samedan airport in Switzerland (Elevation 5600ft). The effect of mixture adjustment on emission factors (and fuel flow) is very big and therefore we decided to do additional “high” altitude flight tests in Samedan (see section 3.e).

3.c) HC emission factors at flight idle

In order to study the effect of high HC emission factors in flight idle (figures 7 and 9) we climbed several times to 4500ft and started descent with engine idle at different indicated air speeds: normal final approach speed of 115 km/h, and higher speeds of 140, 160 and 180 km/h. Measurements were performed each time when descending through 4000ft.

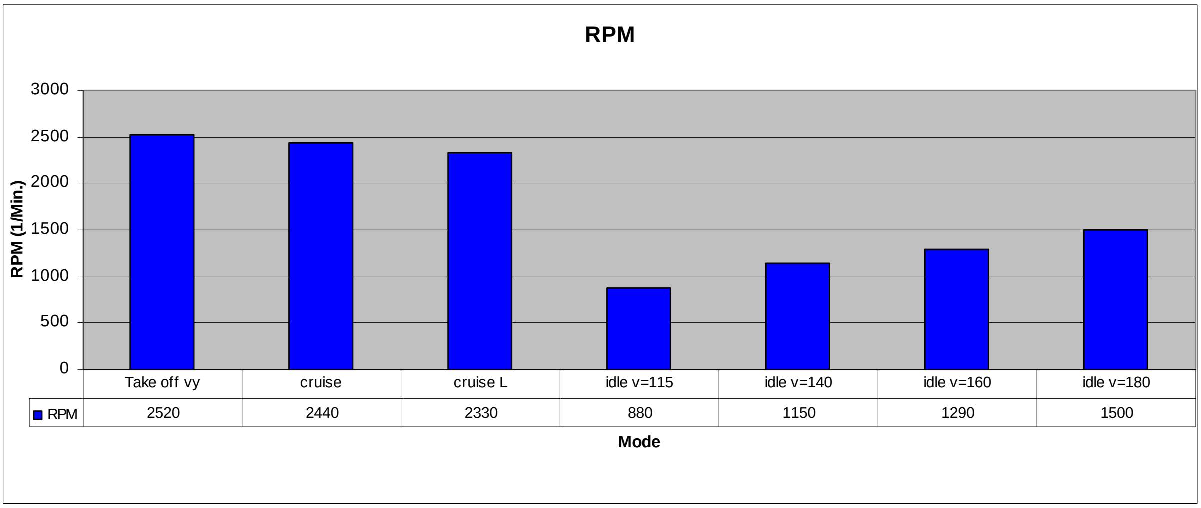


Figure 16: Engine RPM (Revolutions per Minute) at take-off and cruise (for comparison) and with engine idle at an indicated airspeed of 115, 140, 160 and 180 km/h. Idle RPM increases with increasing airspeed. (ECERT 4.4)

[1] „flight idle“ is used here as short expression for „engine throttle fully pulled back to idle position during flight“. This does not in any case correspond to the term “flight idle” used for turboprops or jet engines.

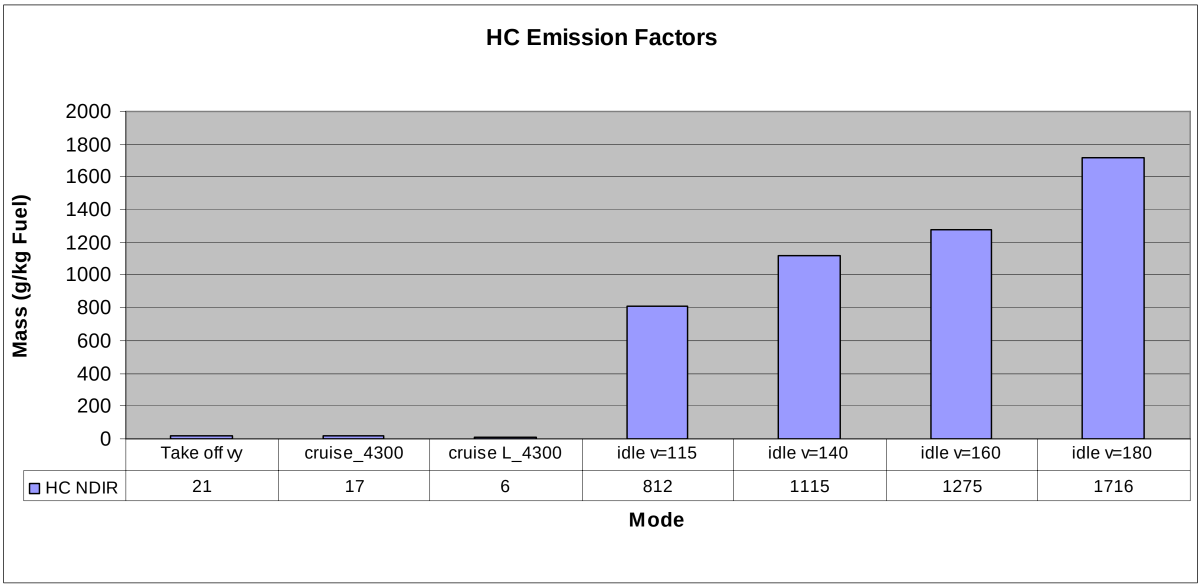


Figure 17: HC emission factors for engine idle at an indicated airspeed of 115, 140, 160 and 180 km/h (take-off and cruise for comparison and system check). HC emission factors increase drastically with increasing airspeed at engine idle. Note that the absolute scale of HC emission factors at engine flight idle may have a considerable error. (ECERT 4.4)

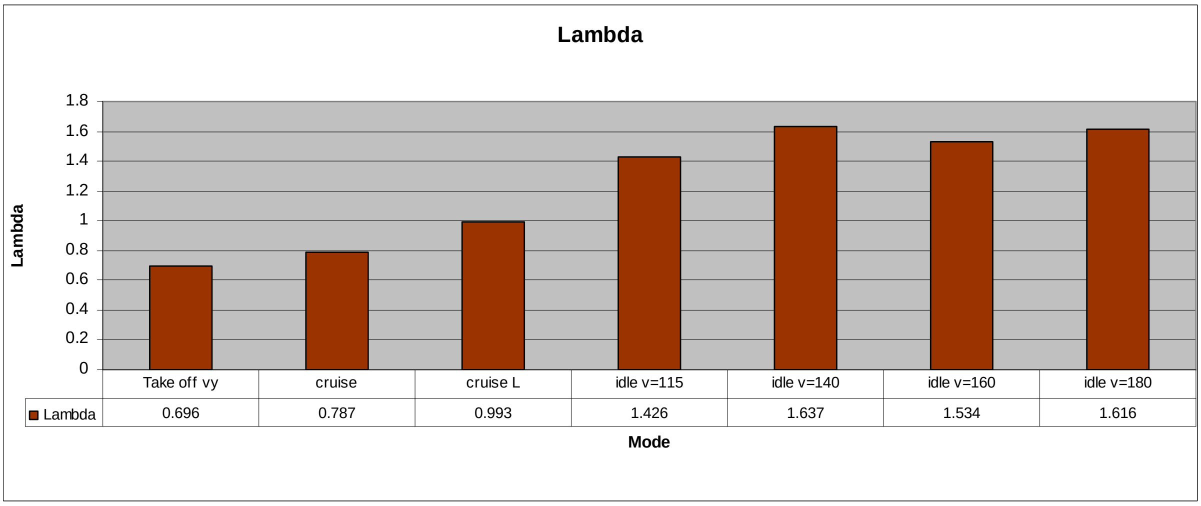


Figure 18: Lambda for engine idle at an indicated airspeed of 115, 140, 160 and 180 km/h (take-off and cruise for comparison and system check). Lambda increases far above 1 at engine flight idle condition, which shows the presence of excess oxygen in the combustion chambers of the engine, producing very lean conditions. (ECERT 4.4)

3.d) Discussion

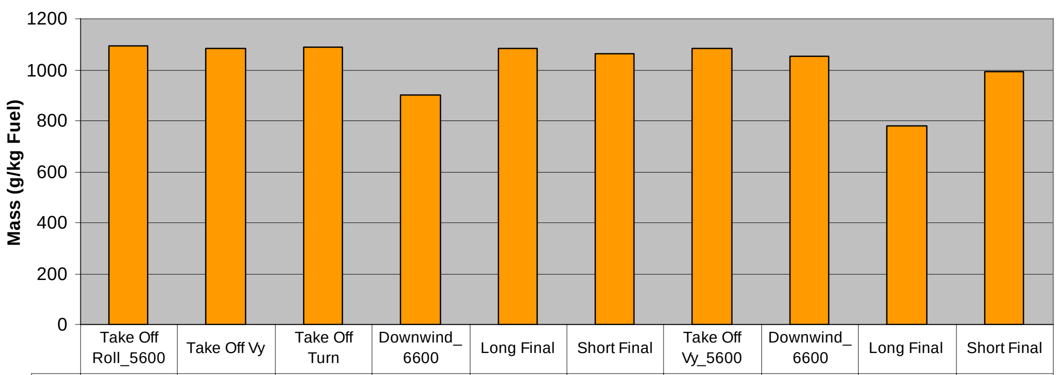
The findings presented in figure 7 and 9 have been confirmed. The flight test showed that HC emission factors increase drastically at flight idle. The effect increases with increasing airspeed (and therefore increasing engine idle RPM). Figure 18 proves the presence of excess oxygen in the combustion chambers of that engine at these flight conditions. Standing on ground, the engine idles at about 650 RPM. At normal approach speed, idle RPM is around 900. The RPM increase comes from the air stream, pushing the propeller to elevated RPM, working like a propeller of a windmill. One possible explanation for the measured effect on HC emission factors might be that the engine “pumps” air through the intake into the combustion chambers due to the elevated RPM from the propeller windmill. At the same time the throttle is nearly closed, therefore dispersing very little fuel. The little fuel quantity at idle setting is not burnt anymore, which causes extremely high HC emission factors. In fact the engine has practically a “flame out”. This is normally not observed by the pilots because the air stream turns the propeller.
From point of view of emissions inventory calculation, the measured effect can be neglected in simple method or first order calculations. Normally, flight idle occurs only in short final, just before touch down. Duration of this event and fuel flow are both very small, resulting in a small emission change. However, if such an aircraft/engine was operated at long flight idle descents, HC total emissions increase would be considerable.

3.e) Additional high altitude circuit flight testing at Samedan Airport (5600ft AMSL), Switzerland

At this high altitude airport, the engine air/fuel mixture should be adjusted to less rich conditions already prior to take-off. We wanted to compare the resulting emission factors when the mixture was adjusted on ground and not during flight, as we had done in the simulated circuits at 6000ft (figures 6, 9, 12 and 15).

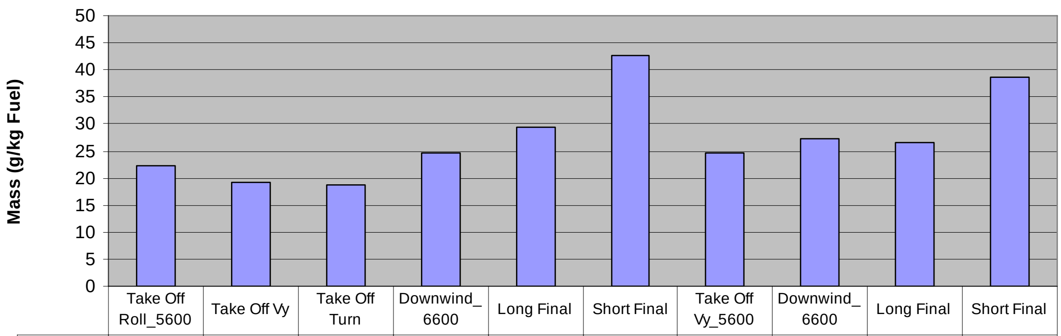
The "rule of thumb" procedure consisted of

- going to full throttle, full rich, static aircraft.
- pulling the mixture lever until maximum RPM was noted (with fixed pitch propeller). This can be described as best power mixture, still rich.
- Slightly pushing the mixture lever, thus enriching the mixture again (for engine internal cooling reasons at high power).



	Take Off Roll_5600	Take Off Vy	Take Off Turn	Downwind_ 6600	Long Final	Short Final	Take Off Vy_5600	Downwind_ 6600	Long Final	Short Final
CO	1092	1082	1089	903	1083	1066	1084	1051	778	991

Figure 19: CO emission factors, measured during two circuits at Samedan airport. (ECERT 13)



	Take Off Roll_5600	Take Off Vy	Take Off Turn	Downwind_ 6600	Long Final	Short Final	Take Off Vy_5600	Downwind_ 6600	Long Final	Short Final
HC NDIR	22	19	19	25	29	43	25	27	27	39

Figure 20: HC emission factors, measured during two circuits at Samedan airport. (ECERT 13)

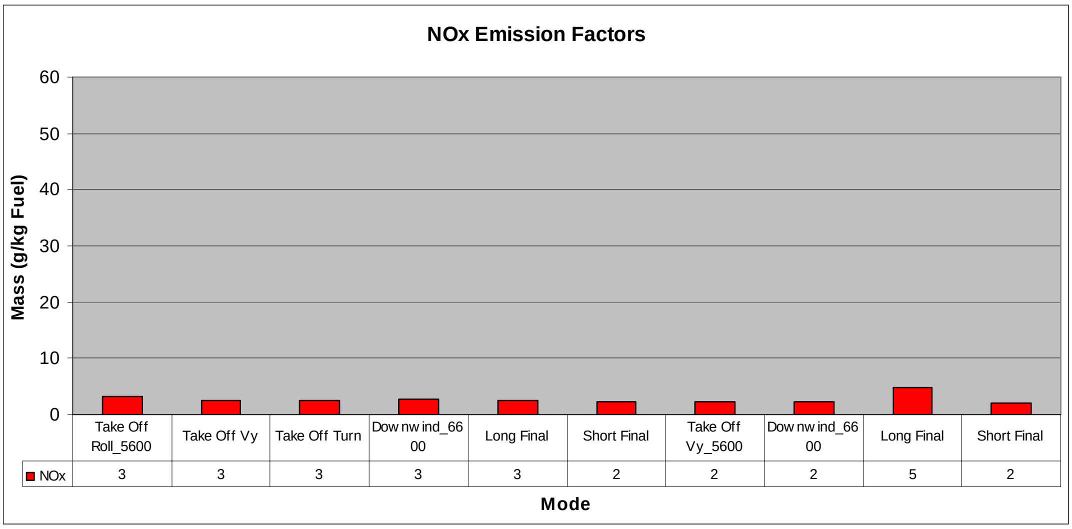


Figure 21: NO_x emission factors, measured during two circuits at Samedan airport. (ECERT 13)

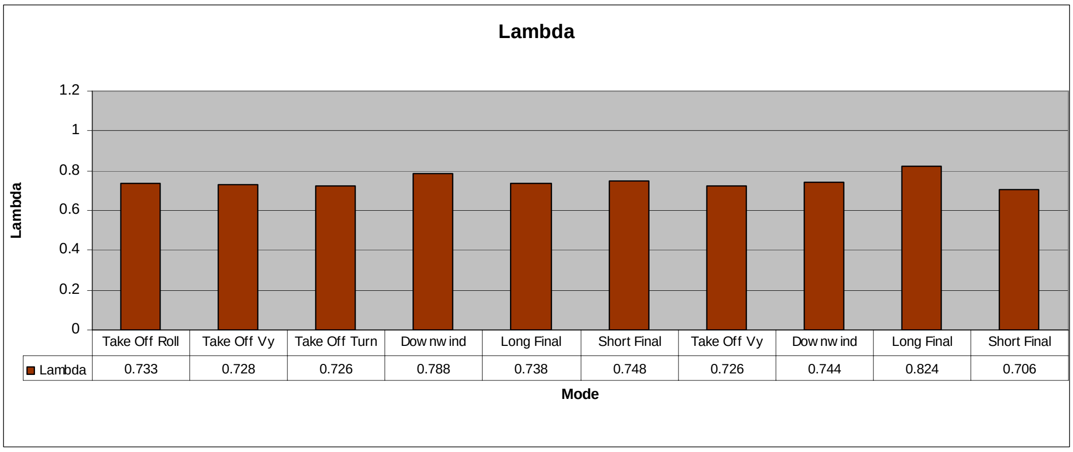


Figure 22: Lambda, measured during two circuits, starting at 5600ft, downwind at 6600ft. (ECERT 13)

3.f) Discussion

From comparison between figure 22 and figure 15, one can see that the mixture adjustment which had been prepared on ground was richer than that of the simulated circuit. But it had the same magnitude as “full rich” mixture on sea level. With the described mixture adjustment, the engine can be brought back to approximately the same rich mixture level which those types of engines normally have at sea level at “full rich” position. If the mixture adjustment is done properly at high altitude airports, emission factors will be similar to low altitude airports (figures 19, 20, 21 and 6, 9, 12). However, the fuel flow is lower at high altitude airports (as the power). A comparison of total emissions in the circuits at different airport levels is done in the next section.

3.g) Inventory: Total emissions in aerodrome circuits at different flight altitudes

For this comparison of total emissions in the circuits, we use the mean circuit times measured at Bern airport (LSZB).

Table 1:

Mode	Times in Mode (s)
TAXI OUT	467
TAKE-OFF	20
CLIMB OUT	75
DOWNWIND	90
BASE	105
FINAL	20
TAXI IN	200

Emission factors were taken from the previously discussed measurements, with "full rich" emission factors for 2000 and 4000ft and less rich conditions for 6000ft as presented in section 3.e). Because of very incomplete combustion, the mean emission factor for CO_2 is far below the theoretical 3.17 kg / kg fuel. For this calculation we assume a conservative factor of 2 kg CO_2 / kg fuel and 1.2 kg H_2O / kg fuel. The lead content in AVGAS 100LL is considered 0.794 g / kg fuel, the fuel density 0.72 kg / liter.

Tables 2 and 3 (emissionsinventar.volten.HBEYS_060825_rit):

Total circuit emissions (taxi-in, 1 circuit, taxi-out)

Elevation	fuel (kg)	CO (g)	HC (g)	NOx (g)	CO2 (kg)	H20 (kg)	lead (g)
2000ft	2.83	3305	73	3	5.66	3.40	2.25
5600ft (Samedan)	2.76	2562	67	8	5.51	3.31	2.19

Total circuit emissions (1 circuit without taxi)

Elevation	fuel (kg)	CO (g)	HC (g)	NOx (g)	CO2 (kg)	H20 (kg)	lead (g)
2000ft	1.90	2200	45	3	3.79	2.28	1.51
5600ft (Samedan)	1.82	1898	44	5	3.65	2.19	1.45

3.h) Systematic measurements at full power and approach power settings between 3000 and 7000ft flight altitude

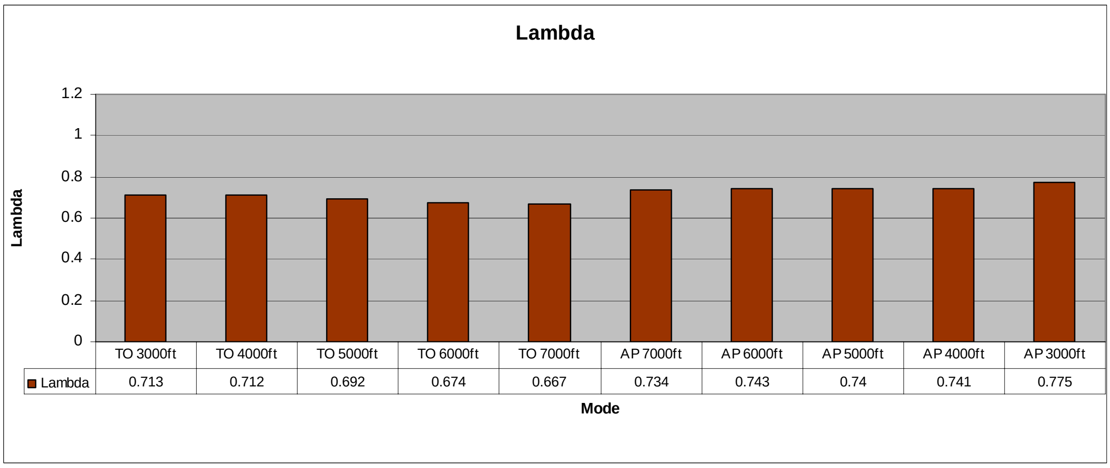


Figure 23: Change of lambda during full power climb and approach at 45% engine load. All measurements with mixture "full rich". Lambda decreases with increasing aircraft height. The air/fuel mixture gets richer the higher the aircraft flies. At approach power, the mixture is less rich than at climb full power. (ECERT 8)

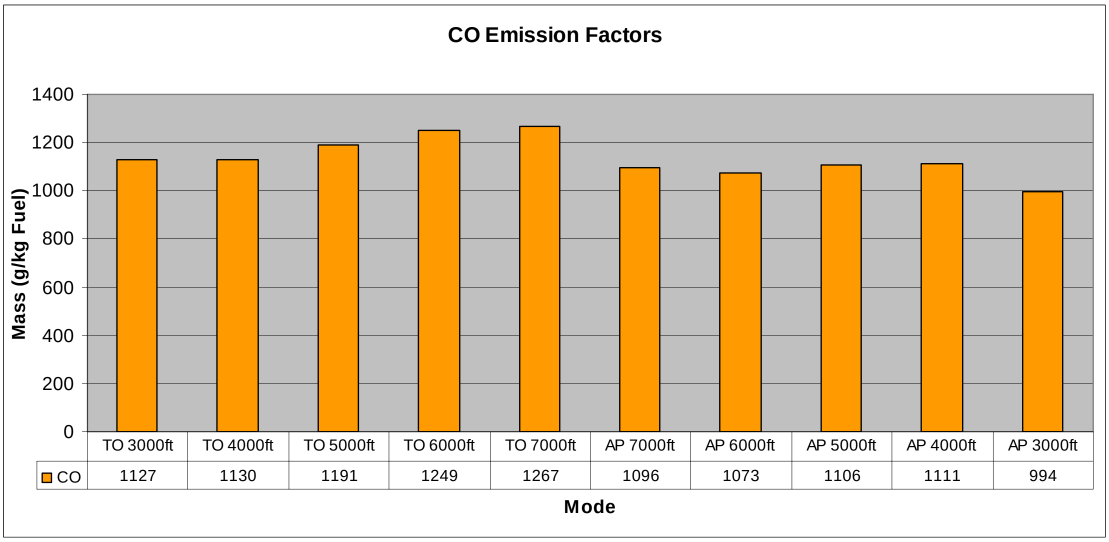


Figure 24: Effect on CO emission factor. With increasing height, the CO emission factor gets even worse (without mixture adjustment). (ECERT 8)

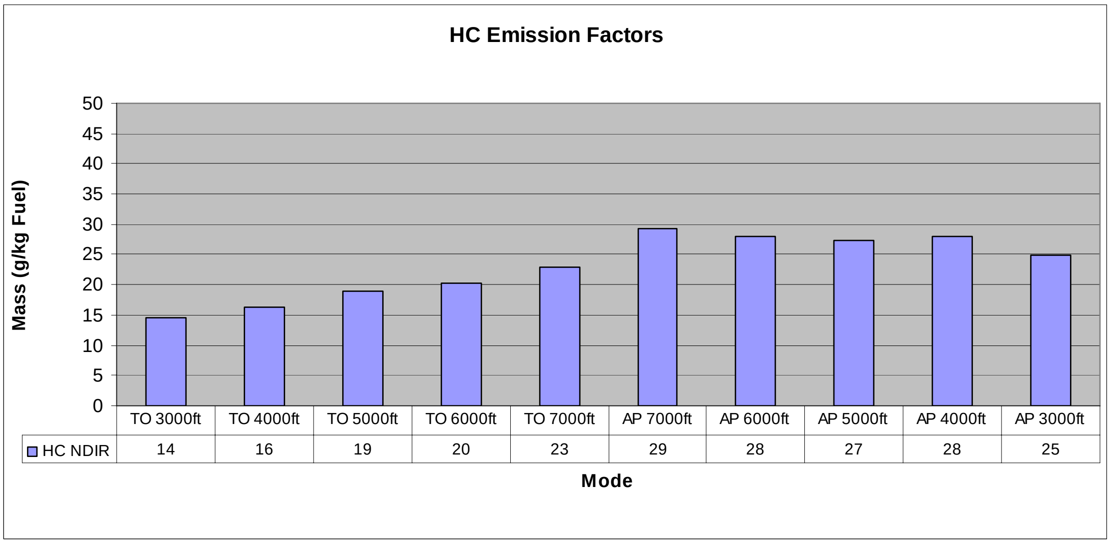


Figure 25: Effect on HC emission factor. With increasing height, the HC emission factor gets even worse (without mixture adjustment). At approach power (45% engine load), HC emission factors are higher than at full power. (ECERT 8)

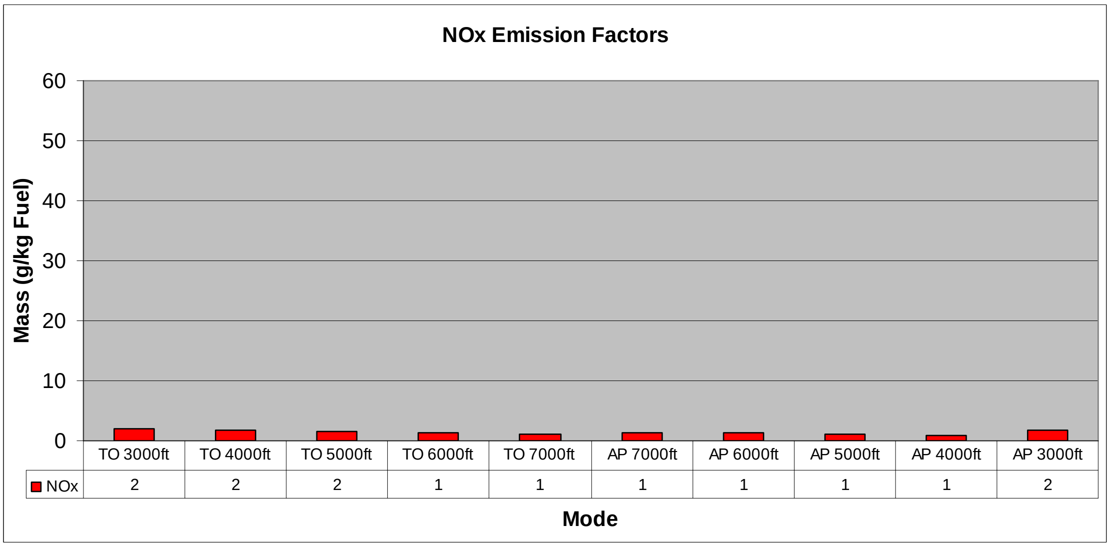


Figure 26: NO_x emission factors are very low due to low internal combustion temperatures. With increasing height, the NO_x emission factor decreases (no mixture adjustment). (ECERT 8)

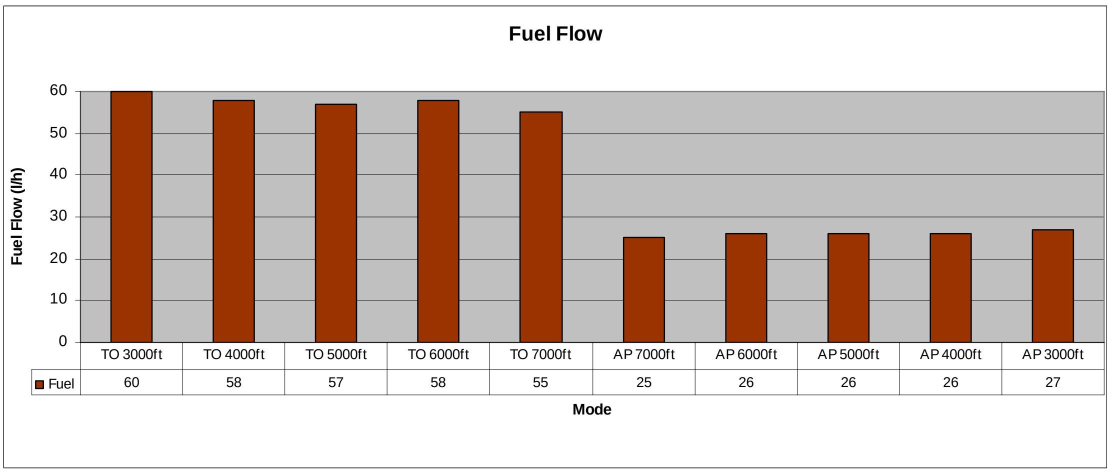


Figure 27: The fuel flow decreases with increasing height. During descent (45% engine load), the fuel flow has been kept constant. (ECERT 8)

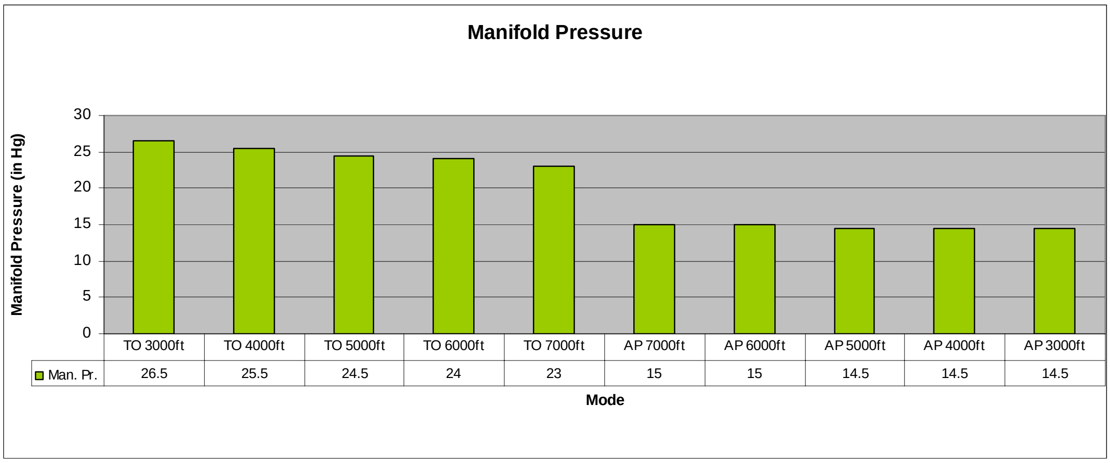


Figure 28: Manifold Pressure (air inlet pressure between carburetor and cylinder inlet): Manifold pressure is a good indicator for engine power. It drops with increasing altitude due to decreasing ambient air pressure. Accordingly, engine power drops. During descent, engine power has been kept constant. (ECERT 8)

3.i) Systematic measurements at climb power and approach power settings between 3000 and 7000ft flight altitude

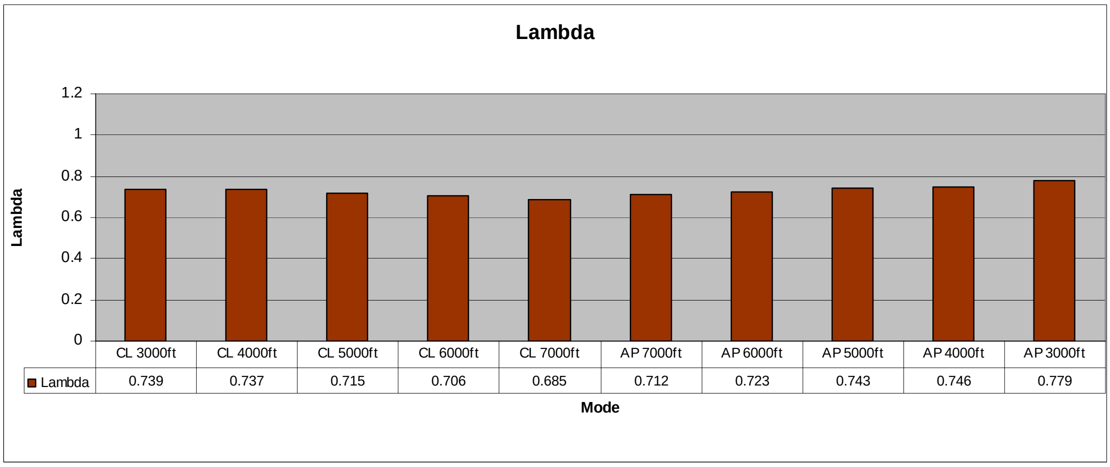


Figure 29: Change of lambda during climb at reduced power (85% engine load below 4000ft) and descent (45% engine load). All measurements with mixture “full rich”. (ECERT 11)

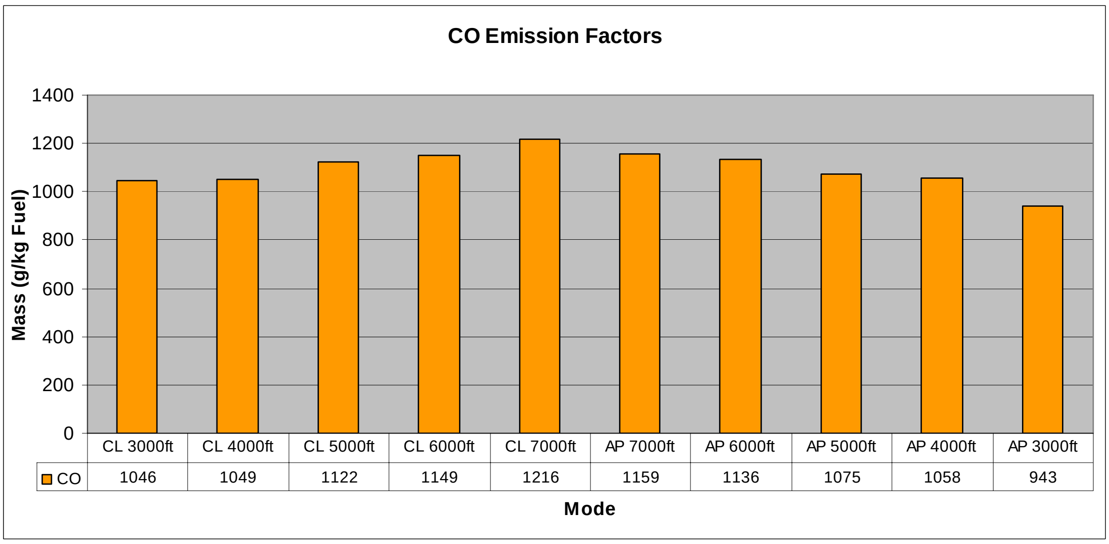


Figure 30: Effect on CO emission factor. With increasing height, the CO emission factor gets even worse (without mixture adjustment). (ECERT 11)

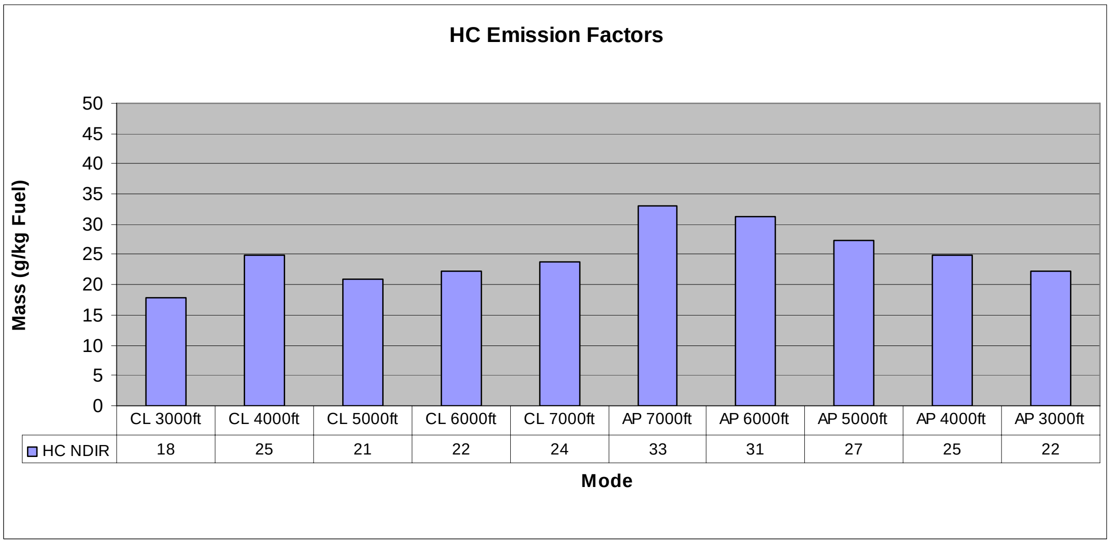


Figure 31: Effect on HC emission factor. At approach power, HC emission factors are higher than at climb power (ECERT 11). During descent, approach power has been slightly increased above 45% engine load, compared to ECERT 8 (figure 25). In spite of that, HC emission factors for approach show similar values between 22 and 33 g/kg fuel.

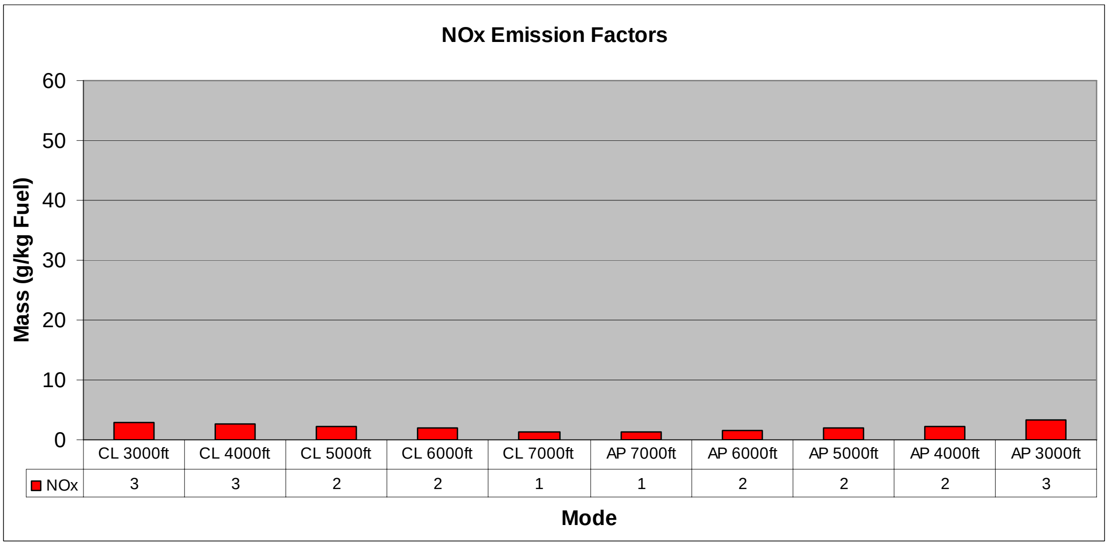


Figure 32: NO_x emission factors are very low and comparable to figure 26 due to low internal combustion temperatures. With increasing height, the NO_x emission factor decreases (without mixture adjustment). (ECERT 11)

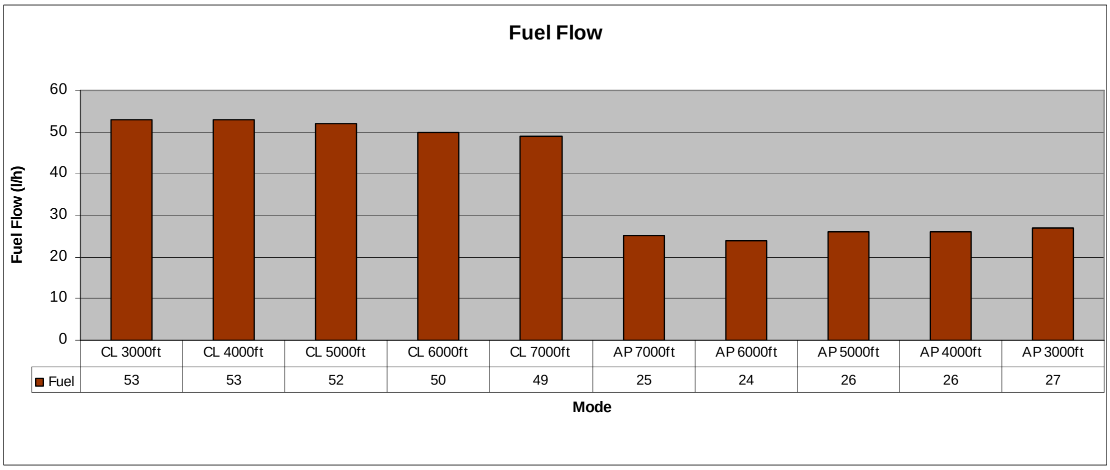


Figure 33: The fuel flow decreases with increasing height. During descent, the fuel flow has slightly increased (ECERT 11). Approach power has been higher at 3000ft than at 7000ft (see figure 34).

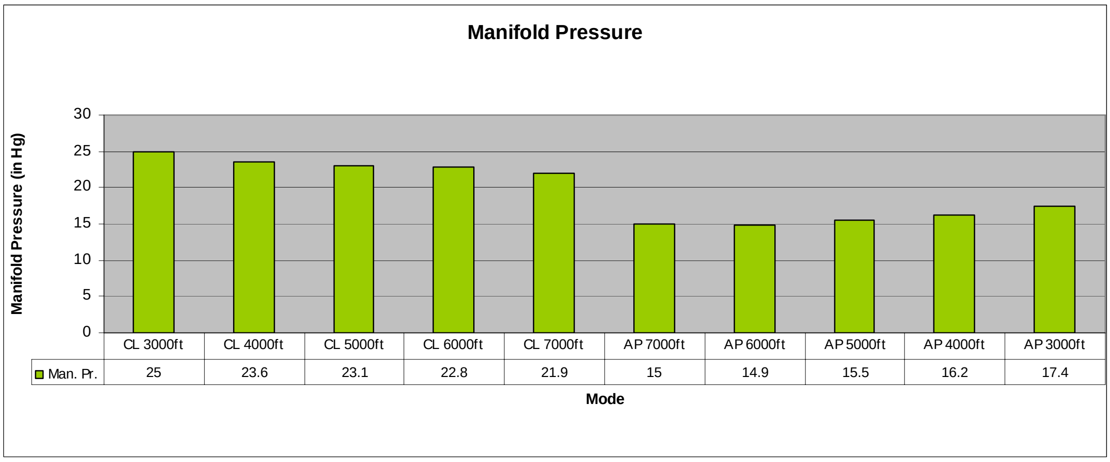


Figure 34: 85% engine load could not be kept above 3000ft. With a manifold pressure of 23.6 at 4000ft, the engine load was already below 85%. During descent, manifold pressure has not been kept constant. Engine load increased slightly with decreasing altitude. Therefore, the results for descent can not be compared to the results of the previous section one to one. (ECERT 11)

3.j) Systematic measurements for cruise power settings at flight altitudes between 3000 and 7000ft

Cruise power emissions have been measured with two flights (ECERT 9/10). The same flight test program as described in section 2, has been used for both flights, starting at 3000ft, mixture “full rich” and 65% of maximum engine fuel flow, followed by a mixture adjustment to lambda = 1 (stoichiometric). The same procedure has been repeated at 4000, 5000, 6000 and 7000ft.

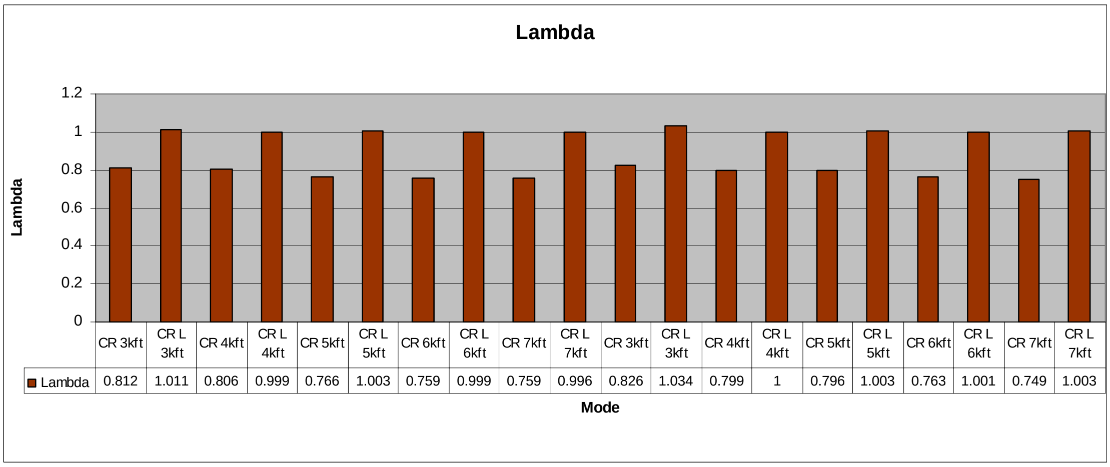


Figure 35: Lambda at “full rich” condition in function of flight altitude (e.g. CR 3 kft = cruise at 3000ft full rich), followed by stoichiometric mixture (e.g. CR L 3kft = cruise leaned at 3000ft). Lambda at “full rich” setting is decreasing with altitude, as usual. Lambda for leaned condition has been set directly by on line reading of emission concentrations during flight. Therefore lambda at CR L could be kept constant around 1. (ECERT 9/10)

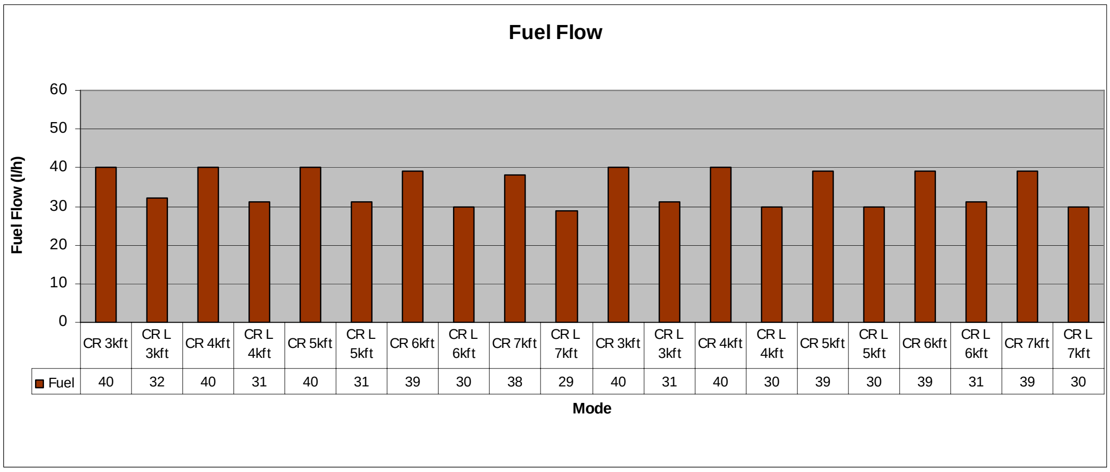


Figure 36: Reproducible fuel flows in both flights. (ECERT 9/10)

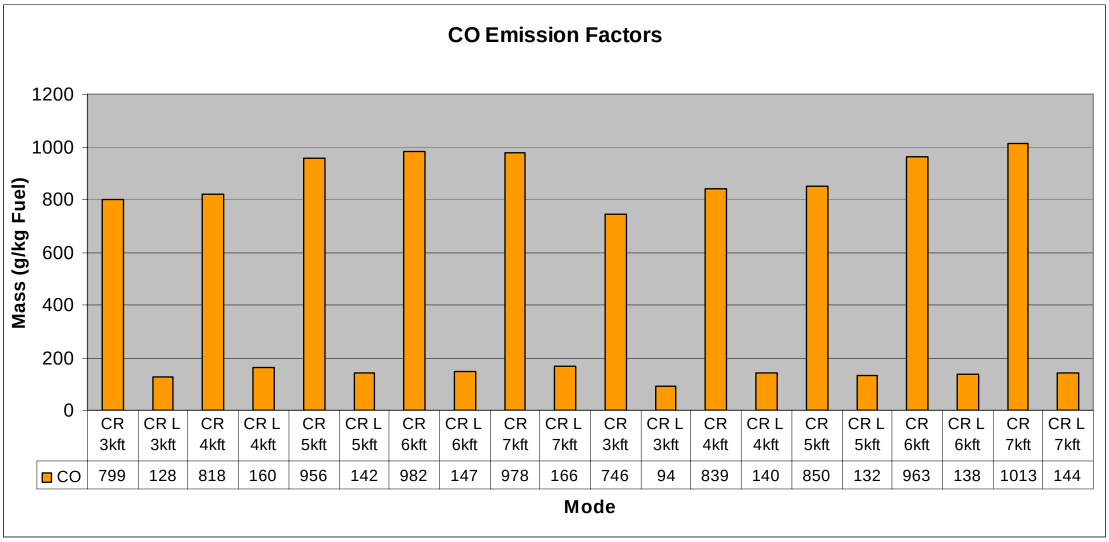


Figure 37: CO emission factors are very high and increasing with altitude without mixture adjustment. At stoichiometric mixture, the values vary around 140 g / kg fuel. In terms of typical emission measurement accuracies, the values are considered reproducible. (ECERT 9/10)

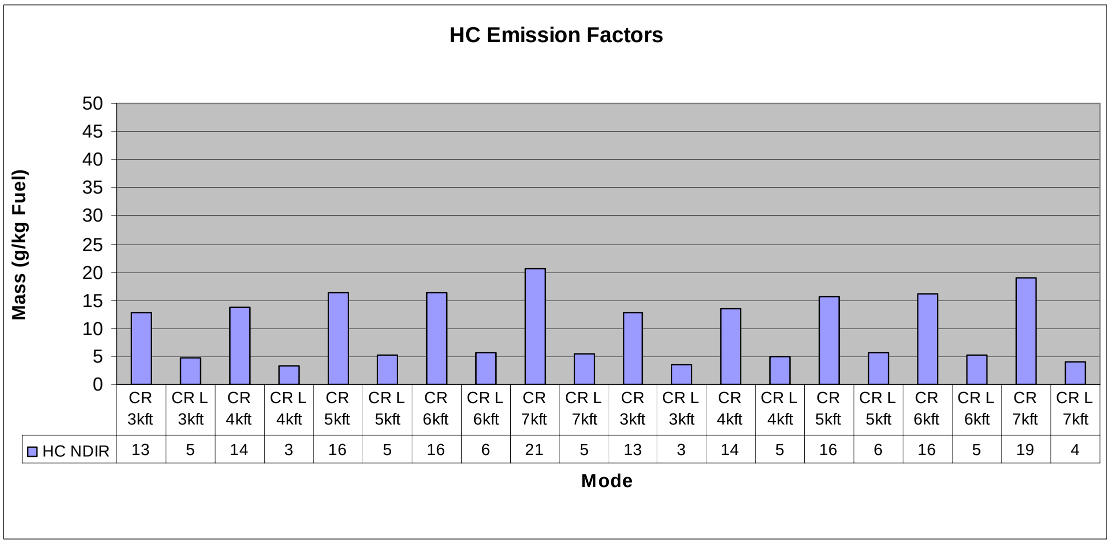


Figure 38: HC emission factors increasing with altitude without mixture adjustment. At stoichiometric mixture, the values vary around 5 g / kg fuel. In terms of typical emission measurement accuracies, the values are considered reproducible. (ECERT 9/10)

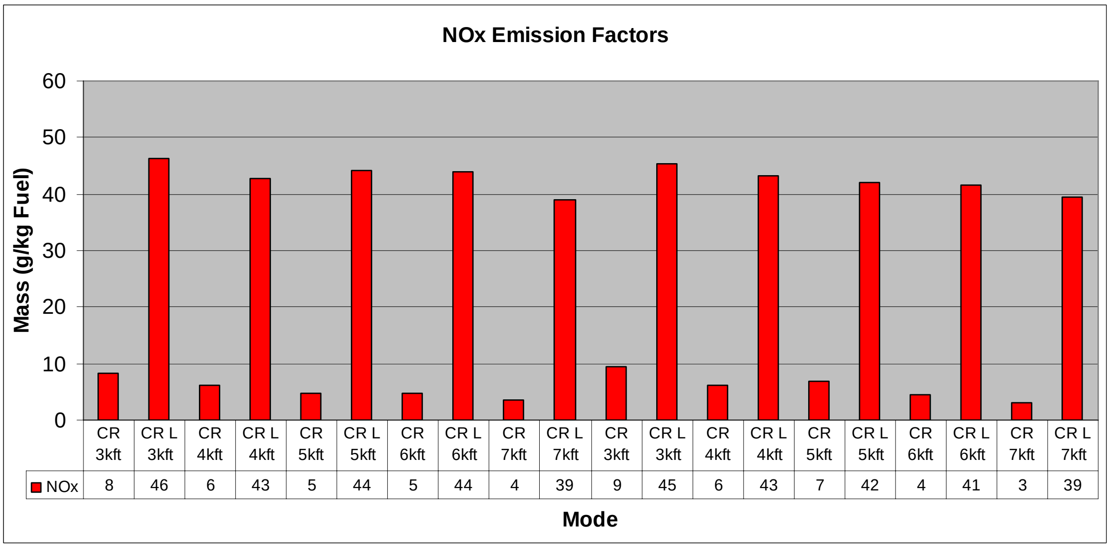


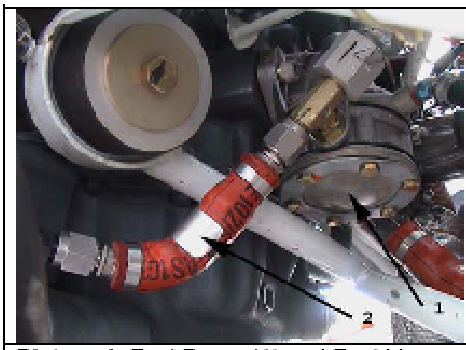
Figure 39: NO_x emission factors decreasing with altitude without mixture adjustment. At stoichiometric mixture, the values get high (trade off with CO and HC) and are around 42 g / kg fuel. In terms of typical emission measurement accuracies, the values are considered reproducible. (ECERT 9/10)

4) HBKEZ (Fuel Injected Engine Lyc IO-360 Series)

Basically, installation of the exhaust emission measurement system in HBKEZ was identical to that of HBEYS.
In addition to HBEYS, this aircraft is equipped with a variable pitch, constant speed propeller. At a given propeller RPM, the propeller governor will keep propeller RPM constant as long as possible (by automatic pitch adjustment) if engine power or aircraft speed change, thus leading to increased propulsion efficiency compared to the fixed pitch propeller.

Power management complexity is increased, with propulsion power depending on throttle, mixture and propeller pitch adjustment!

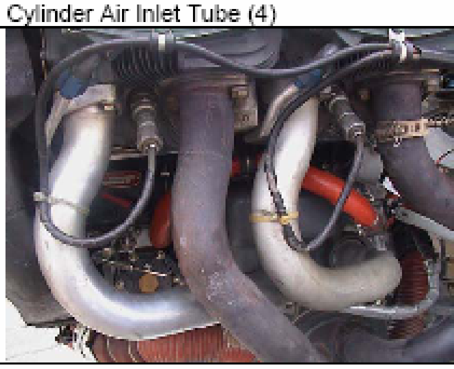
Installation of fuel flow transducer[2] for fuel flow measurement:



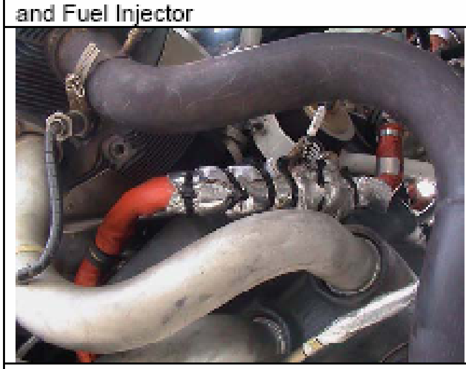
Picture 1: Fuel Pump (1) and Fuel Line Connection to Xducer (2)

Picture 2: Xducer (3) (without cover for documentation) and
Cylinder Air Inlet Tube (4)

Picture 3: Fuel Line Loop between Xducer and Fuel Injector



Picture 4: Overview (taken from bottom)



Picture 5: Xducer final installation (with cover)

Picture 6: Connector plug (6) for FS-450 Fuel Flow Indicator. **Completely independent from A/C electrical system**

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[2] JPI Type 201

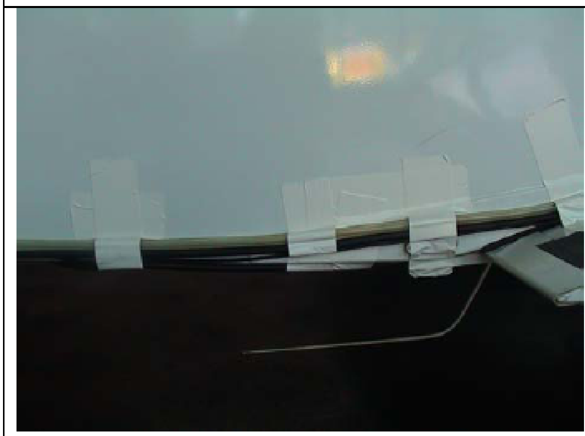
Documentation of sampling probe and measurement system installation:

HB-KEZ

Probe set on exhaust pipe

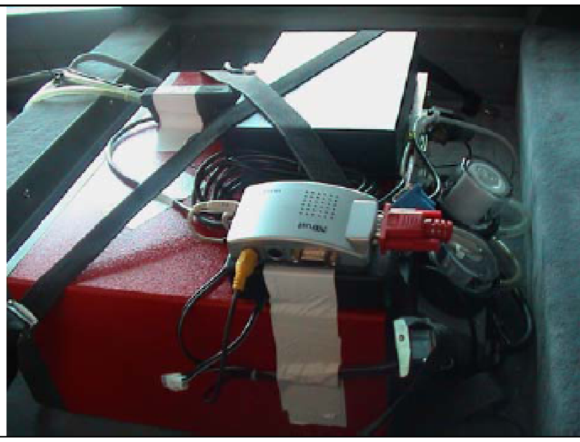
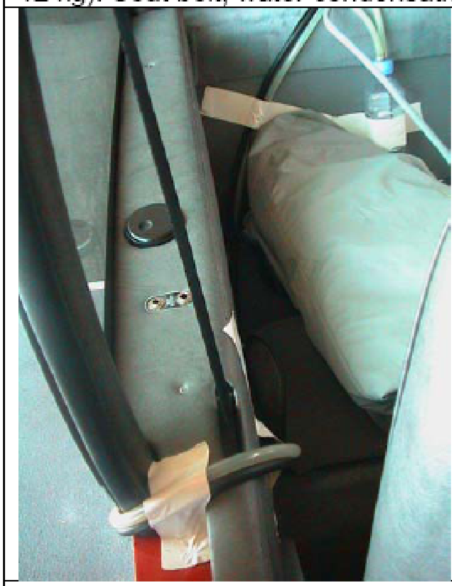
Exhaust line: first fixation point

Exhaust line: view towards tail



Exhaust line: along fuselage

Exhaust line and temperature probe: along fuselage

	
Temperature probe: fixation on right side of fuselage	Exhaust line: incoming and outgoing lines to and from measurement equipment
	
Exhaust tester: fixation on baggage boot (m = 12 kg). Seat belt, water condensation collector	Exhaust tester: view from baggage boot door
	
Exhaust lines: incoming (black) and outgoing (transparent). **The cockpit door (canopy) stays 2 cm open during flight.**	Exhaust tester: control monitor and fuel flow indicator. To control the air quality, a carbon monoxide detector, type Quantum Eye is installed in the cockpit.

Revolution counter: setting

Revolution counter: cable setting

Revolution counter: cable in the engine cowling goes straight down (see also next photo).

Revolution counter: cable on the left side of fuselage

4.a) Results for simulated aerodrome circuits, flown at 2000 to 6000ft

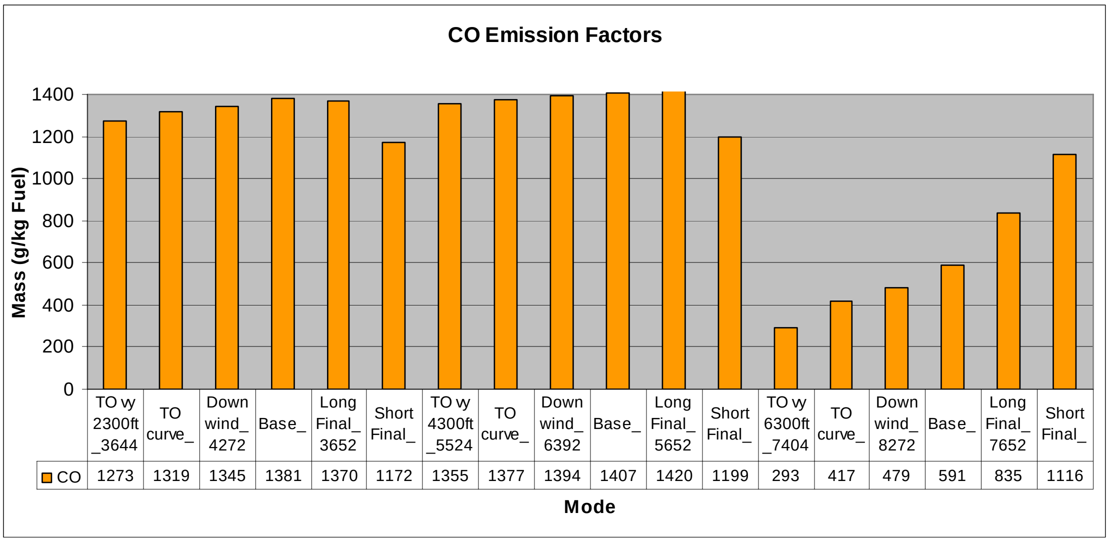


Figure 40: Record braking CO emission factors in three simulated circuits, starting at 2300ft, 4300ft and 6300ft. The first two circuits were flown with air/fuel mixture “full rich”, the circuit above 6300ft with leaned mixture (right hand side). (ECERT22, HBKEZ)

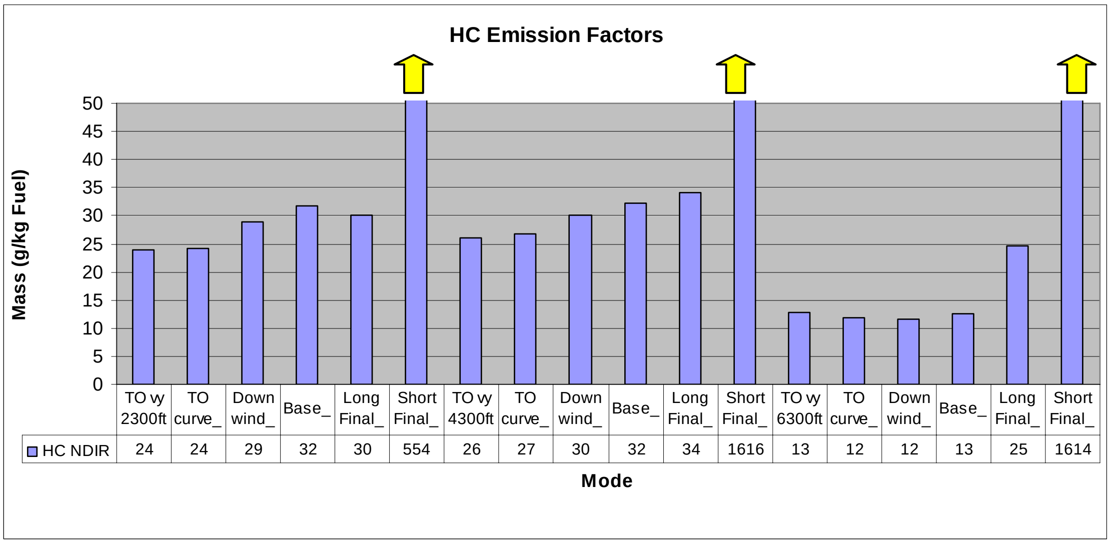


Figure 41: HC emission factors in three simulated circuits, starting at 2300ft, 4300ft and 6300ft. The first two circuits were flown with air/fuel mixture “full rich”, the circuit above 6300ft with leaned mixture (right hand side). Again, the same effect at engine idle, described in sections 3.c/d) can be seen. (ECERT22, HBKEZ)

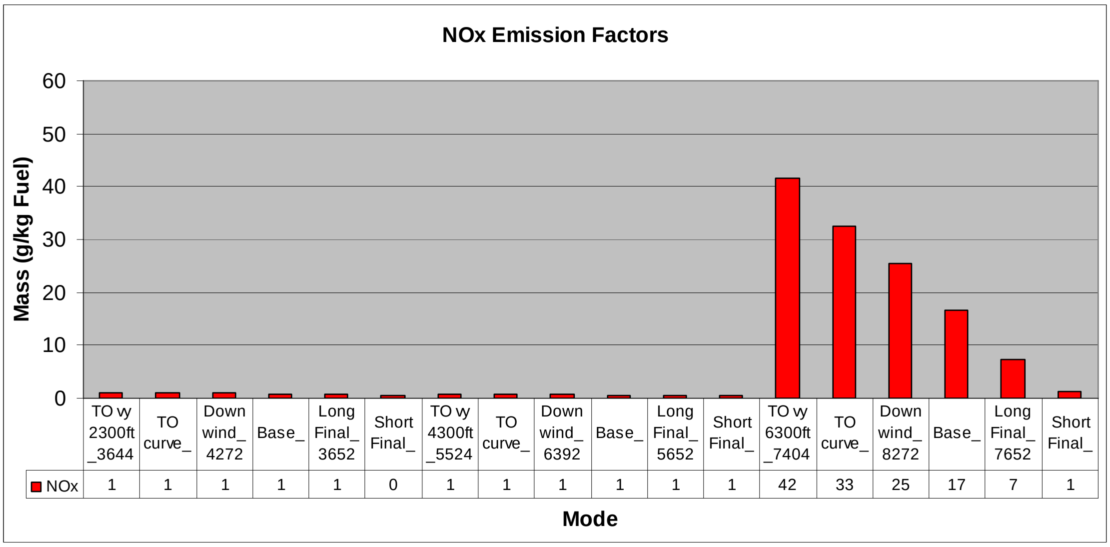


Figure 42: NO_x emission factors in three simulated circuits, starting at 2300ft, 4300ft and 6300ft. The first two circuits were flown with air/fuel mixture “full rich”, the circuit above 6300ft with leaned mixture (right hand side). (ECERT22, HBKEZ)

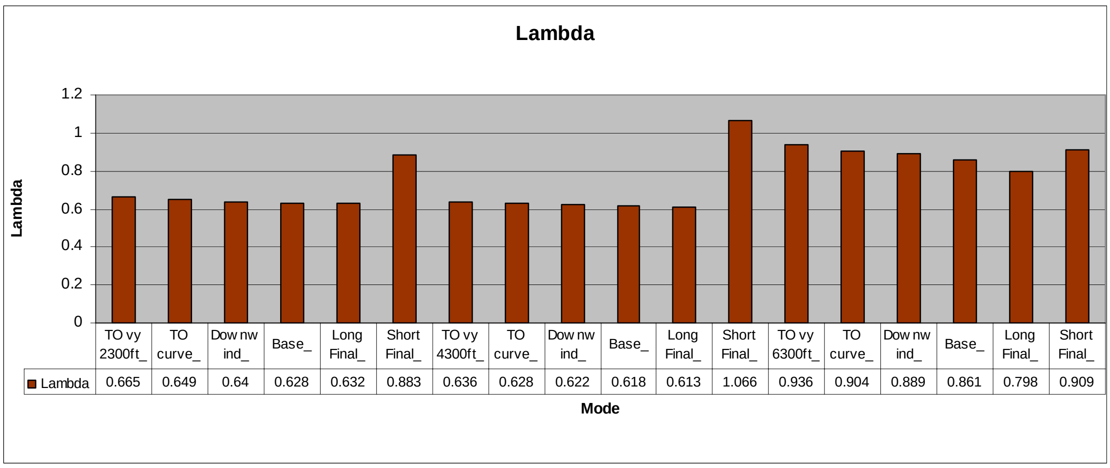


Figure 43: Lambda values in three simulated circuits, starting at 2300ft, 4300ft and 6300ft. The first two circuits were flown with air/fuel mixture “full rich”, the circuit above 6300ft with leaned mixture (right hand side). This engine shows even richer combustion (lower lambda) than that of HBEYS at “full rich” setting. (ECERT22, HBKEZ)

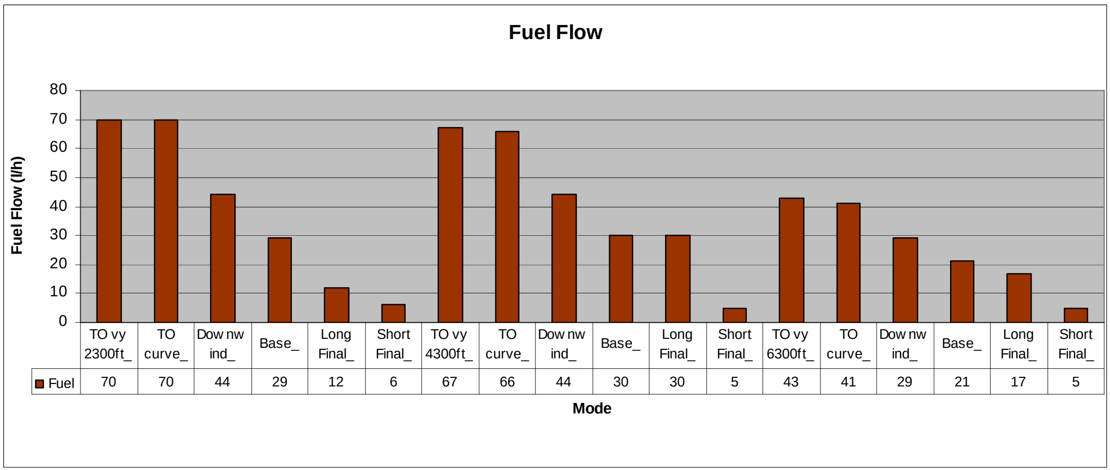


Figure 44: Fuel flows in three simulated circuits, starting at 2300ft, 4300ft and 6300ft. The first two circuits were flown with air/fuel mixture "full rich", the circuit above 6300ft with leaned mixture (right hand side). (ECERT22, HBKEZ)

4.b) Discussion

The fuel injected engine of HBKEZ has an even richer standard air/fuel mixture setting than the carburated one of HBEYS, resulting in CO emission factors up to 1400 g / kg fuel. The reason for this extremely rich setting is not clear – engine cylinder and oil temperatures remained far below threshold values for all observed engine operations. However the aircraft AFM describes a leaning procedure, starting already shortly after lift off, when take-off power is reduced to climb power. This is rather unique for such engines but makes sense, as can be seen from the measurements. Mixture adjustment is easily possible to standard values according to AFM with help from fuel flow indicator and exhaust gas temperature control.
In a conservative approach, we supposed that pilots would not always lean that particular engine on climb. For that reason, the following measurements were made at mixture "full rich".

4.c) Systematic measurements at full power and approach power settings between 3000 and 7000ft flight altitude

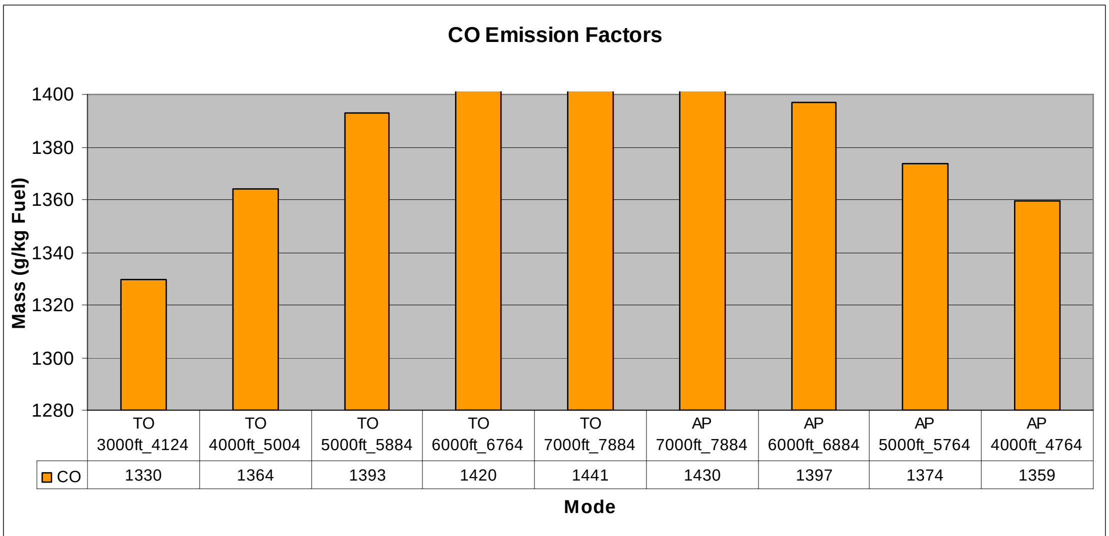


Figure 45: CO emission factors during climb at full power (TO) from 3000 to 7000ft and during descent from 7000 to 3000ft (AP). The second number after aircraft altitude in feet is the density altitude. (ECERT27, HBKEZ)

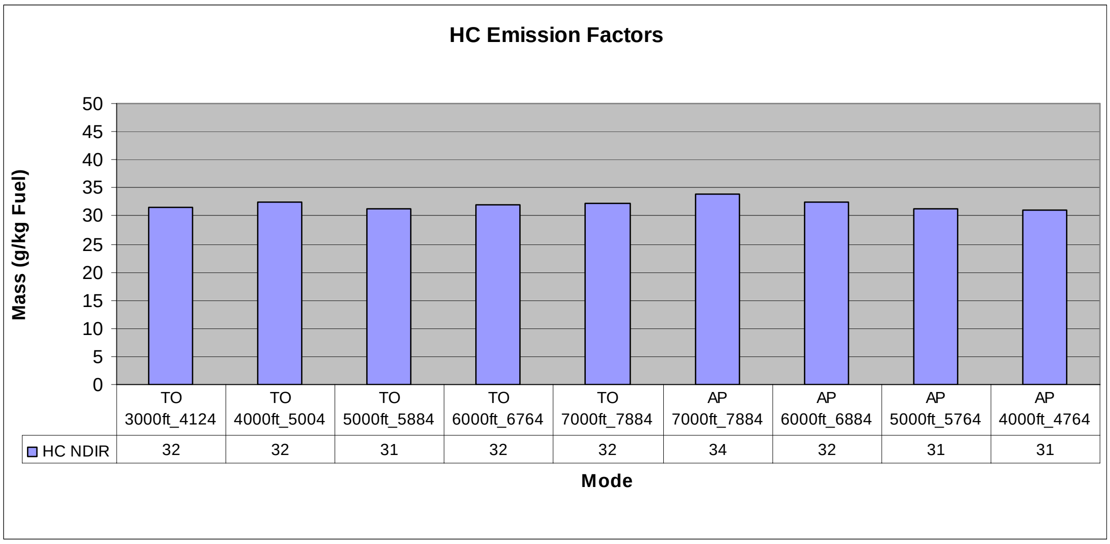


Figure 46: HC emission factors during climb at full power (TO) from 3000 to 7000ft and during descent from 7000 to 3000ft (AP). With the very rich mixture, they vary around 32 g / kg fuel. (ECERT27, HBKEZ)

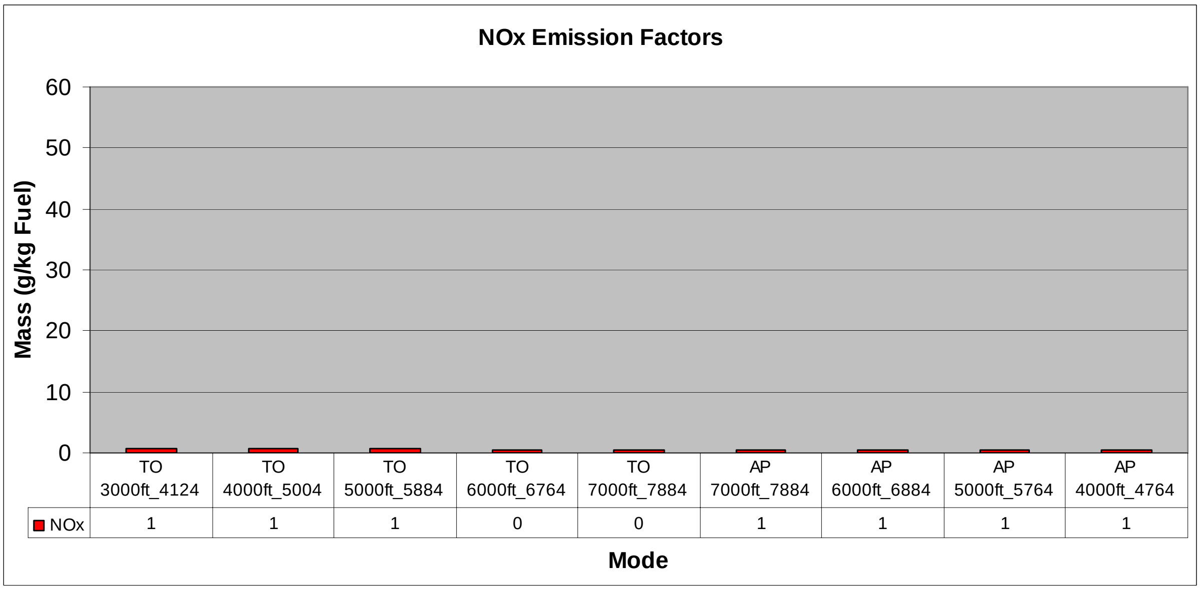


Figure 47: NO_x emission factors during climb at full power (TO) from 3000 to 7000ft and during descent from 7000 to 3000ft (AP). With the very rich mixture, practically no NO_x is built up. (ECERT27, HBKEZ)

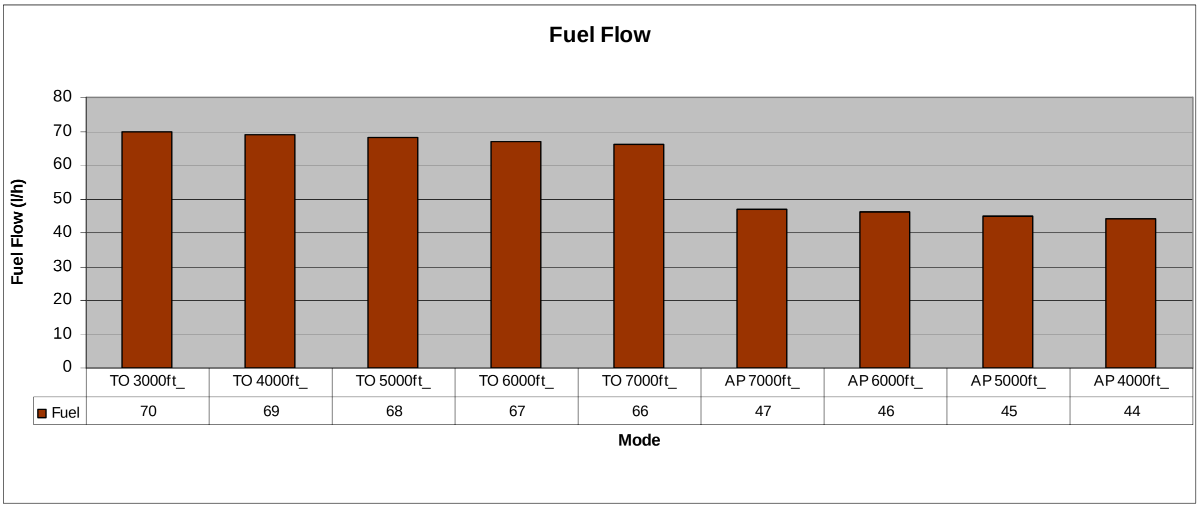


Figure 48: Fuel flow during climb at full power (TO) from 3000 to 7000ft and during descent from 7000 to 3000ft (AP). (ECERT27, HBKEZ)

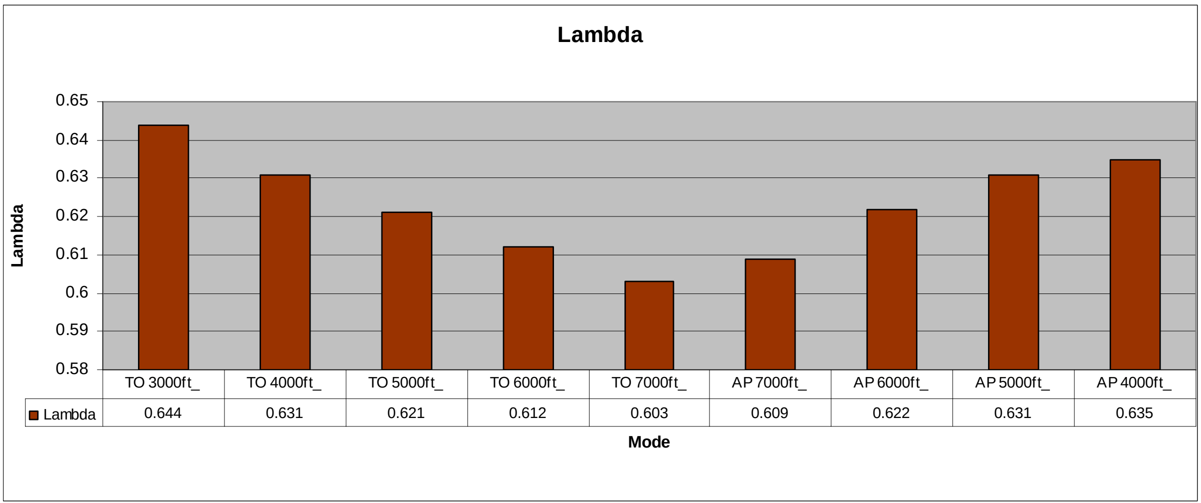


Figure 49: Lambda during climb at full power (TO) from 3000 to 7000ft and during descent from 7000 to 3000ft (AP). It can be seen, how the engine gets even richer without mixture adjustment during climb. At 7800ft density altitude (TO 7000ft), lambda stays at 0.6 and the engine swallows 40% more fuel than necessary for efficient combustion. (ECERT27, HBKEZ)

4.d) Systematic measurements at take-off, climb and approach power at 3500ft flight altitude, mixture “full rich”

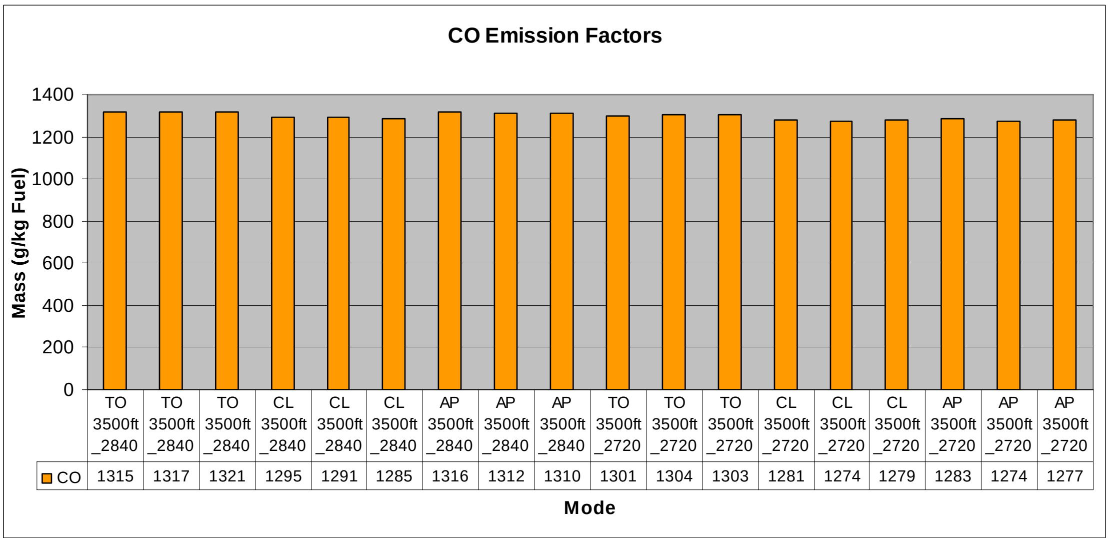


Figure 50: CO emission factors during take-off, climb and approach, when passing 3500ft (2800ft density altitude.) Two flights at different days. (ECERT48+49, HBKEZ)

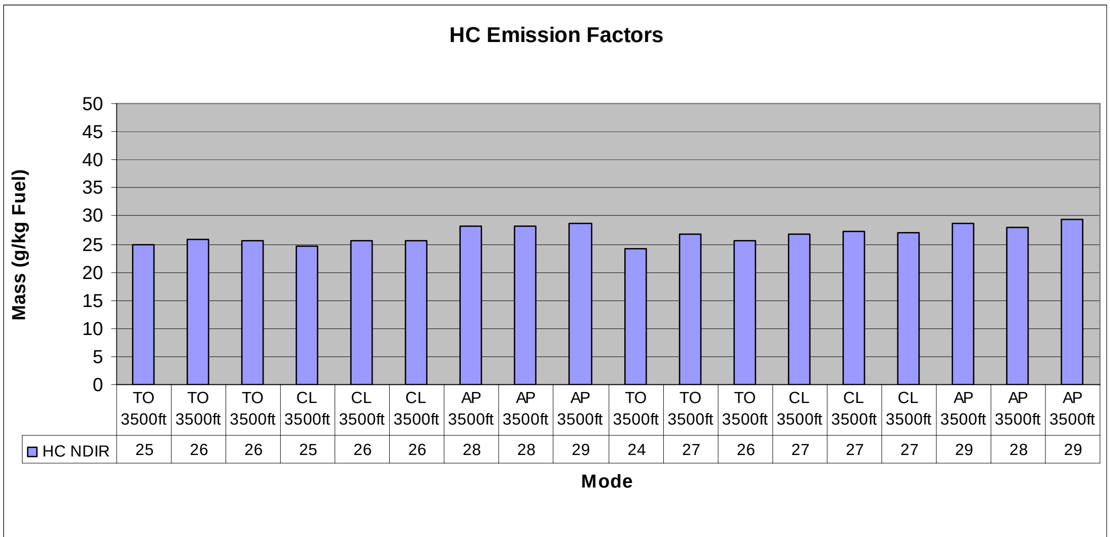


Figure 51: HC emission factors during take-off, climb and approach, when passing 3500ft (2800ft density altitude.) Two flights at different days. (ECERT48+49, HBKEZ)

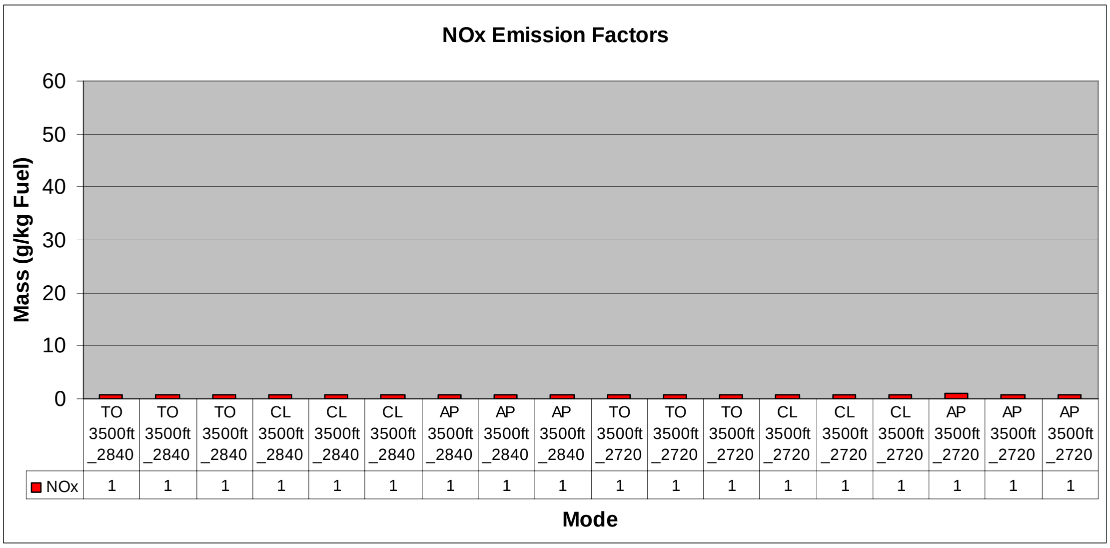


Figure 52: NO_x emission factors during take-off, climb and approach, when passing 3500ft (2800ft density altitude.) Two flights at different days. (ECERT48+49, HBKEZ)

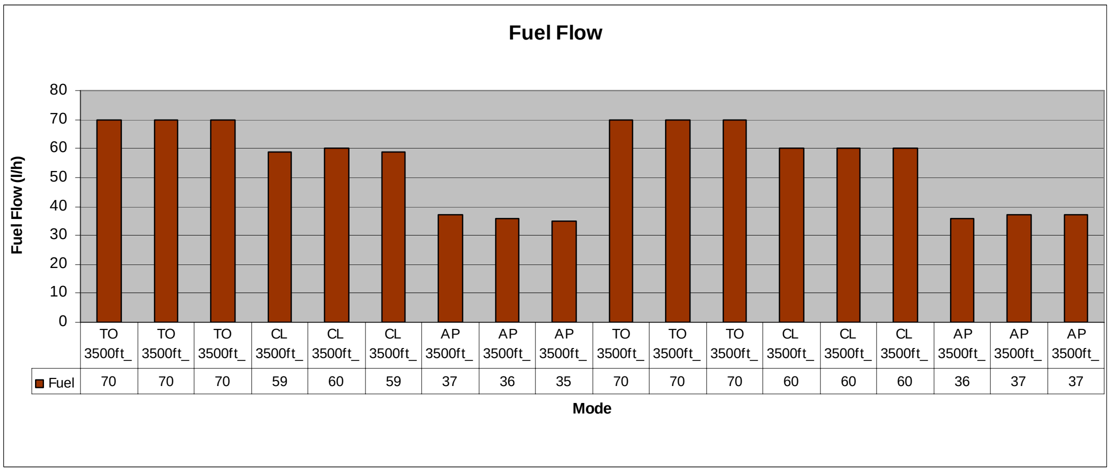


Figure 53: Fuel flow during take-off, climb and approach, when passing 3500ft (2800ft density altitude.) Two flights at different days. (ECERT48+49, HBKEZ)

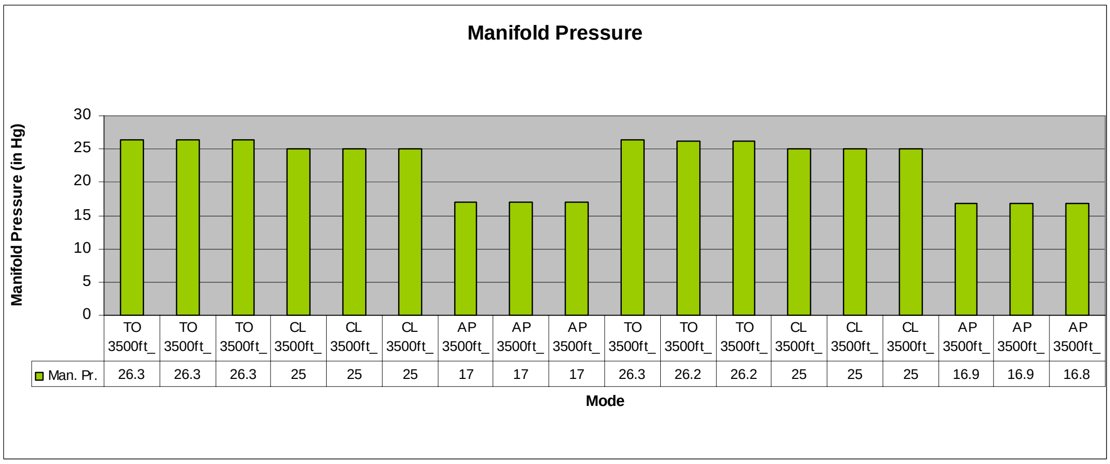


Figure 54: Manifold pressure during take-off, climb and approach, when passing 3500ft (2800ft density altitude.) Two flights at different days. (ECERT48+49, HBKEZ)

4.e) Discussion

The two measurement series have been made with comparable power settings (figure 54) and fuel flows (figure 53). At the extremely rich air/fuel mixture condition of that engine, emission factors do not change significantly from one power condition to the other. It can also be seen that the data can be considered reproducible in the context of emission measurements. CO emission factors stay around 1300 g/kg fuel, HC emission factors around 26 g/kg fuel and NO_x emission factors around 1 g / kg fuel. These are worst case scenario values, assuming that pilots do not lean the engine.

4.f) Systematic measurements at take-off, climb and approach power at 3500ft flight altitude with mixture adjustment according to the aircraft flight manual (AFM).

According to the AFM of HBKEZ, the engine air/fuel mixture should be leaned after obstacle clearance in the following way (normal procedure):

Reduce angle of climb to reach	84 kt
Reduce throttle to	25 InHg
Reduce propeller RPM to	2500 RPM
Mixture: Reduce fuel flow to	**12 US gal/h**

The mixture setting can be checked with exhaust gas temperature (EGT) and cylinder head temperature (CHT). The obtained mixture setting results in an EGT about 150°F rich of EGT peak, which corresponds approximately to best power mixture (at sea level). For descent, mixture has to be set to “full rich” again, according to the AFM.

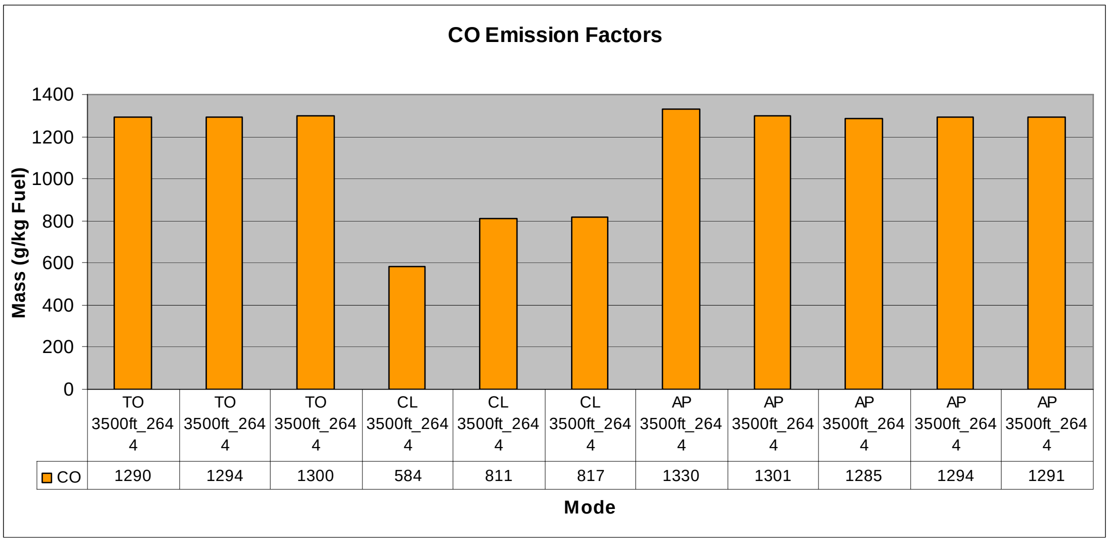


Figure 55: CO emission factors when leaning during climb. (ECERT47, HBKEZ)

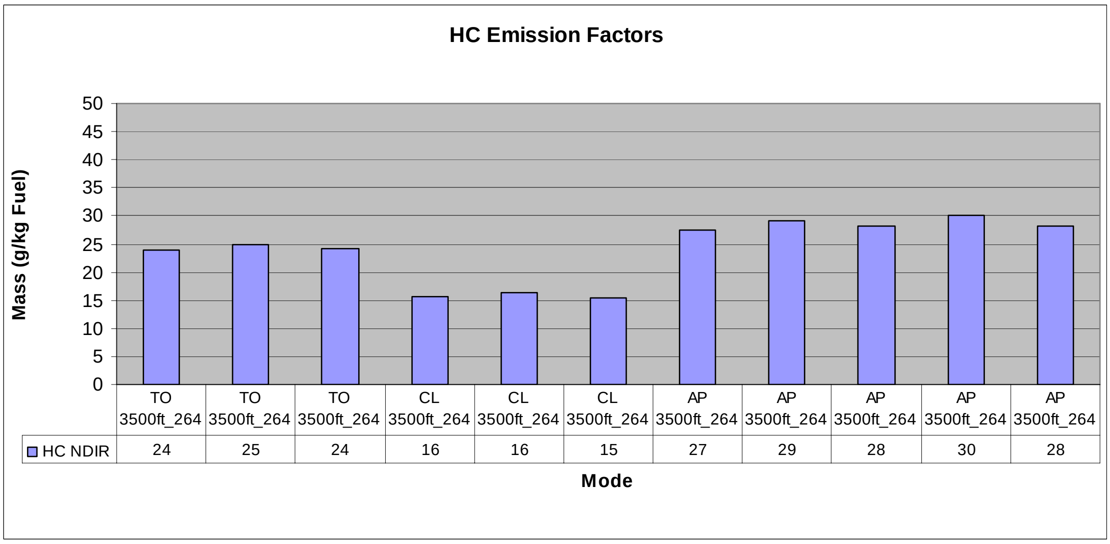


Figure 56: HC emission factors when leaning during climb. (ECERT47, HBKEZ)

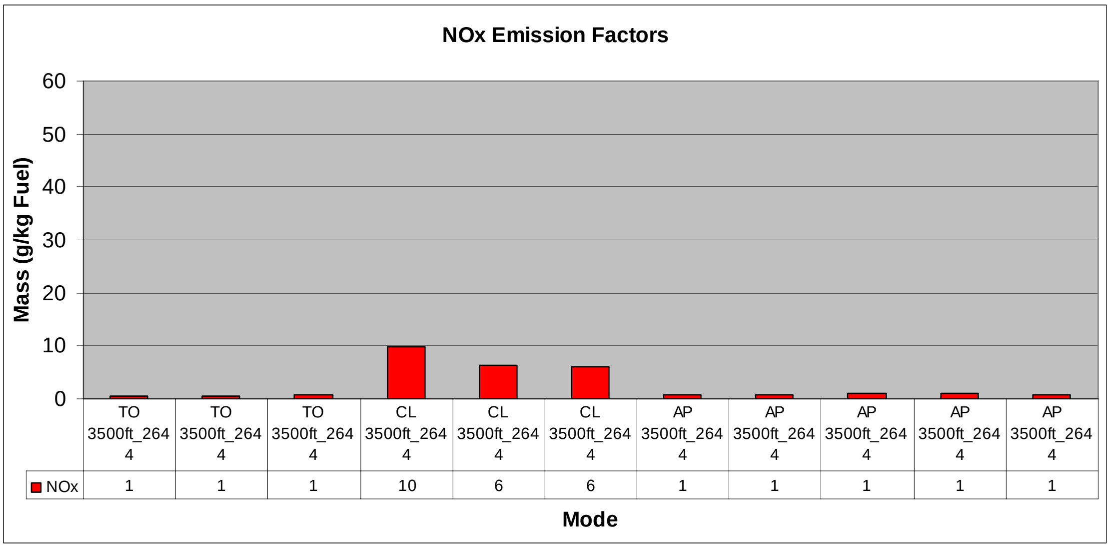


Figure 57: NO_x emission factors when leaning during climb. (ECERT47, HBKEZ)

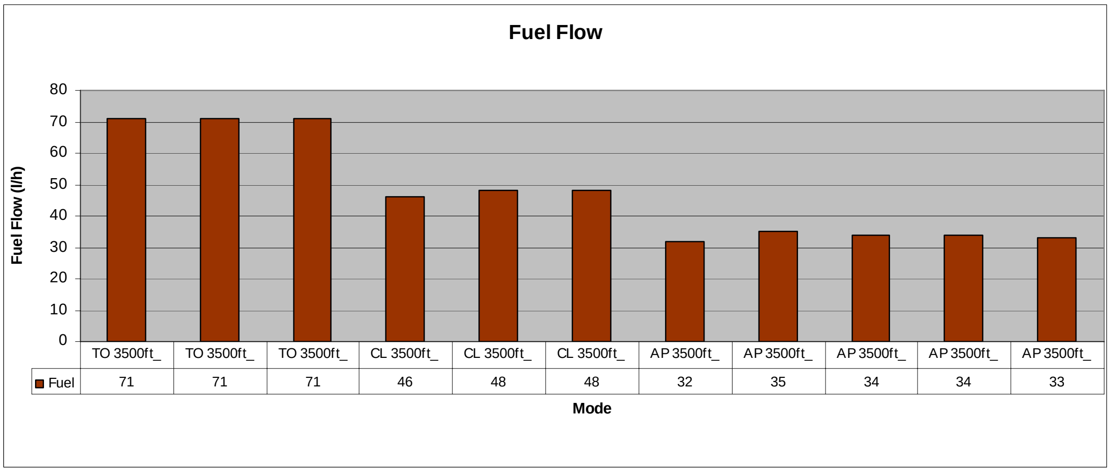


Figure 58: Fuel flow when leaning during climb. (ECERT47, HBKEZ) The engine is still running rich all the time, however consuming about 15% less fuel during climb than at the “full rich” setting (figure 53).

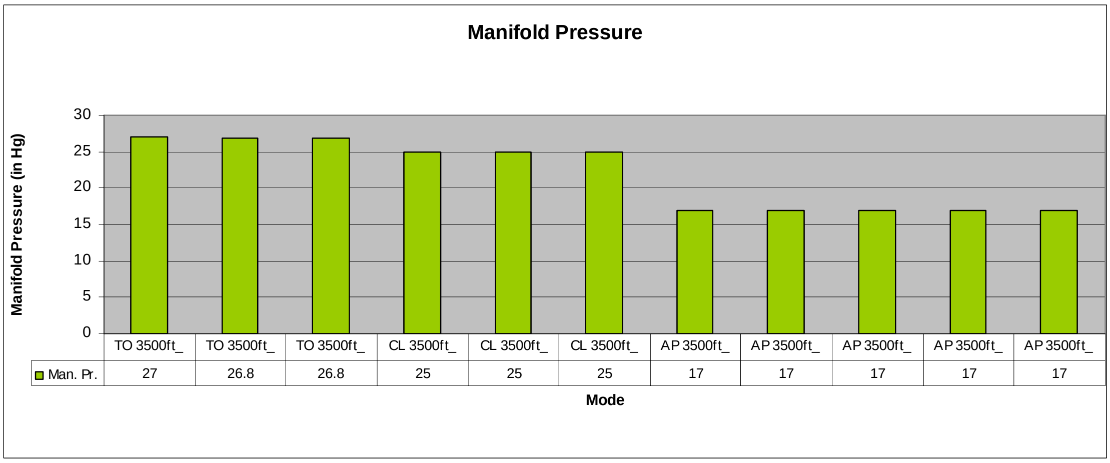


Figure 59: Manifold pressure values. (ECERT47, HBKEZ) The throttle setting can be compared to the flights of section 4.d)

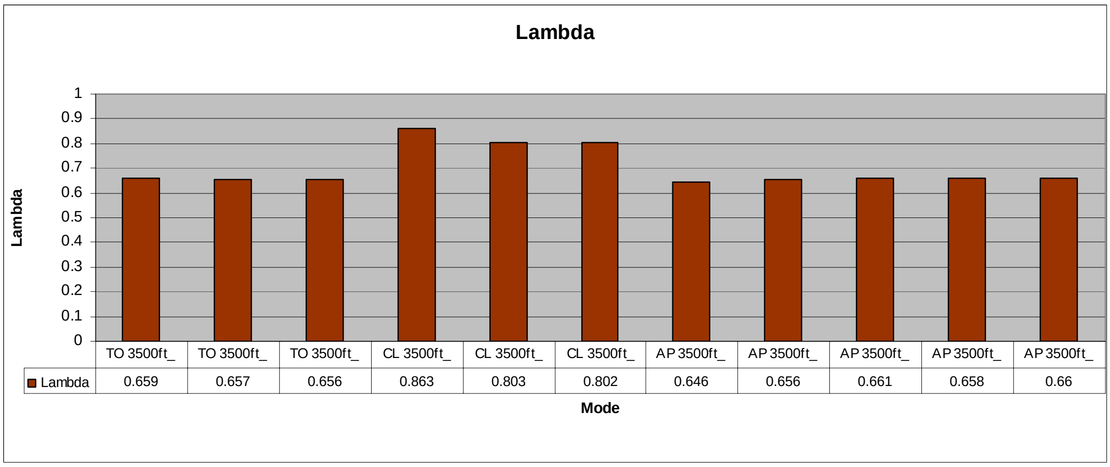


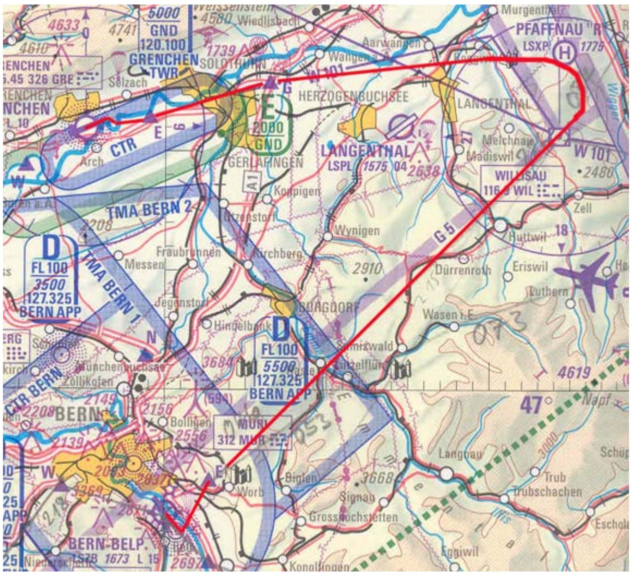
Figure 60: Lambda values: The leaning procedure in climb according AFM leads to lambda values around 0.85 (ECERT 47, HBKEZ).

4.g) Discussion

The leaning procedure during climb of that particular aircraft/engine combination leads to slightly better combustion and better engine power (lambda around 0.85). At all of those measurements, engine cylinder and oil temperatures were staying far below maximum allowed values.
From present experience it is however not fully understood, why the mixture should be immediately set to “full rich” during descent, as described in the AFM. One explanation could be that pilots might forget to gradually enrich the mixture during descent and therefore are asked to go to “full rich” as a general procedure. Note that during descent, the fuel flow at “full rich” is only 30% below the fuel flow at leaned climb power (figure 58)!
The values have shown to be reproducible (see section 4.d).

4.h) Inventory: Standard flight emission measurement from Bern (LSZB) to Grenchen (LSZG)

What we see in this section is the result of a real measured emission inventory for a half an hour VFR[3] flight from Bern (LSZB) to Grenchen (LSZG) with HBKEZ.



The pilot got the following route briefing:

- Bern outbound route E – Hasle
- Direct WIL VOR
- Climb to 5500ft QNH[4] and level off
- Cruising altitude 5500ft QNH
- Grenchen approach Aarwangen, G-E
- E altitude 3200ft QNH
- RWY 25 in use

The actual take-off mass of HBKEZ was 1040 kg (+- 10 kg).

The picture on the left shows the route flown with HBKEZ on 16th July 2004 (red line).

[3] VFR = Visual Flight Rules
[4] QNH = actual barometric air pressure in hPa, calculated to sea level & standard atmosphere, used for altimeter setting

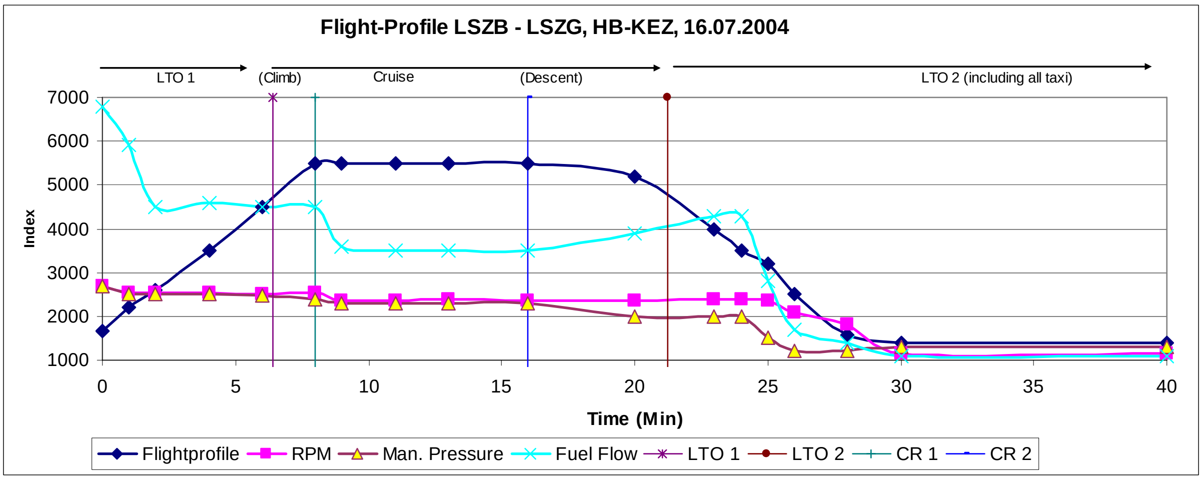


Figure 61: Altitude profile (dark blue), fuel flow (light blue), engine RPM (violet) and manifold pressure (brown) during flight from Bern to Grenchen. The taxi time which was spent in Bern has been added to the end of the flight for calculation purposes.
The altitude profile on the left shows the climb phase to 5500ft. Most of this phase is spent in the LTO 1 (if the upper limit of the LTO is 3000ft AGL). During cruise, the flight altitude is kept constant and after 16 minutes flight time, the pilot starts the descent.
Looking at the fuel flow: A first significant reduction of fuel flow is obtained when the pilot starts to lean the engine in climb, about two minutes after brake release (see also section 4.f). The second reduction appears after top of climb (TOC), when the pilot sets cruise power, cruise propeller pitch and adjusts the air/fuel mixture (line CR 1). At top of descent (TOD, line CR 2), power is reduced (manifold pressure is dropping) but the fuel flow is increasing and higher as in cruise until around 24 minutes, when power is further reduced. The increasing fuel burn comes from the mixture adjustment, as described in sections 4.f/g). At about 23 minutes flight time, at the approach check, the mixture is set to “full rich”. (ECERT 29, HBKEZ)

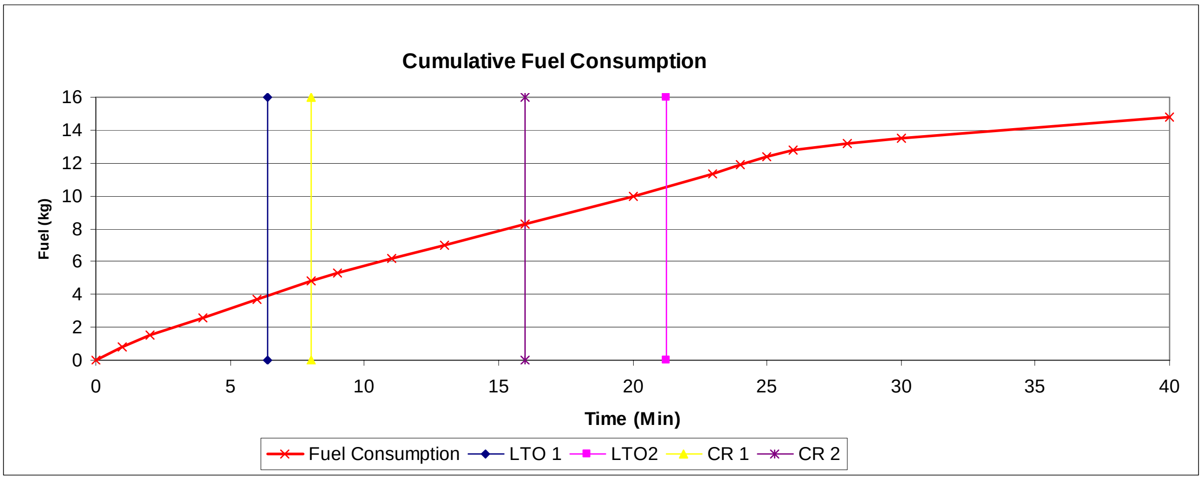


Figure 62: Integrated fuel burn over time (ECERT 29, HBKEZ)

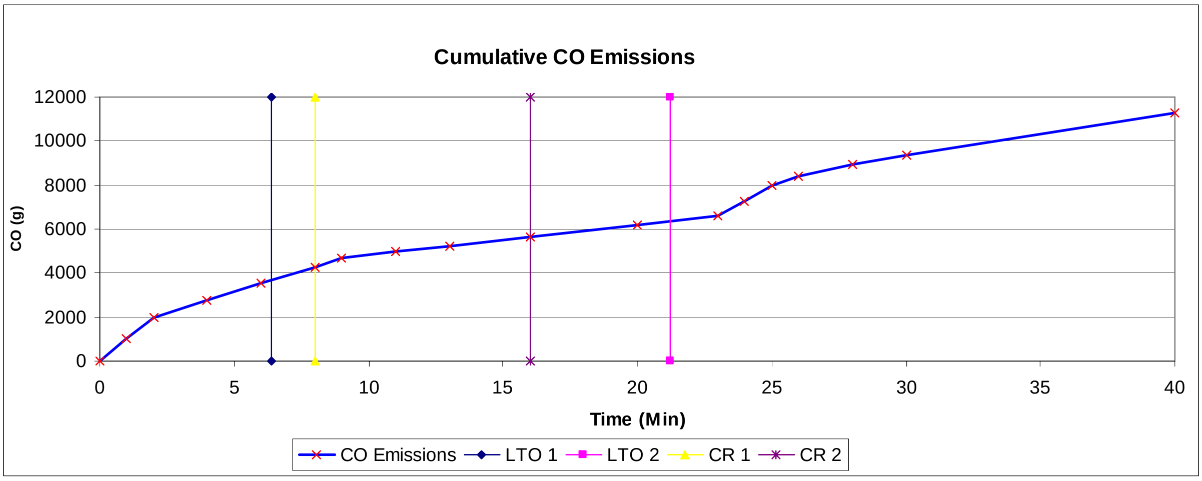


Figure 63: Integrated CO emissions over time (ECERT 29, HBKEZ)

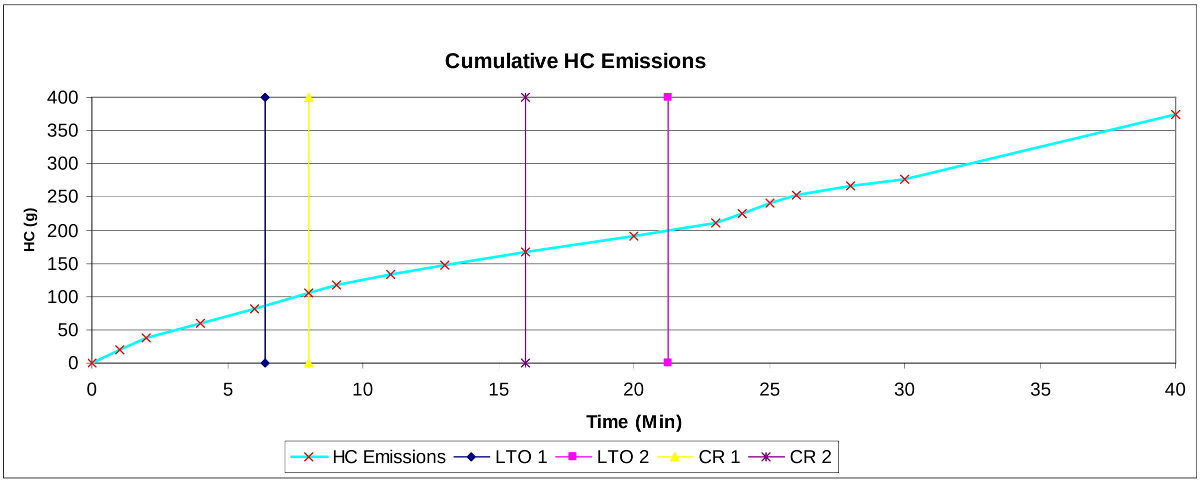


Figure 64: Integrated HC emissions over time (ECERT 29, HBKEZ)

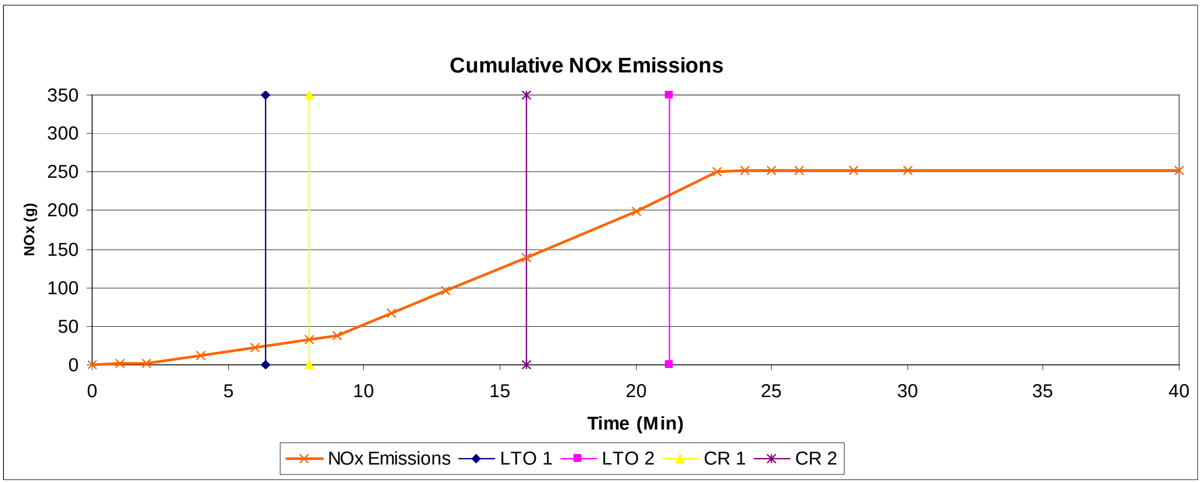


Figure 65: Integrated NO_x emissions over time (ECERT 29, HBKEZ)

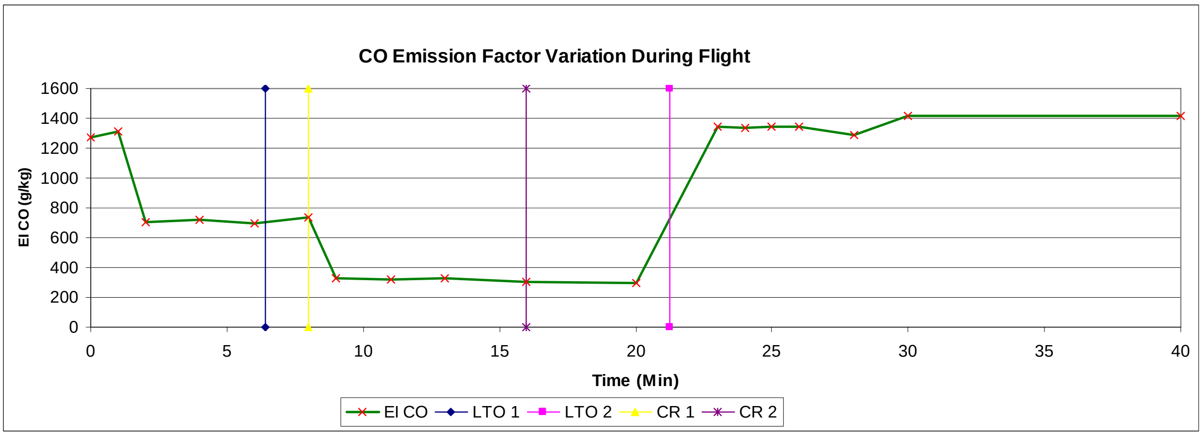


Figure 66: Variation of CO emission factor over time (ECERT 29, HBKEZ)

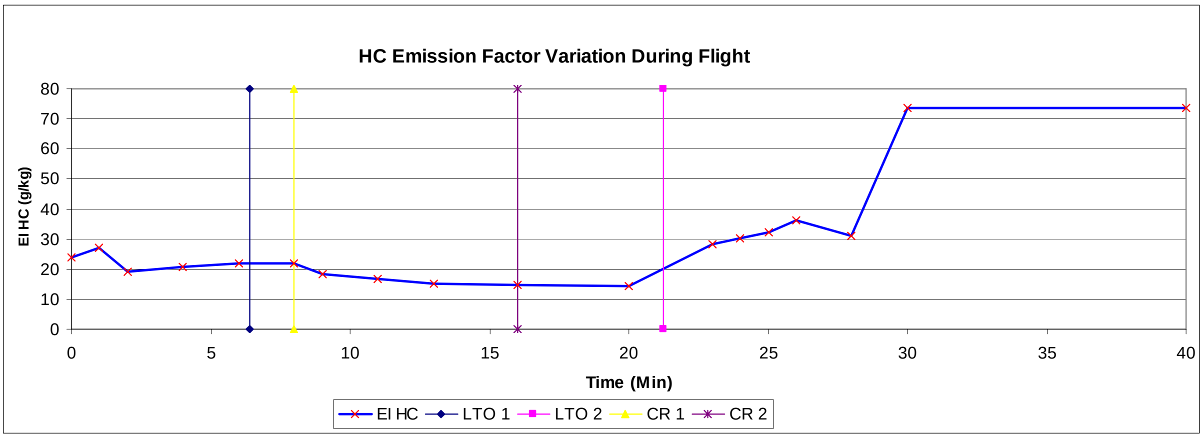


Figure 67: Variation of HC emission factor over time (ECERT 29, HBKEZ)

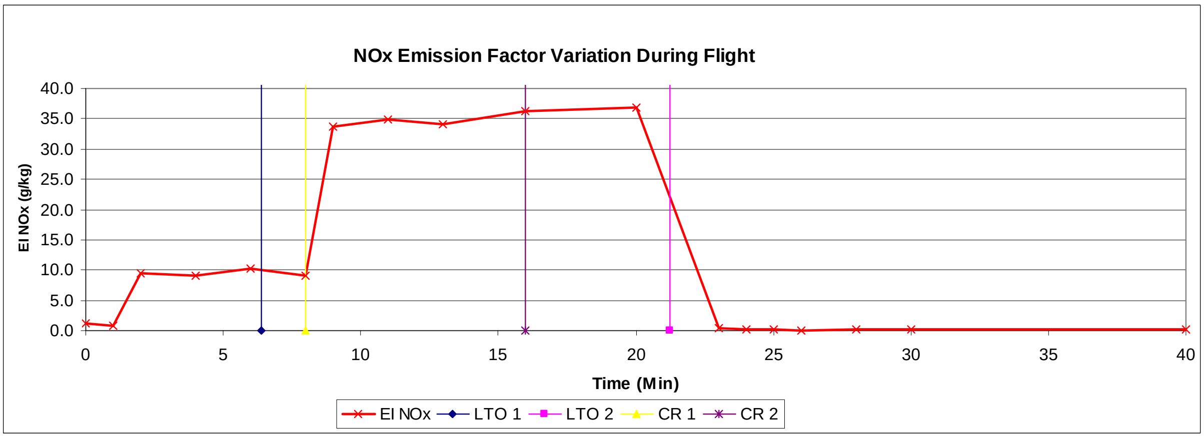


Figure 68: Variation of NO_x emission factor over time (ECERT 29, HBKEZ)

5) HBKIA (Fuel Injected Engine TCM IO-550 B)

Basically, installation of the exhaust emission measurement system in HBKIA was similar to that of HBEYS and HBKEZ.
As HBKEZ, this aircraft is equipped with a variable pitch, constant speed propeller. At a given propeller RPM, the propeller governor will keep propeller RPM constant as long as possible (by automatic pitch adjustment) if engine power or aircraft speed change, thus leading to increased propulsion efficiency compared to the fixed pitch propeller. The complexity of the aircraft is increased with the relatively high power six cylinder engine, higher speed and retractable gear.

Not many pilots seem to know that this type of engine has auto-leaning capabilities. There is still a manual mixture handle but the fuel pump has what appears to be an aneroid that senses changes in ambient pressures. Ambient pressures are routed to the aneroid through the drain fitting via a bolt hole channel in the pump body. High rpm pressures are set by means of a tapered needle (like those seen on naturally aspirated models) housed in a brass boss on the side of the pump. So in fact, this air cooled engine is **always automatically leaned even during climb** and therefore engine temperatures should be watched with additional care.

So, this type of engine added a further degree of complexity to representative measurements, because of the auto-leaning effects on emissions which could only be measured and “seen” in flight.

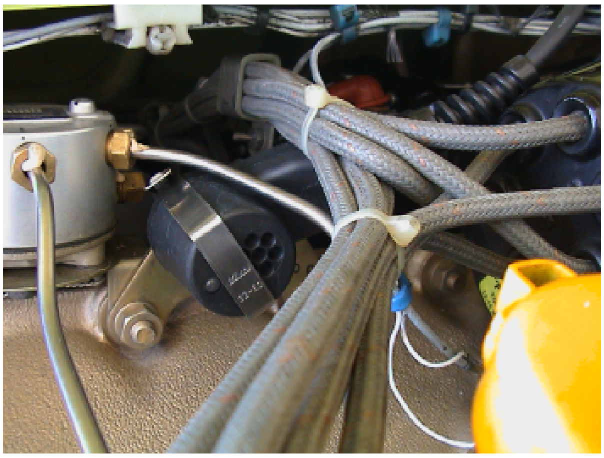
In addition to previous flights with HBEYS and HBKEZ, repetitive patterns were flown by different pilots in order to study the effect on emissions depending on different pilot operations.

Installation of FOCA emissions measurement unit in HBKIA:

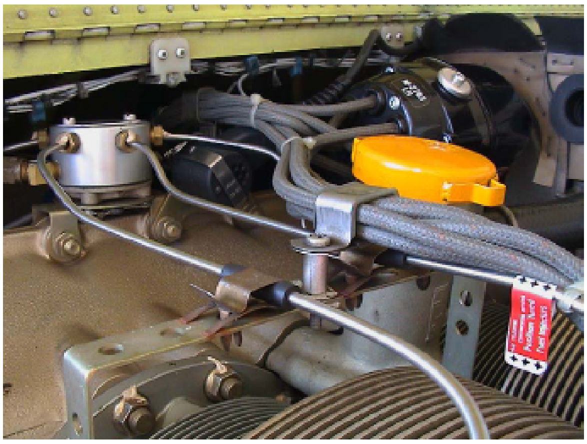
A) Installation of Battery (total Mass 25 kg)

B) Installation of Stargas898 unit (total Mass 10 kg)

C) Installation of RPM sensor, independent from A/C electrical system, at main hook of engine, behind fuel divider (experience from HBKEZ)



D) Installation of RPM sensor, overview



E) RPM sensor signal line (black, from left top to right bottom)

F) RPM signal line and exhaust probes

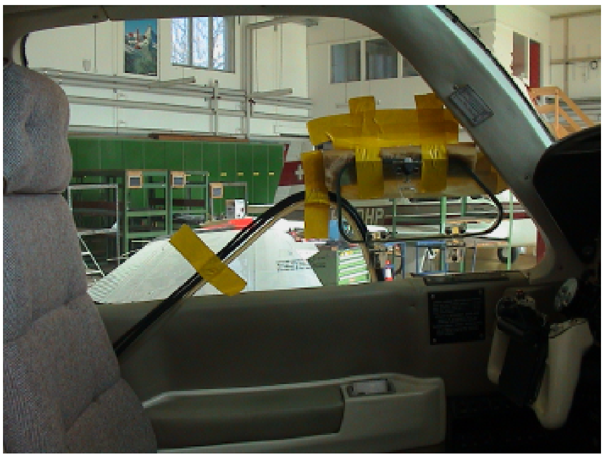
G) Exhaust probe and fixation (mounted with experience from HBEYS and HBKEZ in-flight testing). Flexible sampling line (Viton) with t-shape tube. First fixation point of sampling line is most important. In case, sampling line would disconnect or would be teared backwards, no obstruction of flight safety relevant parts has been found.

H) Fixation of exhaust in – and out lines on left hand fuselage. Tape placing with experience from HBEYS and KEZ testing. HBKEZ has been operated up to 130 kn without tape becoming loose.

I) First fixation point of flexible sampling line from below.

J) Guiding of exhaust sampling lines through side window. Window opening angle is defined by peace of foam.

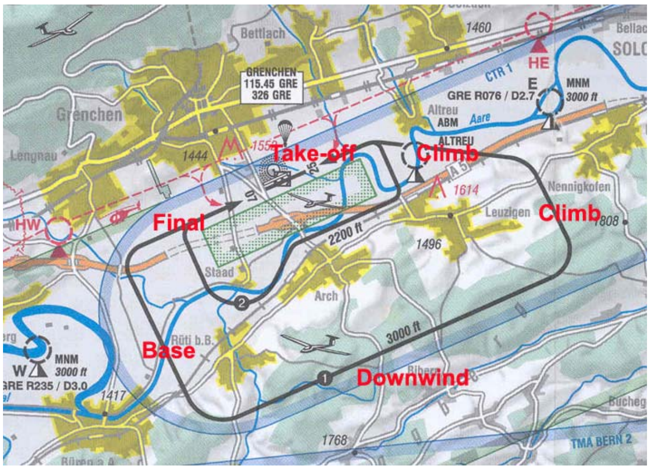
K) Sampling line guidance from inside. Reduced visibility to left hand side for the PIC has to be taken into account during in-flight tests. -> AFM supplement.



L) Sampling line guidance along airframe near flap section. Even loose flexible sampling line can not obstruct flap operation.

Installation of the exhaust measurement system in the documented way has been tested after the last 100 hour inspection of HBKIA (March 2005), during ground engine and system tests. During these standard tests, the system has been operated. Exhaust probe fixation has also been tested during several hours of ground emission tests, without becoming loose.

5.a) Results for aerodrome circuits, flown at LSZG (Grenchen Airport, Switzerland)



In Grenchen, high performance single engine piston aircraft like HBKIA have to fly the outer circuit No.1 (see picture). Runway in use during the measurements was 07. Take-off measurements took place shortly before lift-off. After departure, the pilot had to fly a slight right turn to avoid Altreu village, for noise abatement. The first climb measurement took place abeam ALTREU, the second (if possible) between Leuzigen and Nennigkofen. The downwind measurement was performed abeam tower (if possible) and the base measurement when crossing the river. The final measurement took place approximately in the middle between turning final and touch down points. Two sets of circuit patterns have been flown (ECERT 56 and 62), with the same aircraft at the same initial take-off mass and comparable meteorological conditions. But the second set of measurements was flown by a different pilot (ECERT 62).

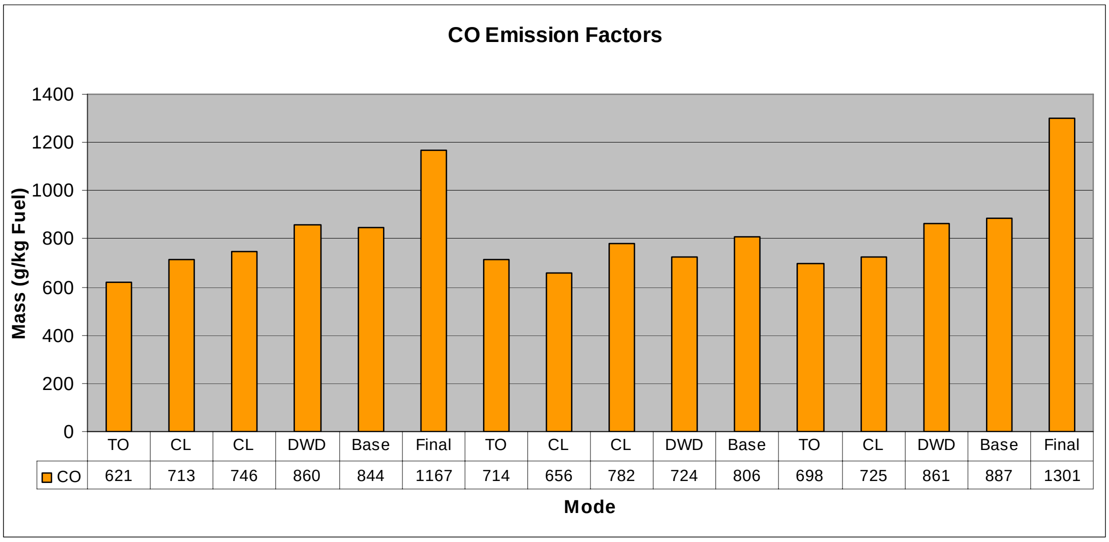


Figure 69: CO emission factors during three aerodrome circuits (TO = Take off roll, CL = Climb at vy[5], DWD = downwind). No “Final” measurement at the second circuit. (ECERT 56, HBKIA)

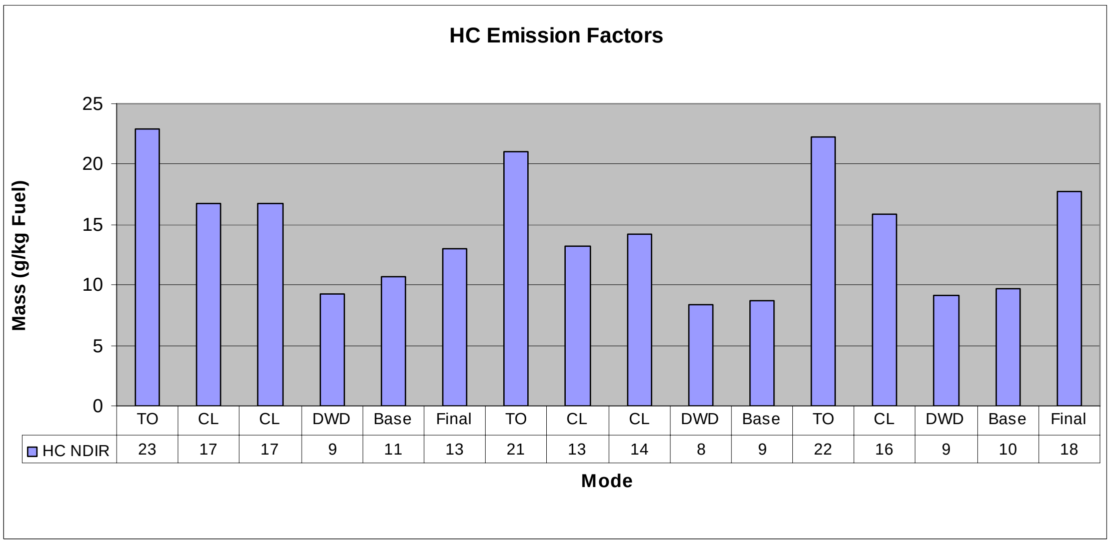


Figure 70: HC emission factors during three aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = downwind). No “Final” measurement at the second circuit. (ECERT 56, HBKIA)

[5] Vy = indicated airspeed for best rate of climb

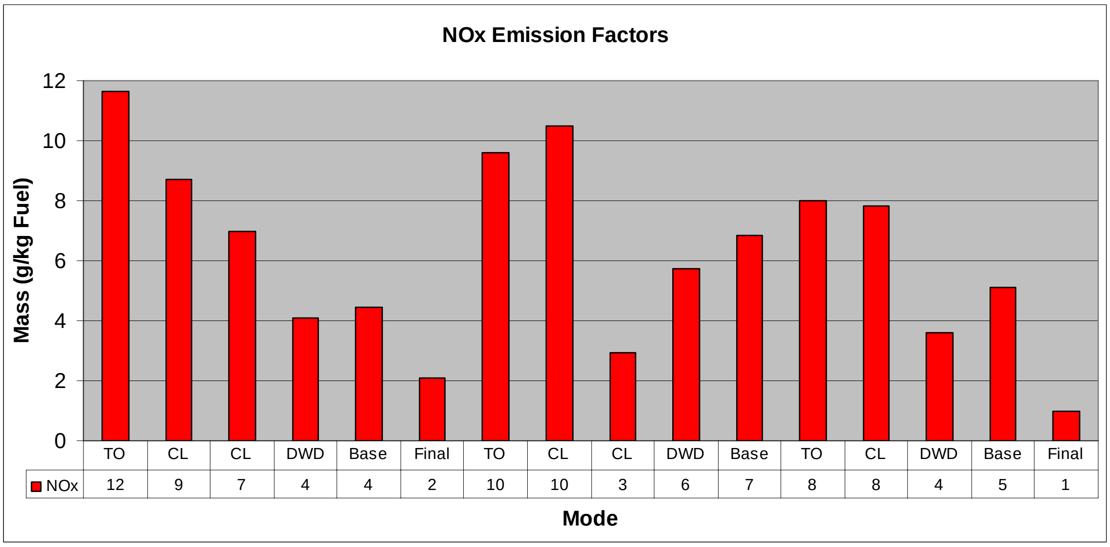


Figure 71: NO_x emission factors during three aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = downwind). No “Final” measurement at the second circuit. (ECERT 56, HBKIA)

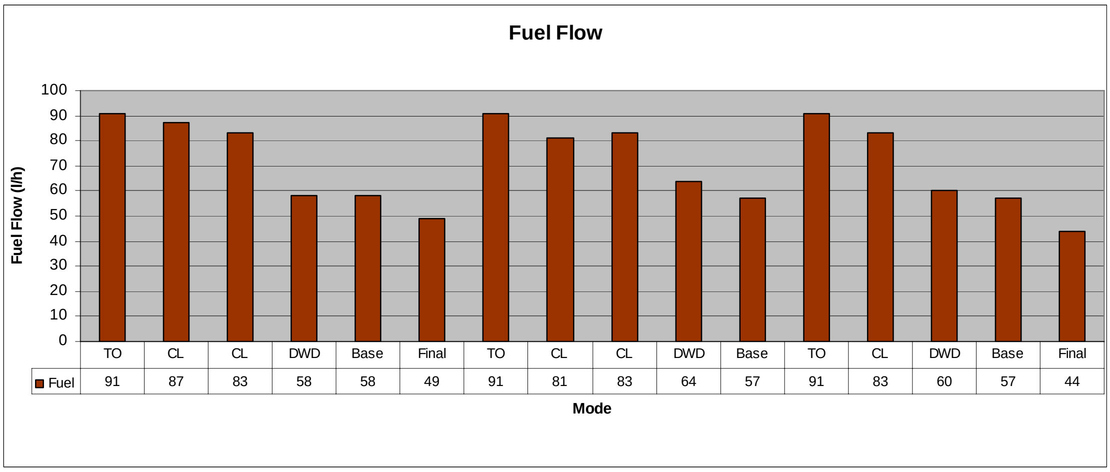


Figure 72: Fuel flow during three aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = downwind). No “Final” measurement at the second circuit. (ECERT 56, HBKIA)

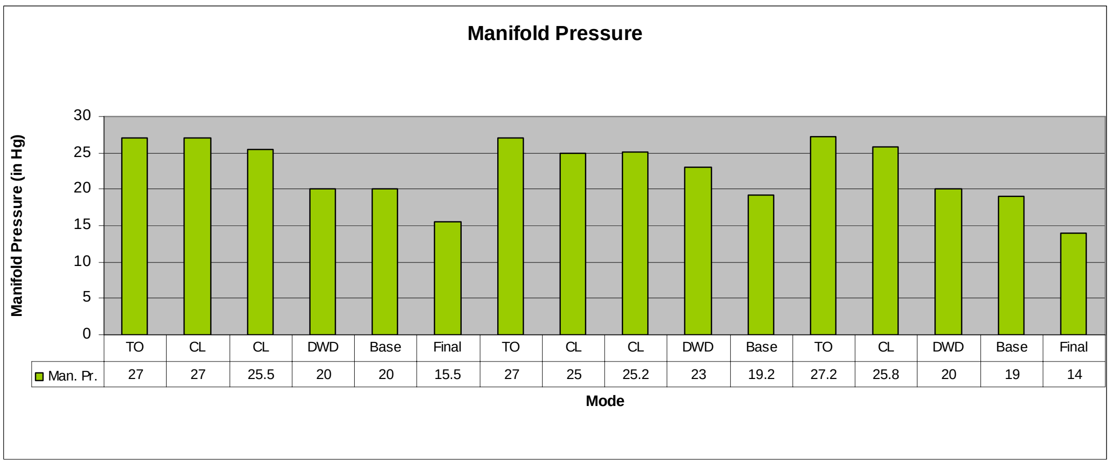


Figure 73: Manifold pressure during three aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = down-wind). No “Final” measurement at the second circuit. (ECERT 56, HBKIA)

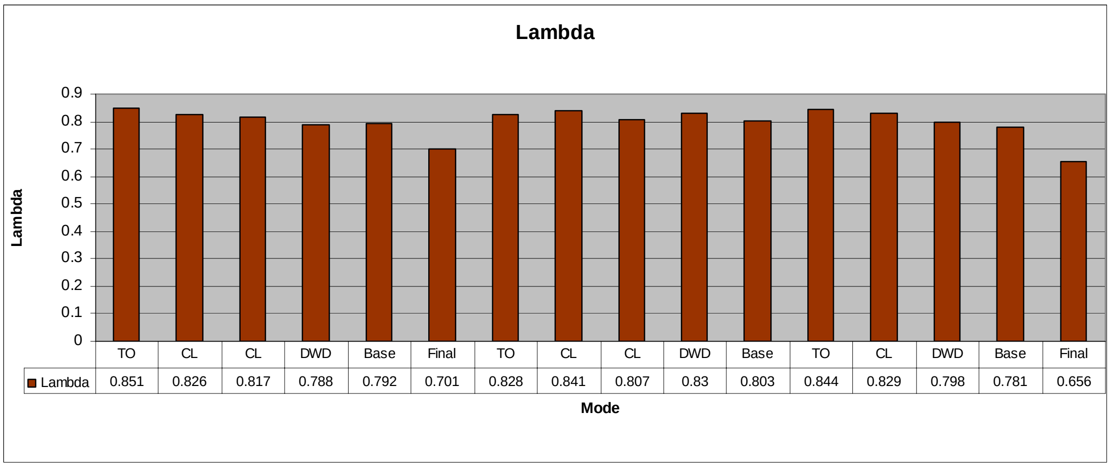


Figure 74: Lambda during three aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = downwind). No "Final" measurement at the second circuit. (ECERT 56, HBKIA)

Second set, flown by different pilot:

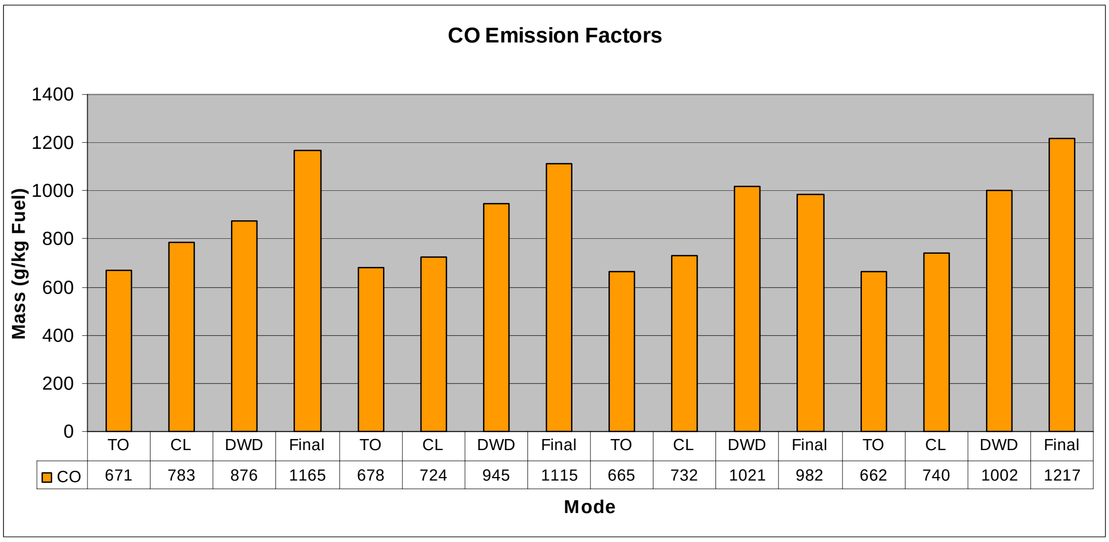


Figure 75: CO emission factors during four aerodrome circuits (TO = Take off roll, CL = Climb at vy[6], DWD = downwind), flown with second pilot (ECERT 62, HBKIA)

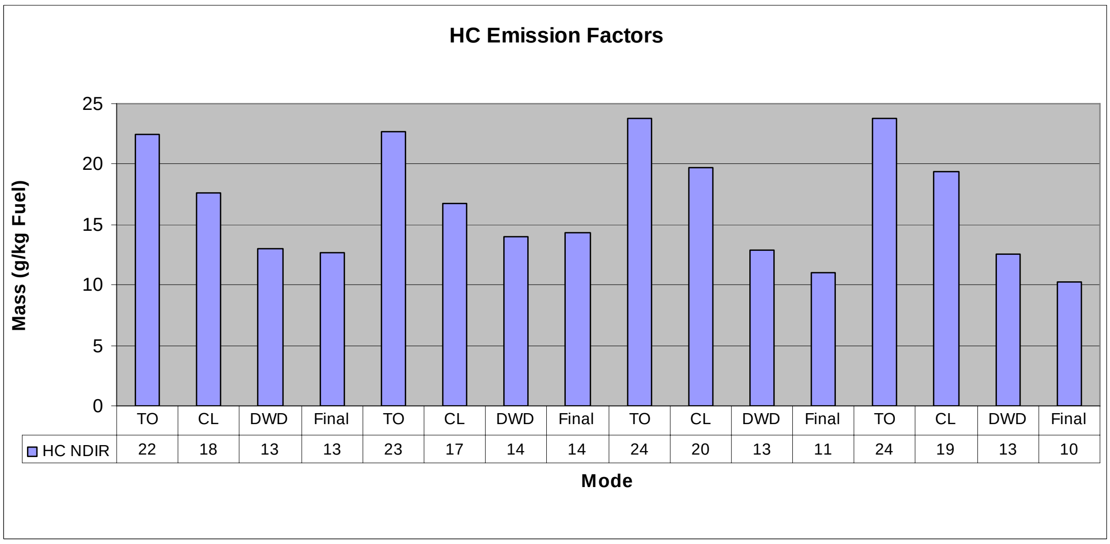


Figure 76: HC emission factors during four aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = downwind), flown with second pilot (ECERT 62, HBKIA)

[6] Vy = indicated airspeed for best rate of climb

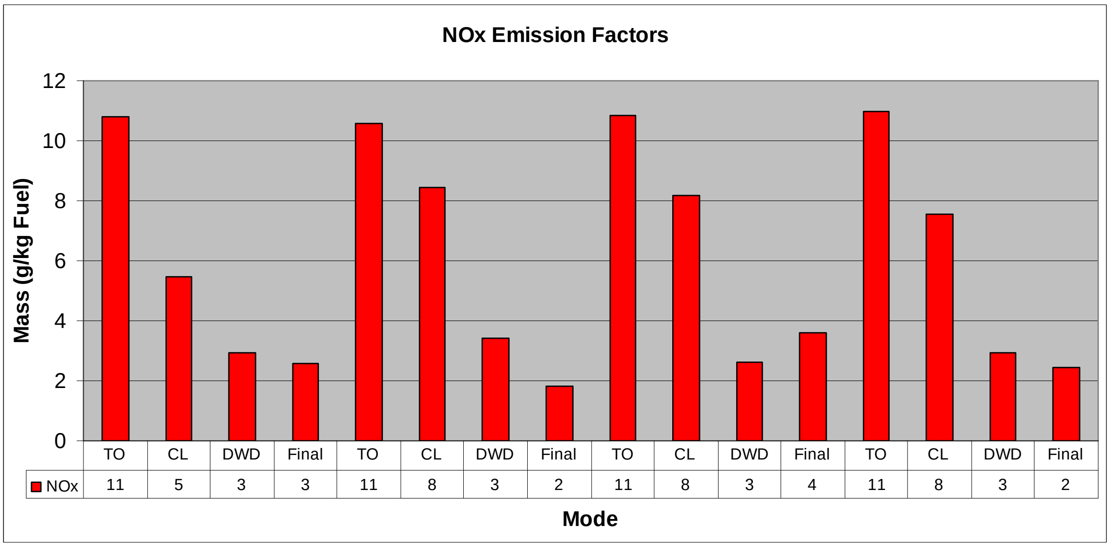


Figure 77: NO_x emission factors during four aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = downwind), flown with second pilot (ECERT 62, HBKIA)

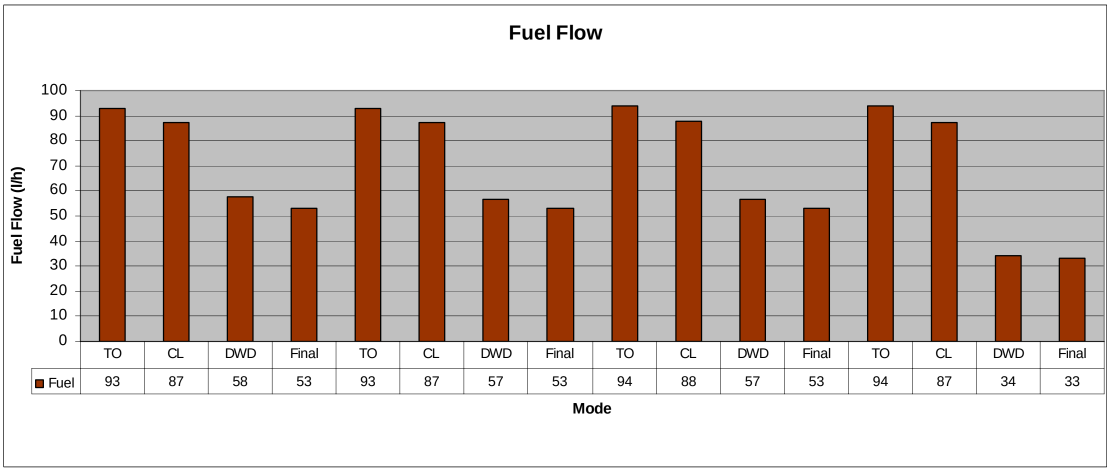


Figure 78: Fuel flow during four aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = downwind), flown with second pilot (ECERT 62, HBKIA)

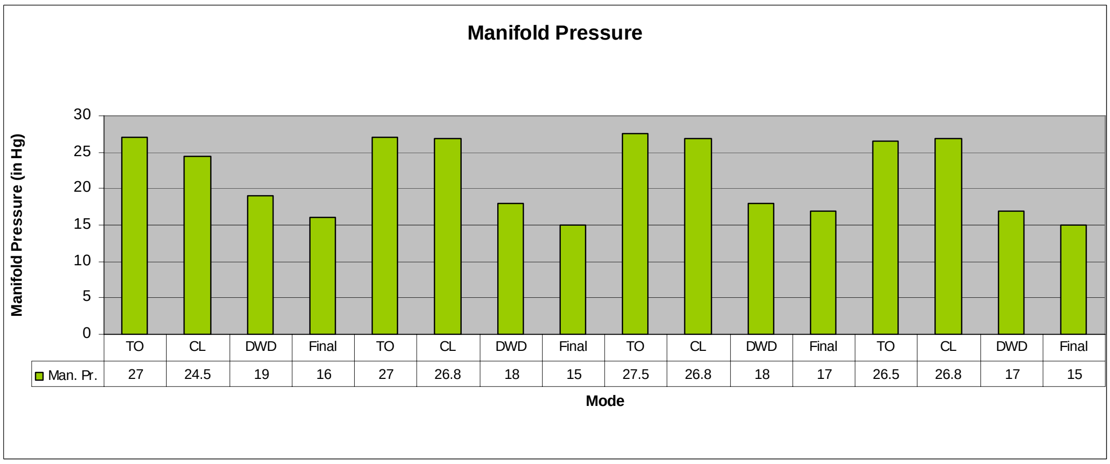


Figure 79: Manifold pressure during four aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = down-wind), flown with second pilot (ECERT 62, HBKIA)

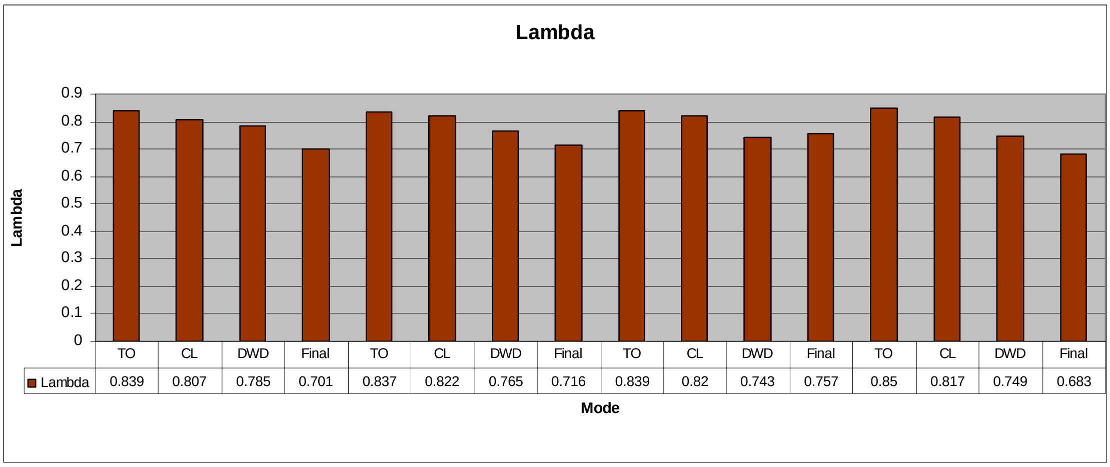


Figure 80: Lambda during four aerodrome circuits (TO = Take off roll, CL = Climb at vy, DWD = downwind), flown with second pilot (ECERT 62, HBKIA)

5.b) Discussion

In contrast to the engines of HBEYS and HBKEZ, the engine of HBKIA is auto-leaned (see 5, Introduction). This can be seen in figures 74 and 80. Lambda values at take-off are around 0.83 to 0.85, significantly higher than the values of the previously measured engines at “full rich” mixture. A lambda value of 0.85 corresponds approximately to best power mixture. However, engine cylinder head temperatures reach easily its limits at this condition and therefore considerable care must be taken, not to exceed engine temperature limits during climb. At low power settings, the auto-lean feature does not seem to have an effect. The engine is running extremely rich again (lambda around 0.7), like the previously measured engines at “full rich” mixture adjustment.
The second pilot has been flying the circuits very regularly compared to the first pilot. This can be seen in the variation of the engine manifold pressure, lambda, fuel flow and emission factors.
Due to auto-lean at high power, CO emission factors are lowest and NO_x emission factors highest for high power setting (take-off and climb). Interestingly, HC emission factors are highest as well for high power settings. Normally HC correlates to CO and HC would have been expected to be lowest at high power settings.

5.c) Inventory: Total emissions of HBKIA in aerodrome circuits and comparison between two pilots

For this comparison of total emissions in the circuits, we used the same mean circuit times as in 3.g) and the data of 5.a). In order to obtain more general results, we used mean FOCA standard times instead of Grenchen circuit times for this comparison.

Table 4:

Mode	Times in Mode (s)
TAKE-OFF	20
CLIMB OUT	75
DOWNWIND	90
BASE	105
FINAL	20

Emission factors were taken from the previously discussed measurements, with mixture control in “full rich” position and the engine doing auto-lean, as discussed in 5.b). Because of very incomplete combustion (as described in section 3 of this Appendix), the mean emission factor for CO_2 is far below the theoretical 3.17 kg / kg fuel. For this calculation we assume again a conservative factor of 2 kg CO_2 / kg fuel and 1.2 kg H_2O / kg fuel. The lead content in AVGAS 100LL is considered 0.794 g / kg fuel, the fuel density 0.72 kg / liter.

Table 5: Total emissions for 1 circuit (emissionsinventar.volten.HBKIA_060921_rit)

HBKIA	fuel (kg)	CO (g)	HC (g)	NOx (g)	CO2 (kg)	H20 (kg)	lead (g)
Pilot 1	4.10	3291	52	24	8.19	4.92	3.25
Pilot 2	3.88	3371	62	20	7.77	4.66	3.08

5.d) Discussion

During 1 circuit, HBKIA burns around 4 kg fuel and produces roughly 3 kg CO, 50 g HC and 20 g NO_x, 8 kg CO_2, 5 kg H_2O and 3 g lead.
From the existing measurement experience, FOCA assumes that significant differences in the results between pilot 1 and pilot 2 of more than 5% can be attributed to pilot operations. Table 5 shows that pilot 2 was flying more efficient. This can be explained by lower power settings, especially in the down-wind leg (see figures 79 and 73). Part of this gain would be compensated by longer downwind time. The lower power setting results in slightly higher CO and HC emissions and lower NO_x emissions, as can be seen in table 5. CO_2, H_2O and lead emissions are directly proportional to fuel burn, hence are lower for pilot 2 operations.
Generally speaking, the differences between the two measurement sets and the influence of the pilot are not significantly high for this aircraft during circuit flying. This may be attributed mainly to the fact, that the engine of HBKIA is automatically leaned and hence produces similar combustion conditions in both cases. Remaining differences outside possible measurement statistical errors may be caused from different power settings in the downwind, base and final leg of the circuit.

5.e) Additional high altitude circuit flight testing at Samedan Airport (5600ft AMSL), Switzerland

As in 3.e) we wanted to investigate the emissions performance at a high altitude airport. The function of the auto-lean feature of the tested engine and the effect on emissions was of particular interest.

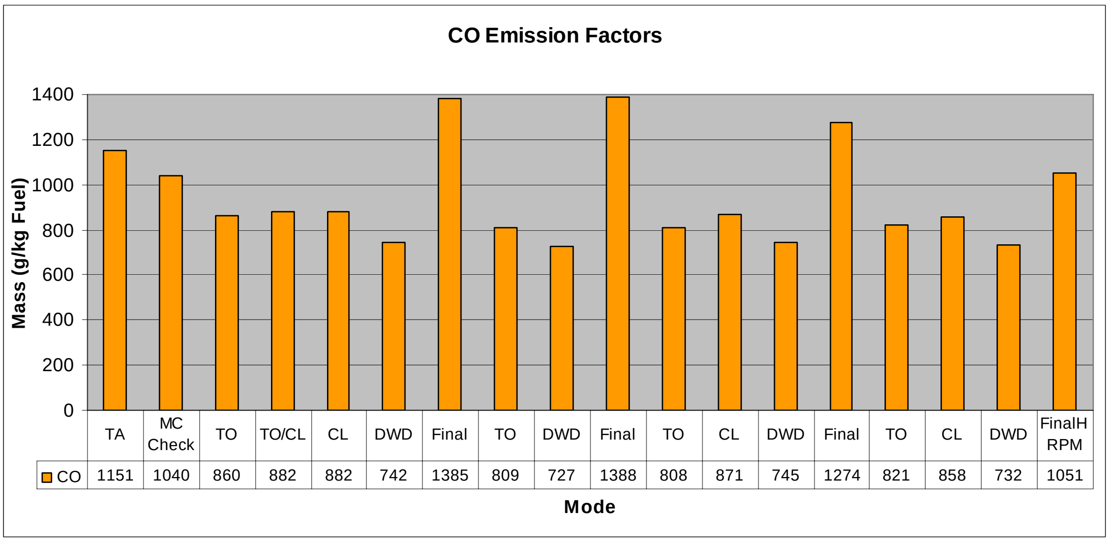


Figure 81: CO emission factors during four aerodrome circuits (TA = Taxi, MC = Magneto Check, TO = Take off roll, CL = Climb at vy[7], DWD = downwind), flown at Samedan Airport (ECERT 59, HBKIA)

[7] Vy = indicated airspeed for best rate of climb

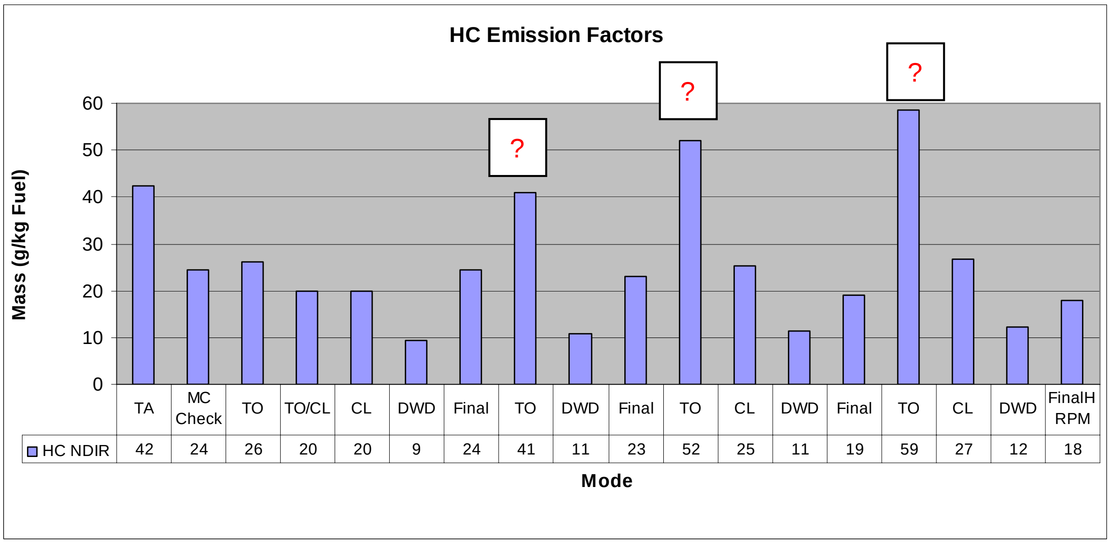


Figure 82: HC emission factors during four aerodrome circuits (TA = Taxi, MC = Magneto Check, TO = Take off roll, CL = Climb at vy, DWD = downwind), flown at Samedan Airport (ECERT 59, HBKIA)

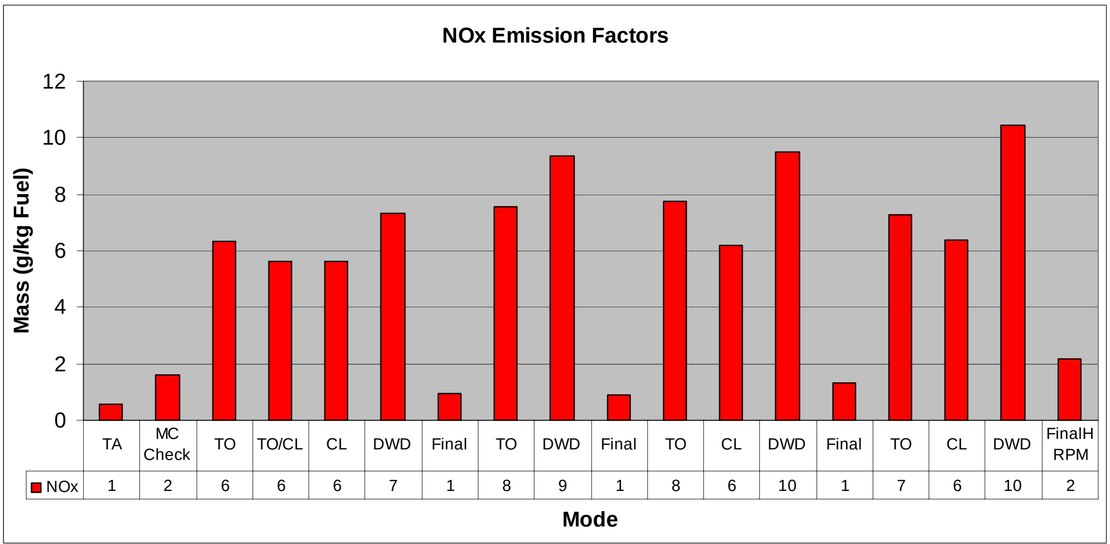


Figure 83: NO_x emission factors during four aerodrome circuits (TA = Taxi, MC = Magneto Check, TO = Take off roll, CL = Climb at vy, DWD = downwind), flown at Samedan Airport (ECERT 59, HBKIA)

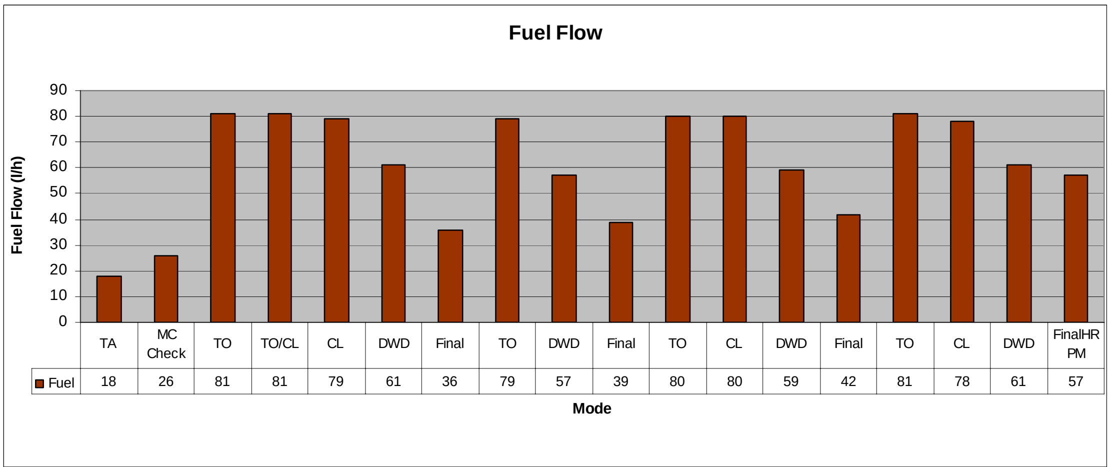


Figure 84: Fuel flow during four aerodrome circuits (TA = Taxi, MC = Magneto Check, TO = Take off roll, CL = Climb at vy, DWD = downwind), flown at Samedan Airport (ECERT 59, HBKIA)

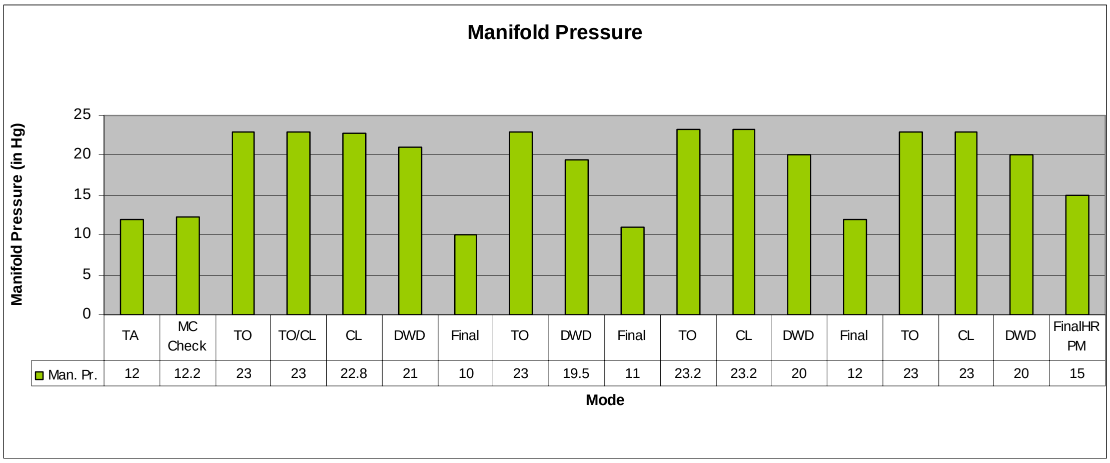


Figure 85: Manifold pressure during four aerodrome circuits (TA = Taxi, MC = Magneto Check, TO = Take off roll, CL = Climb at vy, DWD = downwind), flown at Samedan Airport (ECERT 59, HBKIA)

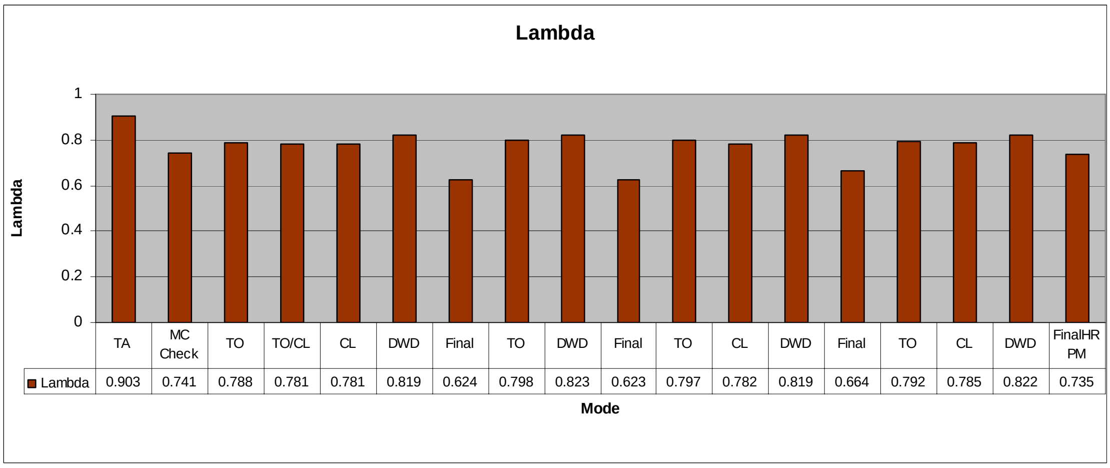


Figure 86: Lambda during four aerodrome circuits (TA = Taxi, MC = Magneto Check, TO = Take off roll, CL = Climb at vy, DWD = downwind), flown at Samedan Airport (ECERT 59, HBKIA)

5.f) Discussion

The circuits at Samedan have been flown by the same pilot, as in ECERT 62 (circuits at Grenchen airport, see 5.a). Therefore the results of ECERT 62 are compared to that of ECERT 59 (circuits at Samedan airport). ECERT 59 data do not contain the base leg. In Samedan, the base leg consists basically of a 180° turn.

First of all, it can be seen from figures 79 and 85 that the four circuits flown in Samedan did not show a consistent repetitive power setting. There is no clear repetition of the power setting pattern as shown in figure 79. This can be explained by the fact that the wind conditions in the alpine valley were very variable, resulting in different power adjustments. Because of the high altitude (in fact the density altitude varied between 6800 and 7800ft in the circuits), maximum manifold pressure at take off was only at 23 In Hg[8] (figure 85) and maximum engine power was approximately as low as normal cruise power.

From comparison between figures 80 and 86 it can be seen that the auto-lean mixture adjustment for take-off power was not as good as in the lower altitude measurement (5.a). The engine ran still very rich. In fact, it seems that the measured engine does not automatically fully compensate the air-fuel-mixture for the lower air density and additional manual leaning would have been necessary in this situation. The result can be seen with higher CO and HC values at high power settings compared to ECERT 62. Once again, HC values are highest for take-off. We were not able to find out, whether this was real and resulted from the particular engine condition with low manifold pressure in the air intake, richer conditions and the throttle fully open or resulted from a systematic error in the measurement. (figure 82).

[8] In Hg = Inches mercury column, 23 In Hg = 779 hPa

5.g) Inventory: Comparison of total emissions of HBKIA in the low and high altitude aerodrome circuit

For this comparison of total emissions in the circuits, we used the same mean circuit times as in 3.g), 5.c) and the data of 5.e). In order to obtain more general results, we used mean FOCA standard times instead of Samedan circuit times for this comparison.

Table 6:

Mode	Times in Mode (s)
TAKE-OFF	20
CLIMB OUT	75
DOWNWIND	90
BASE	105
FINAL	20

Emission factors were taken from the previously discussed measurements, with mixture control in "full rich" position and the engine doing auto-lean, as discussed in 5.b) and 5.f). Because of very incomplete combustion (as described in section 3 of this Appendix), the mean emission factor for CO_2 is far below the theoretical 3.17 kg / kg fuel. For this calculation we assume again a conservative factor of 2 kg CO_2 / kg fuel and 1.2 kg H_2O / kg fuel. The lead content in AVGAS 100LL is considered 0.794 g / kg fuel, the fuel density 0.72 kg / liter.
The missing base leg data in ECERT 59 has been interpolated between "downwind" and "final".

Table 7: Total circuit emissions (1 circuit), calculated with mean values from Grenchen and Samedan measurements and table 6.

	fuel (kg)	CO (g)	HC (g)	NOx (g)	CO2 (kg)	H20 (kg)	lead (g)
Samedan (ECERT 59)	3.81	3309	72	22	7.63	4.58	3.03
Grenchen (ECERT 62)	3.88	3371	62	20	7.77	4.66	3.08

5.h) Discussion

The result for high altitude circuits with HBKIA suggests similar total emissions, which are within measurement uncertainties. The higher emission factors of the richer running engine are partly compensated by a lower fuel burn during the high power segments of the circuit. For emission inventories with TCM IO-550 engine, the following values are suggested for 1 circuit (based on table 6 times):

Table 8: Suggested emission totals for 1 aerodrome circuit with TCM IO-550 B. (33-05-003 emissionsinventar.volten.HBKIA_060921_rit)

TCM IO-550 B	fuel (kg)	CO (g)	HC (g)	NOx (g)	CO2 (kg)	H20 (kg)	lead (g)
1 Aerodrome circuit	3.9	3300	60	22	7.8	4.6	3.1

5.i) Systematic measurements at full power settings between 3000 and 6000ft flight altitude

The following measurements, ECERT 58, 61 and 65 have been performed on three different days, with different meteorological conditions. Measurements for take-off, climb and approach have been separated into different sets of figures.

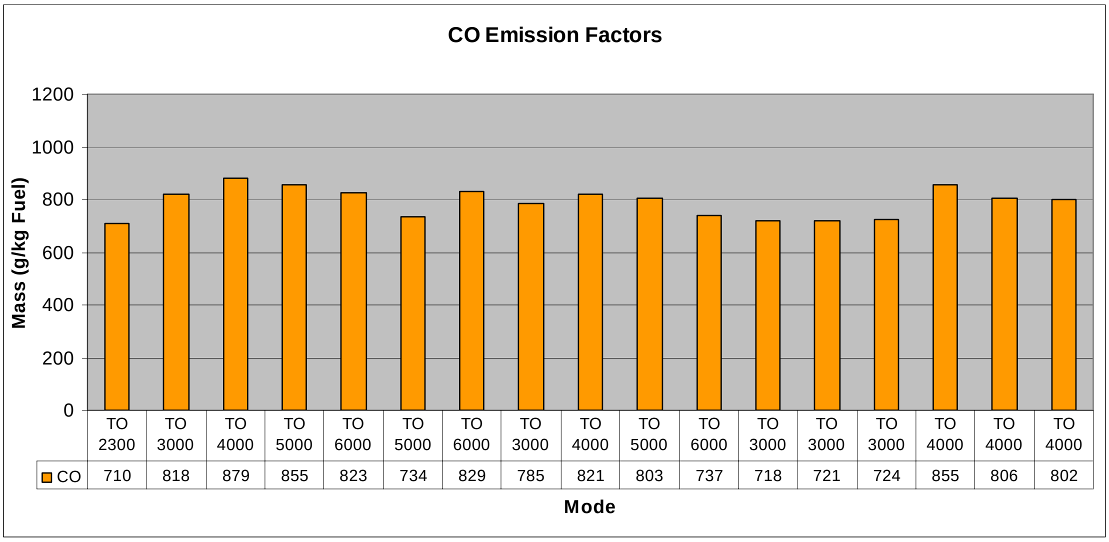


Figure 87: CO emission factors for full power climb, measured at different flight altitudes, e.g. TO 2300 means take-off measurement at 2300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

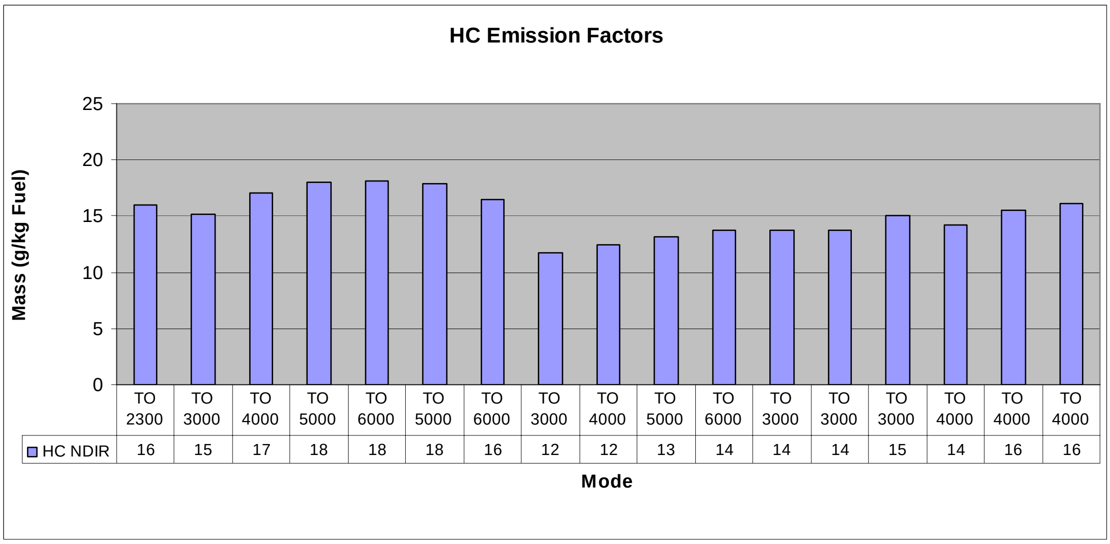


Figure 88: HC emission factors for full power climb, measured at different flight altitudes, e.g. TO 2300 means take-off measurement at 2300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

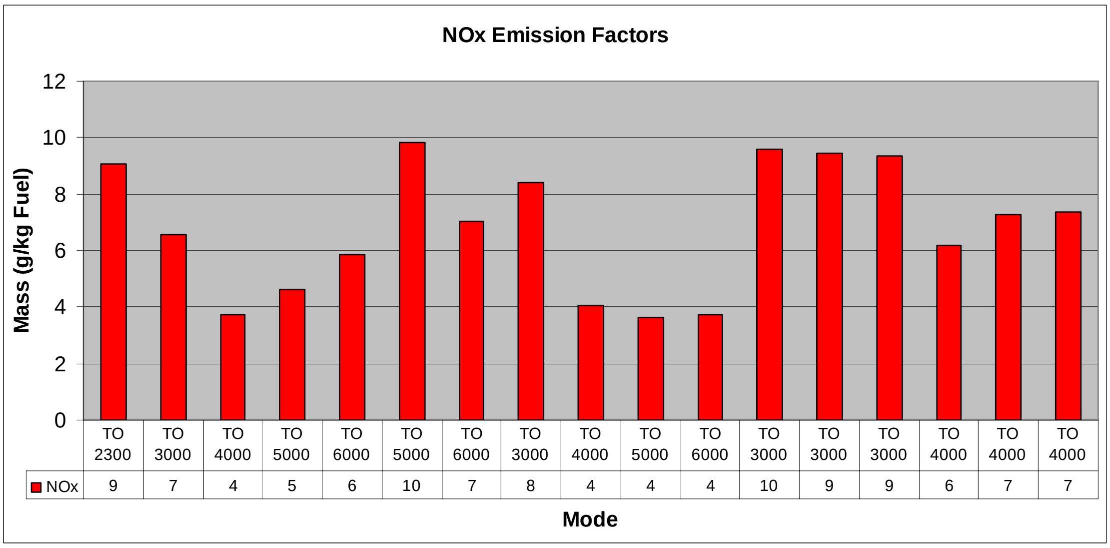


Figure 89: NO_x emission factors for full power climb, measured at different flight altitudes, e.g. TO 2300 means take-off measurement at 2300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

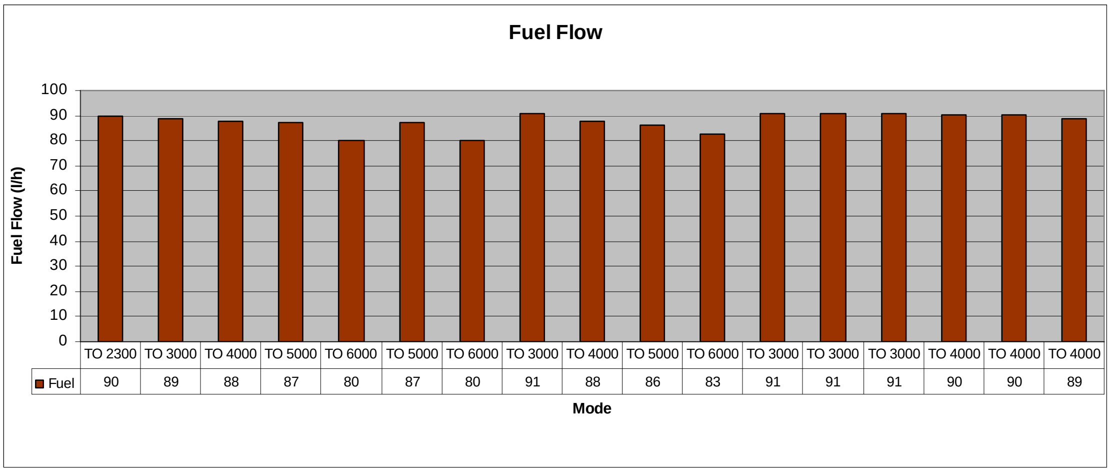


Figure 90: Fuel flow for full power climb, measured at different flight altitudes, e.g. TO 2300 means take-off measurement at 2300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

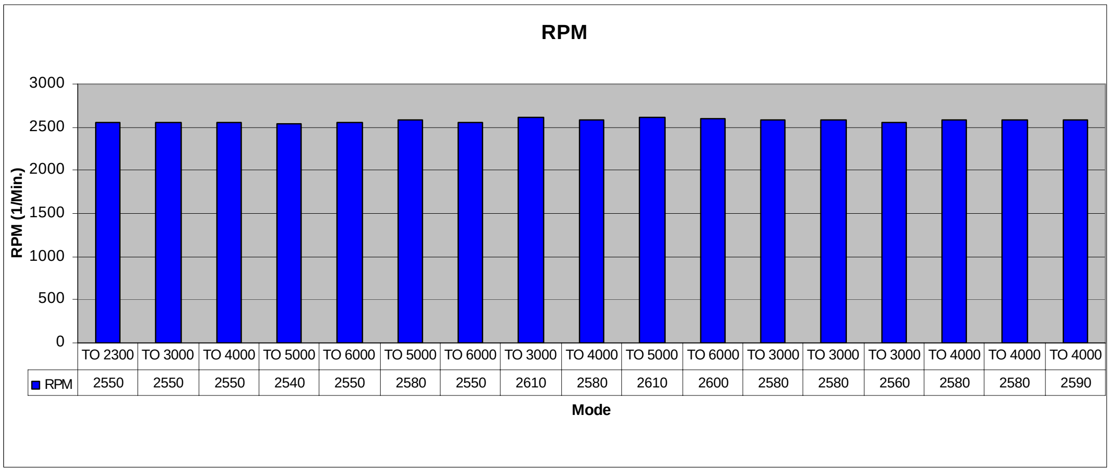


Figure 91: Engine revolutions per minute for full power climb, measured at different flight altitudes, e.g. TO 2300 means take-off measurement at 2300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

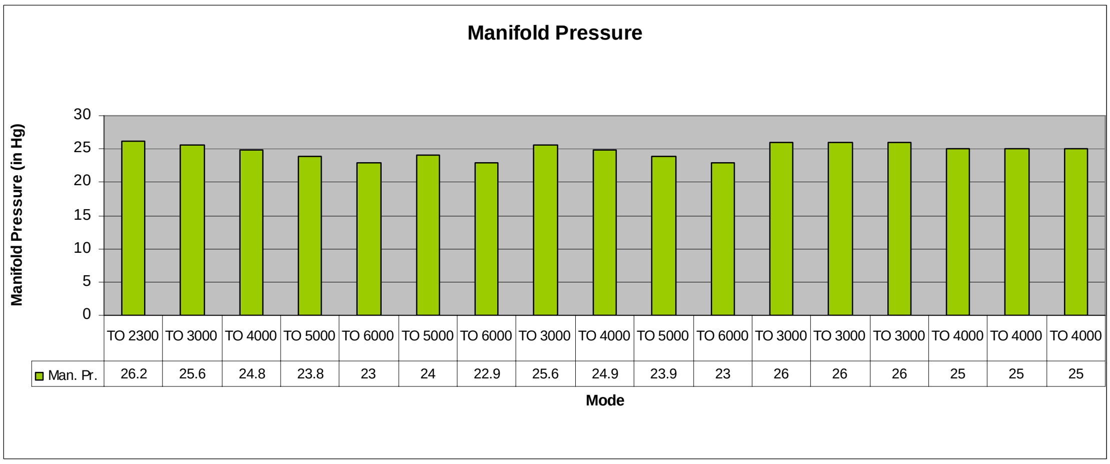


Figure 92: Manifold pressure for full power climb, measured at different flight altitudes, e.g. TO 2300 means take-off measurement at 2300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT65).

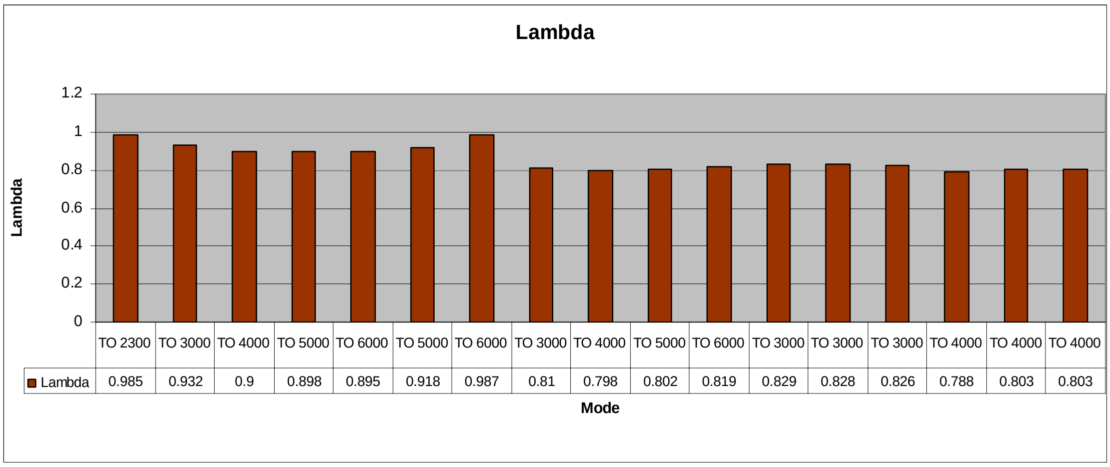


Figure 93: Lambda for full power climb, measured at different flight altitudes, e.g. TO 2300 means take-off measurement at 2300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT65).

5.j) Discussion

From figure 93 it can be seen that the engine was running significantly less rich in ECERT58 than in ECERT61 and 65. This could be attributed to a different general engine adjustment before and after regular maintenance. In ECERT65, after some pilot training and in calm air, power settings and aircraft attitude were more stable, resulting in less fluctuating values. All measurements were made with the mixture lever in “full rich” position. Auto lean works in function of density altitude, therefore the results are showing differences even at the same pressure altitude, because of different ambient air temperatures. The same is true for the following results (5.k and l), measured at climb and approach power settings.

5.k) Systematic measurements at climb power settings between 3000 and 6000ft flight altitude

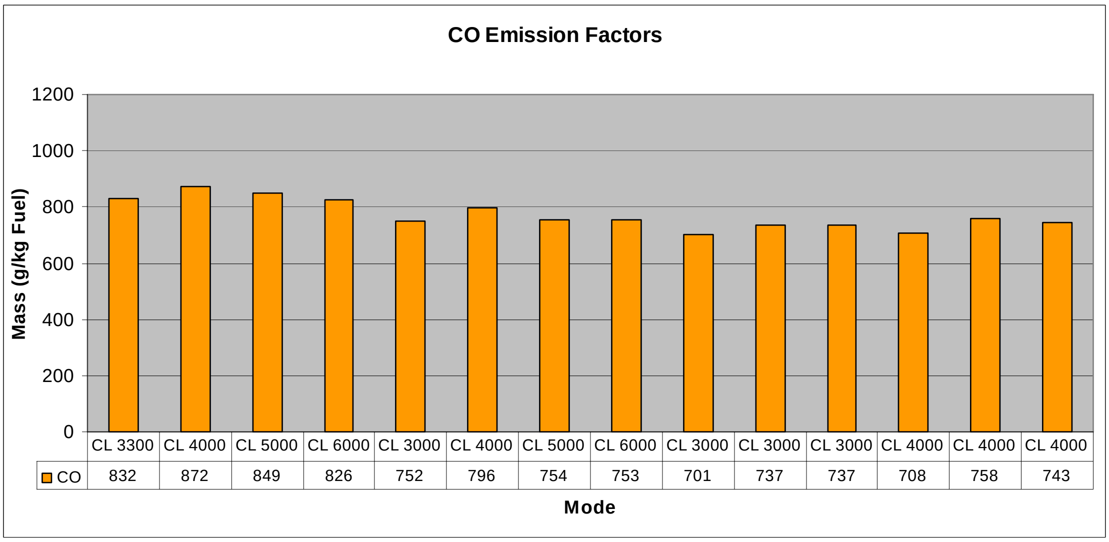


Figure 94: CO emission factors for AFM[9] climb power, measured at different flight altitudes, e.g. CL 3300 means climb measurement at 3300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

[9] AFM = Airplane Flight Manual

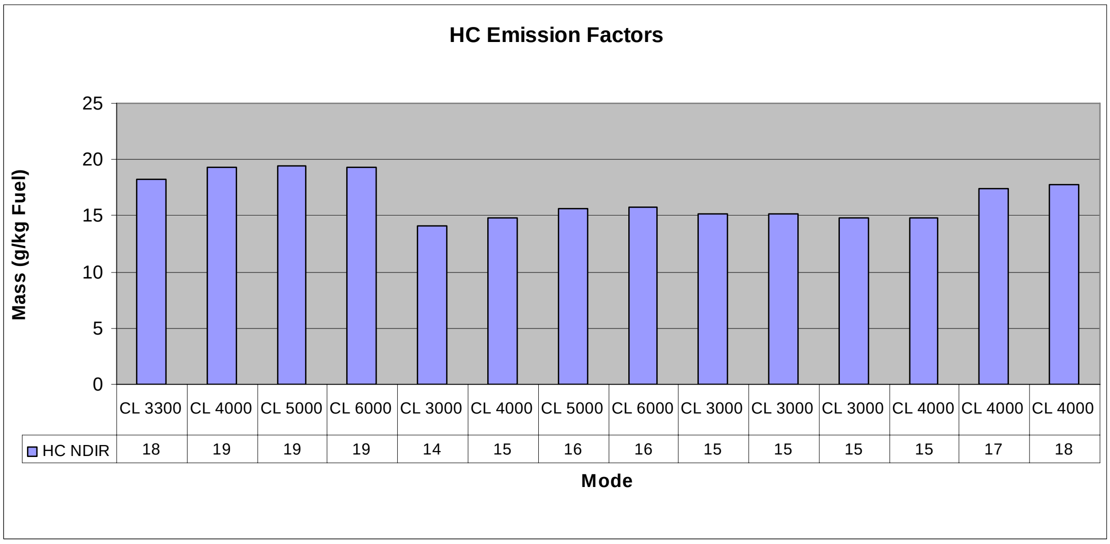


Figure 95: HC emission factors for AFM climb power, measured at different flight altitudes, e.g. CL 3300 means climb measurement at 3300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

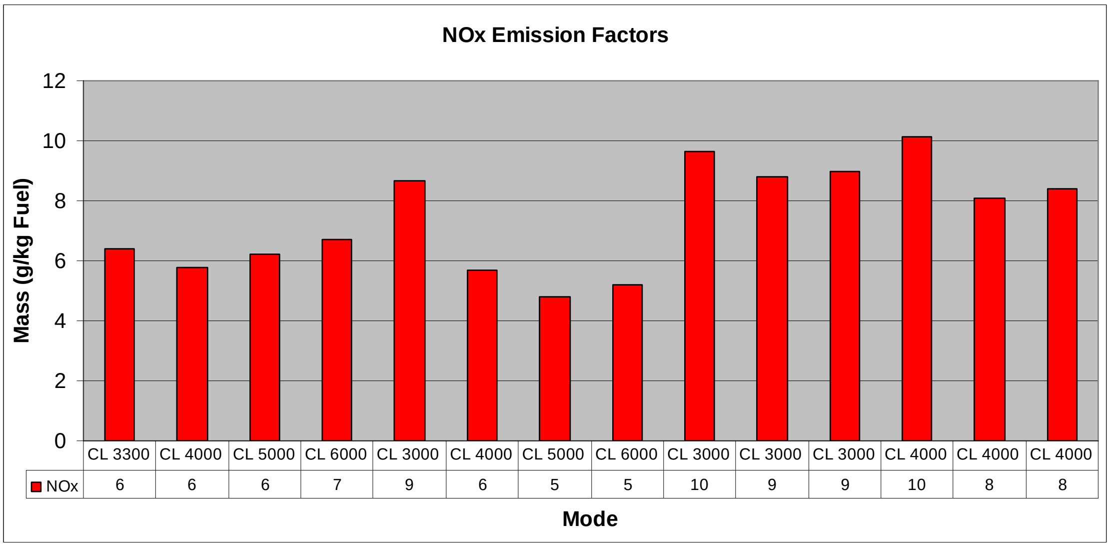


Figure 96: NO_x emission factors for AFM climb power, measured at different flight altitudes, e.g. CL 3300 means climb measurement at 3300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

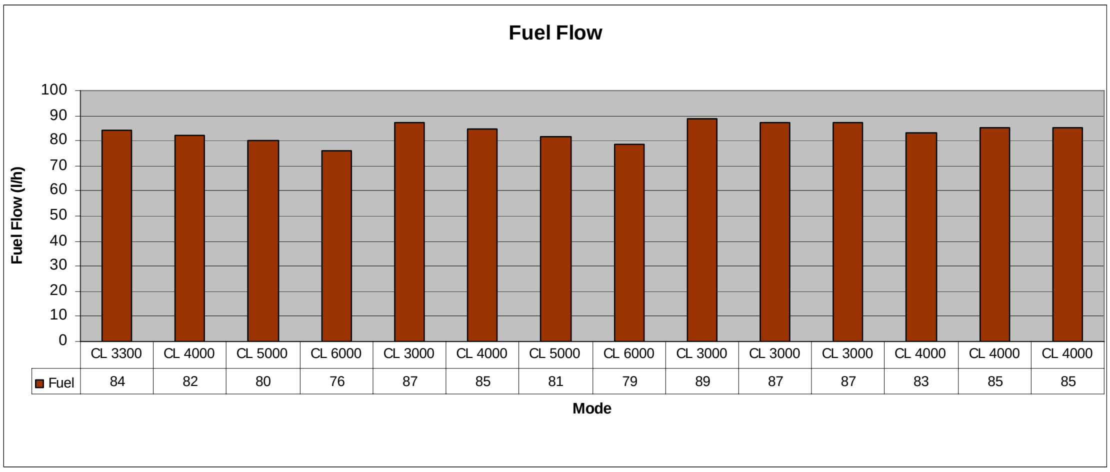


Figure 97: Fuel flow for AFM climb power, measured at different flight altitudes, e.g. CL 3300 means climb measurement at 3300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

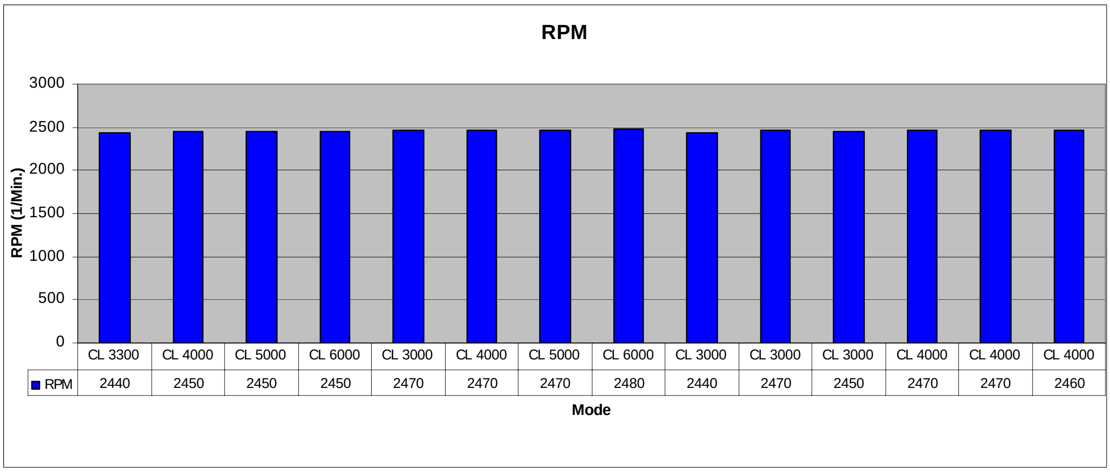


Figure 98: RPM for AFM climb power (Reference 2500 RPM), measured at different flight altitudes, e.g. CL 3300 means climb measurement at 3300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

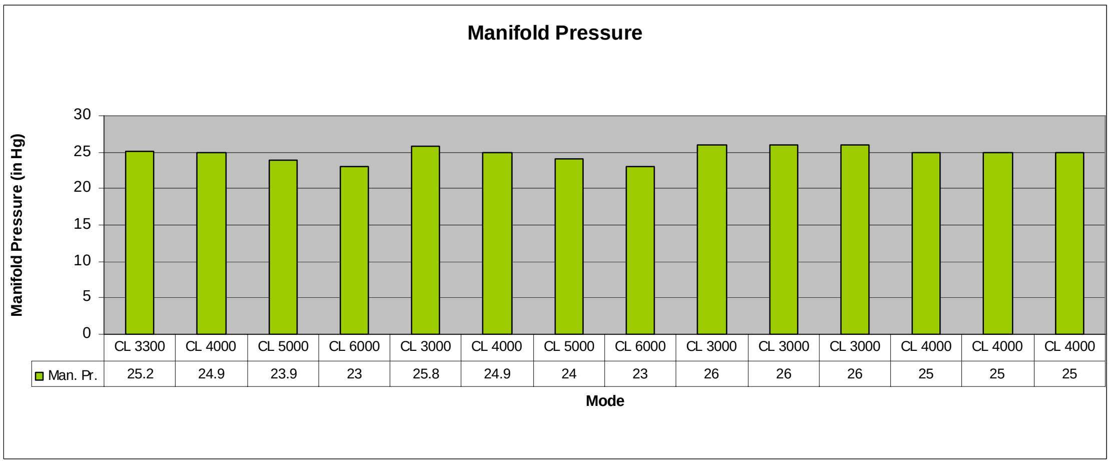


Figure 99: Manifold pressure for AFM climb power, measured at different flight altitudes, e.g. CL 3300 means climb measurement at 3300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

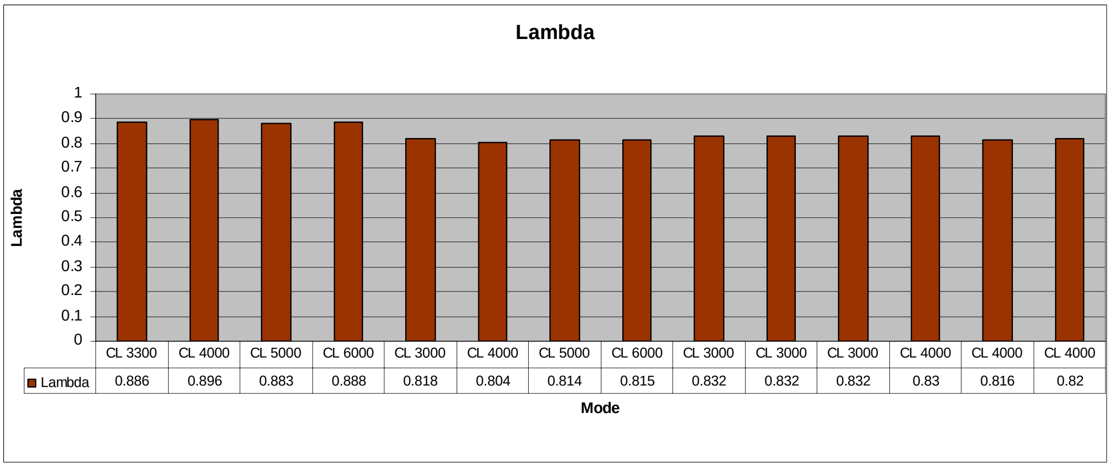


Figure 100: Lambda for AFM climb power, measured at different flight altitudes, e.g. CL 3300 means climb measurement at 3300ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

5.I) Systematic measurements at approach power settings between 3000 and 6000ft flight altitude

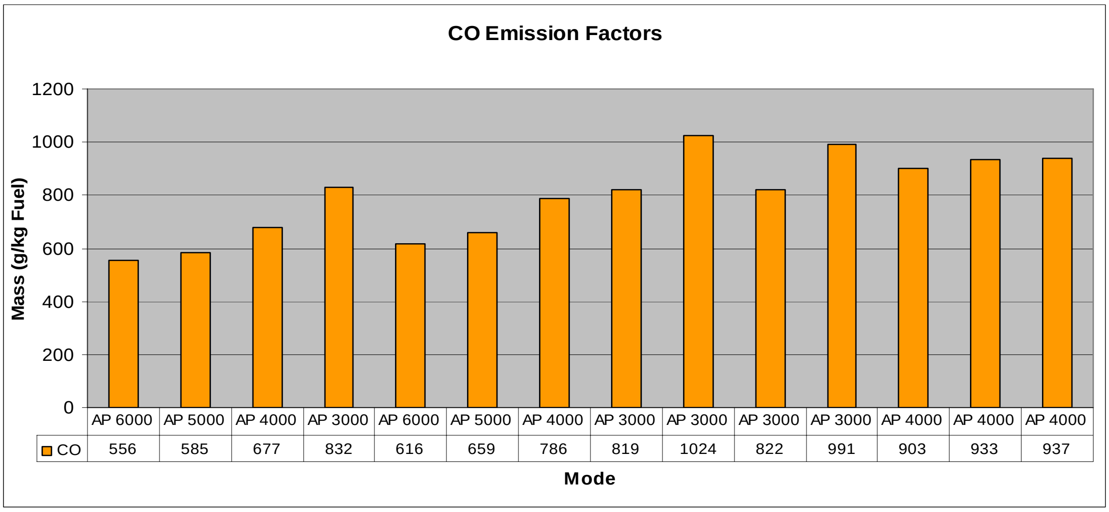


Figure 101: CO emission factors for approach power, measured at different flight altitudes, e.g. AP 6000 means approach measurement at 6000ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

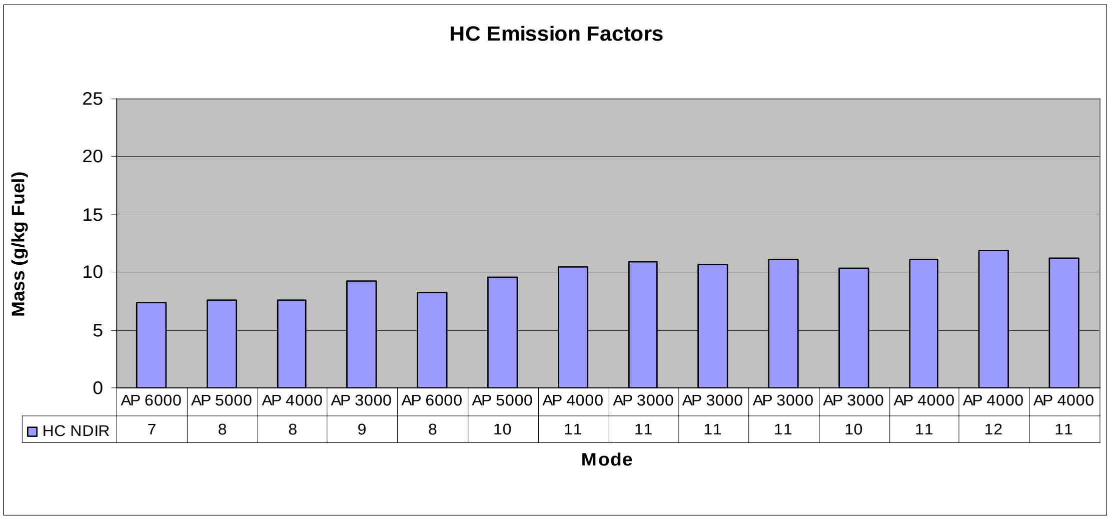


Figure 102: HC emission factors for approach power, measured at different flight altitudes, e.g. AP 6000 means approach measurement at 6000ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

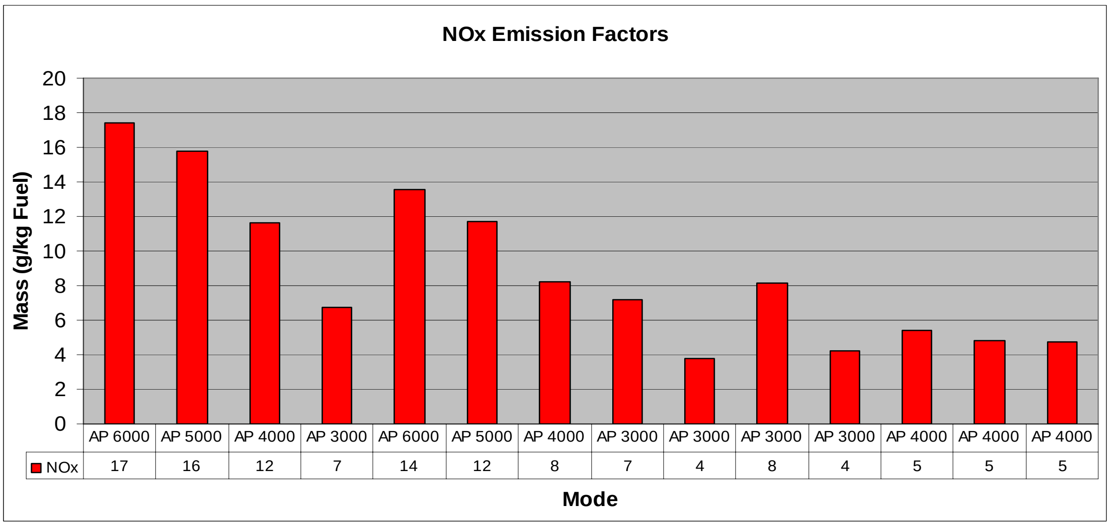


Figure 103: NO_x emission factors for approach power, measured at different flight altitudes, e.g. AP 6000 means approach measurement at 6000ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

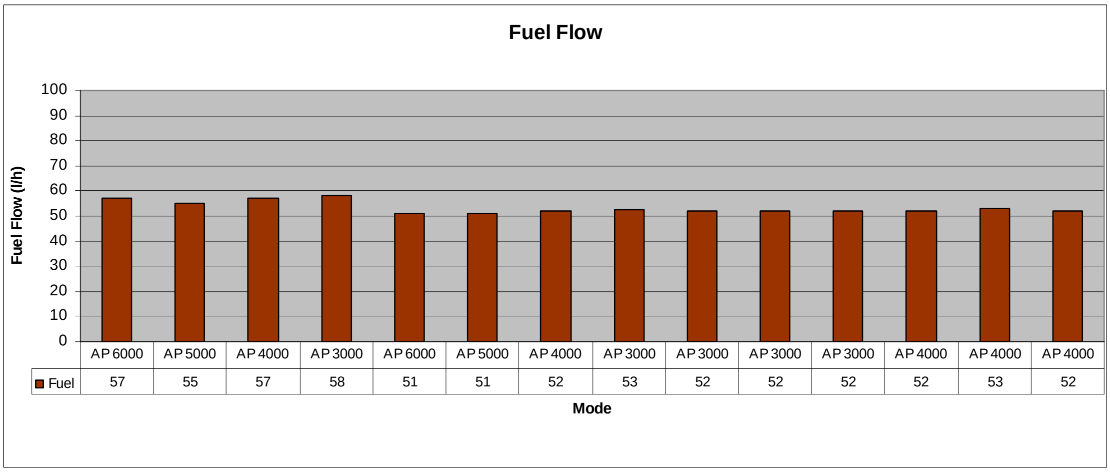


Figure 104: Fuel flow for approach power, measured at different flight altitudes, e.g. AP 6000 means approach measurement at 6000ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

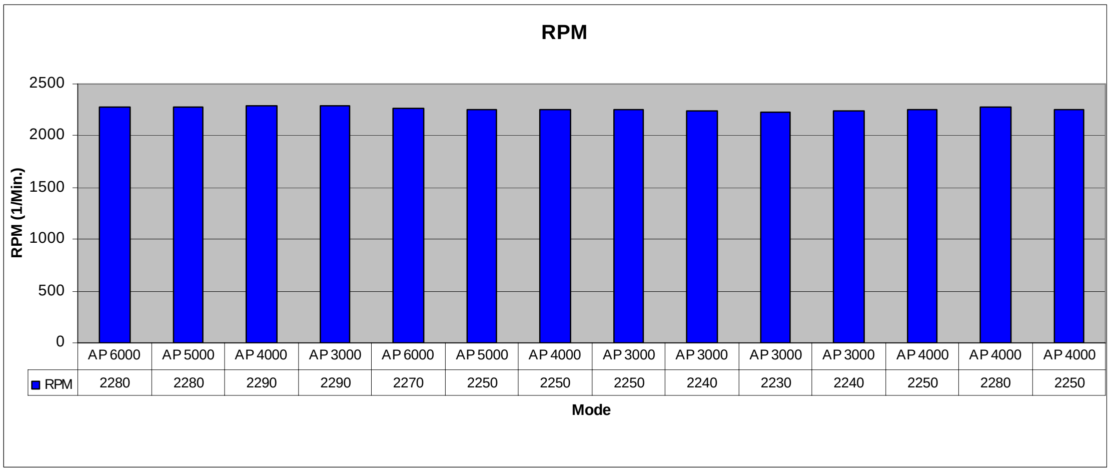


Figure 105: Engine RPM for approach power, measured at different flight altitudes, e.g. AP 6000 means approach measurement at 6000ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

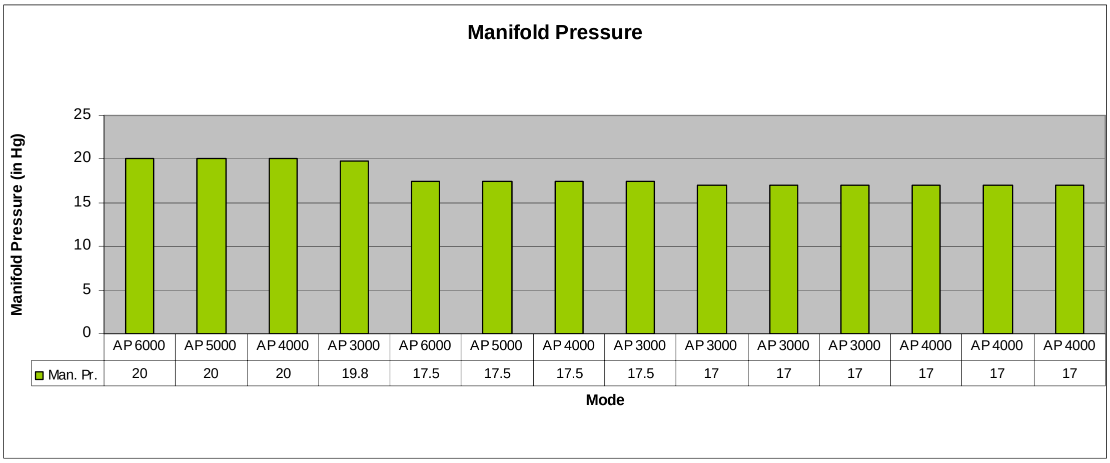


Figure 106: Manifold pressure settings for approach power, measured at different flight altitudes, e.g. AP 6000 means approach measurement at 6000ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65). In ECERT65, manifold pressure has been kept constant during descent.

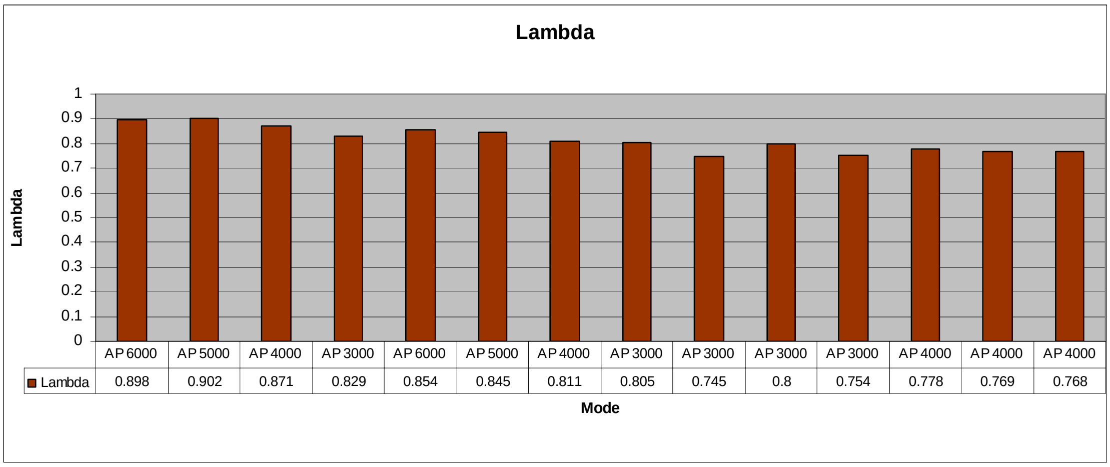


Figure 107: Lambda for approach power, measured at different flight altitudes, e.g. AP 6000 means approach measurement at 6000ft pressure altitude (From left to right: No 1 – 7 from ECERT58, No 8 – 11 from ECERT61 and No 12 – 17 from ECERT 65).

5.m) Standard flight profile emission measurement Bern - WIL[10] - Bern, Switzerland

The following flight profile has been flown at two different days by two different pilots:
- Departure at LSZB (Bern)
- Outbound route E
- Continuous climb to 5500ft
- Level off at 5500ft and maintain
- Track WIL VOR
- Cruise power setting, first full rich (CR 5510), then three measurements (CR 5500) at mixture "25°F rich side of EGT[11] peak according to AFM[12], followed by "best power mixture, 125°F rich of EGT peak" (CR 5500 BP) and again two measurements at mixture "25°F rich side of EGT peak". After that, one measurement (CR 5500) at mixture "25°F lean of EGT peak" according to AFM and the last cruise measurement at mixture "25°F rich side of EGT peak" as before.
- Descent and approach were at pilot's discretion and the two pilots were told to always fly according to AFM.
- 180° turn at WIL VOR and return to LSZB (Bern)
- Approach and Landing at LSZB

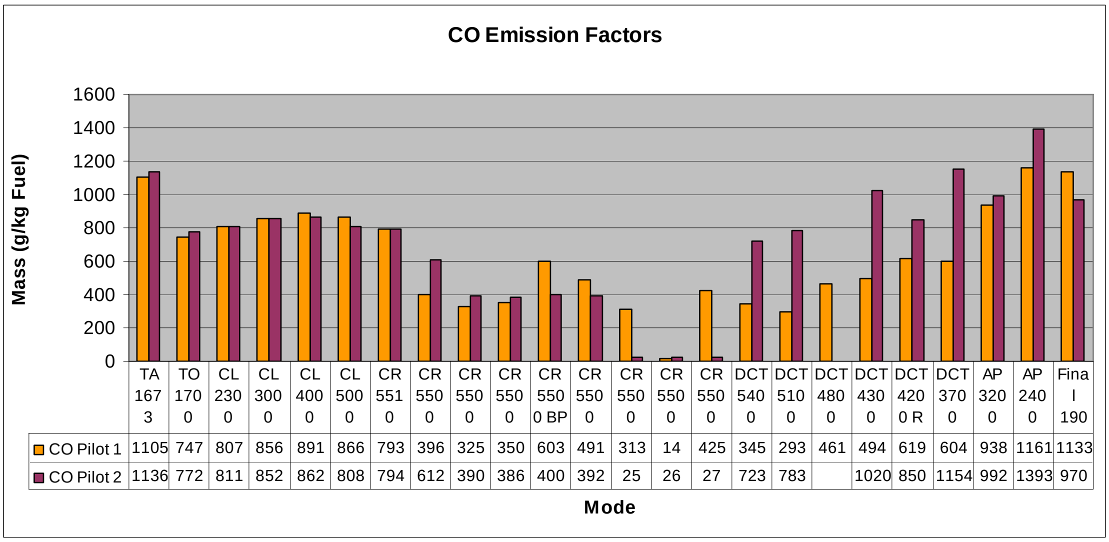


Figure 108: CO emission factors comparison for both flights. TA = taxi, TO = take-off roll, CL = climb, CR = cruise, DCT = descent, AP = approach. The number below the flight mode indicates flight pressure altitude, e.g. DCT 5100 = measurement during descent at 5100ft. (ECERT 57 and 64)

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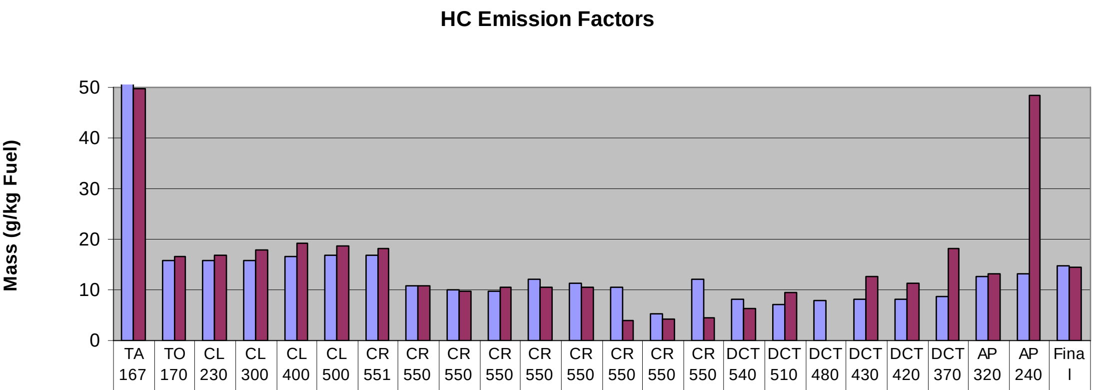
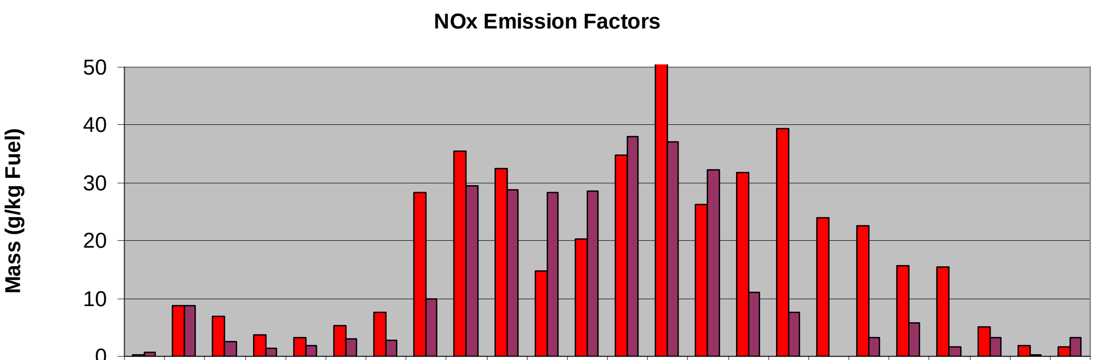
[10] WIL = Willisau VOR (Radio Navigation Facility)
[11] EGT = Exhaust Gas Temperature, at this aircraft, measured in the collector of the exhaust muffler on the right side of the engine (= exhaust gas temperature mixture of three cylinders out of six).
[12] AFM = Airplane Flight Manual



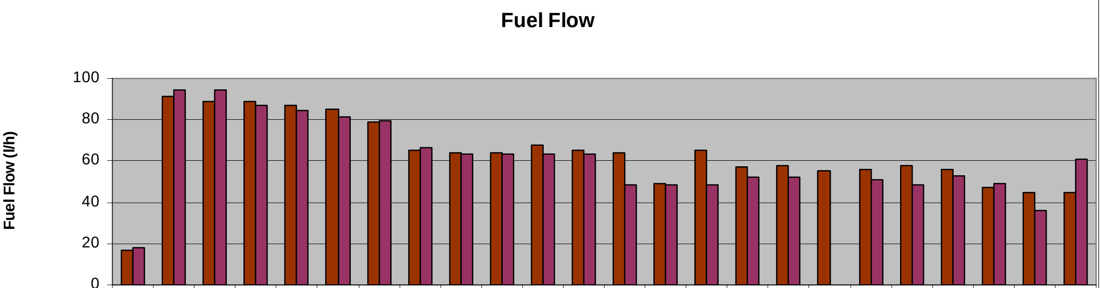
	TA 167	TO 170	CL 230	CL 300	CL 400	CL 500	CR 551	CR 550	CR 550	CR 550	CR 550	CR 550	CR 550	CR 550	CR 550	DCT 540	DCT 510	DCT 480	DCT 430	DCT 420	DCT 370	AP 320	AP 240	Fina l
HC Pilot 1	114	16	16	16	17	17	17	11	10	10	12	11	11	5	12	8	7	8	8	8	9	13	13	15
HC Pilot 2	50	17	17	18	19	19	18	11	10	10	10	11	4	4	4	6	9		13	11	18	13	48	14

Figure 109: HC emission factors comparison for both flights. TA = taxi, TO = take-off roll, CL = climb, CR = cruise, DCT = descent, AP = approach. The number below the flight mode indicates flight pressure altitude, e.g. DCT 5100 = measurement during descent at 5100ft. (ECERT 57 and 64)



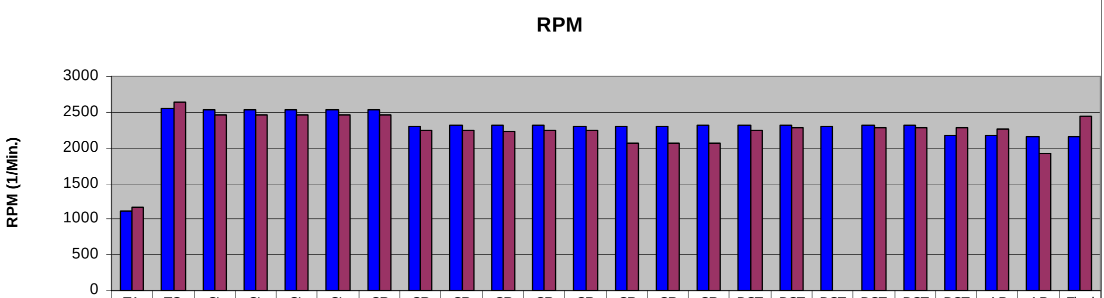
	TA 1673	TO 1700	CL 2300	CL 3000	CL 4000	CL 5000	CR 5510	CR 5500	CR 5500	CR 5500	CR 5500 BP	CR 5500	CR 5500	CR 5500	CR 5500	DCT 5400	DCT 5100	DCT 4800	DCT 4300	DCT 4200 R	DCT 3700	AP 3200	AP 2400	Fina l 190
NOx Pilot 1	0	9	7	4	3	5	8	28	35	32	15	20	35	87	26	32	39	24	22	16	15	5	2	2
NOx Pilot 2	1	9	3	1	2	3	3	10	29	29	28	29	38	37	32	11	8		3	6	2	3	0	3

Figure 110: NO_x emission factors comparison for both flights. TA = taxi, TO = take-off roll, CL = climb, CR = cruise, DCT = descent, AP = approach. The number below the flight mode indicates flight pressure altitude, e.g. DCT 5100 = measurement during descent at 5100ft. (ECERT 57 and 64)



	TA 1673	TO 1700	CL 2300	CL 3000	CL 4000	CL 5000	CR 5510	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	DCT 5400	DCT 5100	DCT 4800	DCT 4300	DCT 4200	DCT 3700	AP 3200	AP 2400	Final 1900
Fue Pilot 1	17	91	89	89	87	85	79	65	64	64	68	65	64	49	65	57	58	55	56	58	56	47	45	45
Fuel Pilot 2	18	95	95	87	84	81	80	66	64	64	64	64	49	49	49	52	52		51	49	53	49	36	61

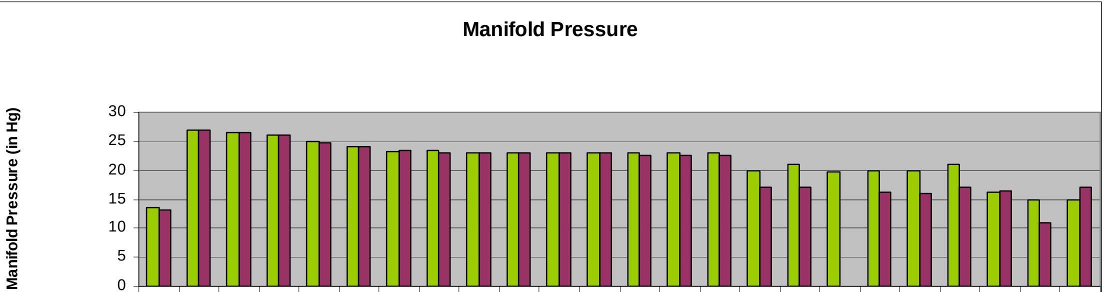
Figure 111: Fuel flow comparison for both flights. TA = taxi, TO = take-off roll, CL = climb, CR = cruise, DCT = descent, AP = approach. The number below the flight mode indicates flight pressure altitude, e.g. DCT 5100 = measurement during descent at 5100ft. (ECERT 57 and 64)



Mode	TA 1673	TO 1700	CL 2300	CL 3000	CL 4000	CL 5000	CR 5510	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	DCT 5400	DCT 5100	DCT 4800	DCT 4300	DCT 4200	DCT 3700	AP 3200	AP 2400	Final 1900
RPM Pilot 1	1120	2550	2540	2530	2530	2530	2530	2300	2310	2320	2320	2300	2300	2300	2310	2310	2310	2300	2310	2310	2170	2170	2160	2150
RPM Pilot 2	1160	2640	2470	2470	2460	2460	2460	2250	2250	2230	2250	2240	2060	2060	2060	2250	2290		2290	2280	2280	2270	1930	2440

Mode

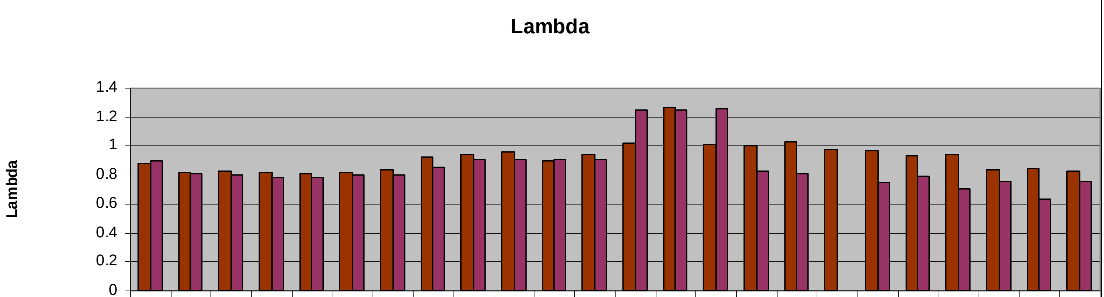
Figure 112: Engine RPM comparison for both flights. TA = taxi, TO = take-off roll, CL = climb, CR = cruise, DCT = descent, AP = approach. The number below the flight mode indicates flight pressure altitude, e.g. DCT 5100 = measurement during descent at 5100ft. (ECERT 57 and 64)



Mode	TA 1673	TO 1700	CL 2300	CL 3000	CL 4000	CL 5000	CR 5510	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	DCT 5400	DCT 5100	DCT 4800	DCT 4300	DCT 4200	DCT 3700	AP 3200	AP 2400	Final 1900
Man. Pr. Pilot 1	13.5	27	26.5	26	25	24	23.2	23.4	23	23	23	23	23	23	23	20	21	19.8	19.9	20	21	16.2	15	15
Man. Pr. Pilot 2	13.2	27	26.5	26	24.8	24	23.5	23	23	23	23	23	22.5	22.5	22.5	17	17		16.2	16	17	16.5	11	17

Mode

Figure 113: Manifold pressure comparison for both flights. TA = taxi, TO = take-off roll, CL = climb, CR = cruise, DCT = descent, AP = approach. The number below the flight mode indicates flight pressure altitude, e.g. DCT 5100 = measurement during descent at 5100ft. (ECERT 57 and 64)



Mode	TA 1673	TO 1700	CL 2300	CL 3000	CL 4000	CL 5000	CR 5510	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	CR 5500	DCT 5400	DCT 5100	DCT 4800	DCT 4300	DCT 4200	DCT 3700	AP 3200	AP 2400	Final 1900
Lambda Pilot 1	0.883	0.821	0.825	0.818	0.809	0.815	0.837	0.925	0.943	0.957	0.9	0.944	1.02	1.269	1.011	1.008	1.031	0.974	0.972	0.937	0.943	0.84	0.848	0.826
Lambda Pilot 2	0.902	0.812	0.798	0.787	0.784	0.799	0.803	0.852	0.909	0.91	0.907	0.908	1.251	1.25	1.259	0.829	0.812		0.747	0.795	0.705	0.754	0.633	0.761

Mode

Figure 114: Lambda comparison for both flights. TA = taxi, TO = take-off roll, CL = climb, CR = cruise, DCT = descent, AP = approach. The number below the flight mode indicates flight pressure altitude, e.g. DCT 5100 = measurement during descent at 5100ft. (ECERT 57 and 64)

5.n) Discussion

Taxi, Take-off, Climb

During taxi, take-off and climb, there are no significant differences between the results of ECERT57 (pilot 1) and 64 (pilot 2). Both pilots operate the aircraft in a similar way with a power reduction to 25 inHG manifold pressure in the climb phase. Manual mixture control is set to “full rich” and the engine is doing automatic lean, producing similar emission factors in both flights. This is also true for the first cruise power setting with mixture “full rich”.

Cruise

The task for the two pilots, to adjust the mixture to “25°F rich of EGT peak”, best power “125°F rich of EGT peak” and economy power “25°F lean of EGT peak” (which is an allowed operating condition for this type of engine), was definitely leading to different results. Most sensitive to differences in mixture are NO_x emission factors (figure 110) and CO emission factors (figure 108). It can also be seen, that the mixture settings of pilot 2 are more constant than those of pilot 1. At “lean of EGT peak” mixture, pilot 2 was able to adjust the engine repeatedly to smooth running lean conditions (lambda around 1.2) with CO and HC emissions falling drastically (figure 108 / 109 middle) and without increasing NO_x emissions (figure 110) too much. [It must also be noted that engine cylinder head temperatures were falling from around 150°C to 140°C during that operating condition and airspeed was reduced by a few knots due to power loss]. From previous results and the results of the cruise phase measured during these flights, it can be concluded:

From point of view of emissions, the “lean of EGT peak” setting is preferred, producing lowest possible emissions. All emission factors and the fuel flow are lower than with “rich of EGT peak” setting. This is especially true for NO_x, because these emissions are highest with the “rich of EGT peak” setting, mainly because of the highest combustion temperatures. Very strict “lean of EGT peak” conditions lead to **lower** cylinder head temperatures.

However, from point of view of operations, the “lean of EGT peak” setting has a lot of limitations:

- The rather simple engine technology of the measured type (air cooled, fuel injection system, not taking individual cylinder operating condition into account) leads to uneven mixture distribution and cylinder filling in the six cylinders (uneven “charging weight”), causing all six cylinders to be in six different operating conditions at a certain mixture setting. There is the risk of one or more cylinders being at higher operating conditions which can cause vibrations, additional wear and valve damage.
- Safety margins for engine operations are more limited, because one or more cylinders may go into the self detonation or flame out condition, if the pilot does not observe the engine carefully or if the pilot forgets to enrich the mixture for descent. At “rich conditions”, the margins for safe operations are much higher.
- Pilots need to be well trained as “lean conditions” require even more attentive engine observation which can distract from the primary air work.

For the emission inventory application, it can be concluded that it is probably more representative to take “rich of EGT peak” conditions as the reference for the cruise phase, because in most cases, such engines will be operated at “rich” conditions. As could be seen in the in-flight tests with HBKEZ and HBEYS, “rich of EGT peak” conditions typically lead to a lambda of around 0.93 to 0.95 which can be a basis value for engine on ground measurements at cruise power setting. This value for “rich of EGT peak” condition has been confirmed with the HBKIA flights.

Descent and Approach

Within the limits of the AFM, pilots were free to choose the “top of descent” point and the power settings for descent and approach. Figure 113 shows that pilot 2 was choosing less power during descent. [Pilot 1 started the descent early, with a small rate of descent and higher power.] The effect of lower power setting in the case of pilot 2 can be seen in lower instantaneous fuel consumption (figure 111) and lower NO_x emission factors but significantly higher CO and HC emission factors. The effect on total emissions will be discussed in the next section 5.o/p). In the first part of the approach, both pilots used similar power settings (around 17 InHg manifold pressure and similar selected propeller RPM. In the second part of the approach, pilot 2 reduced engine power further but later had to increase power during final above the pilot 1 power setting.

For the emission inventory application, it can be seen that the descent and approach phase are very dependent on pilots operational choice (whether forced by the environment, weather etc or not) and therefore, sort of mean power settings have to be derived for standardized ground measurements. From the sum of the in-flight tests with HBEYS, HBKEZ and HBKIA it can be concluded, that a preferred power setting for this phase of flight seems to be around 18 InHg with a fuel flow of 40 to 45% of the maximum take-off power fuel flow. These values are taken as the basic values for engine ground measurements at approach power setting.

5.o) Inventory: Total emissions of HBKIA in a flight, defined in 5.m)

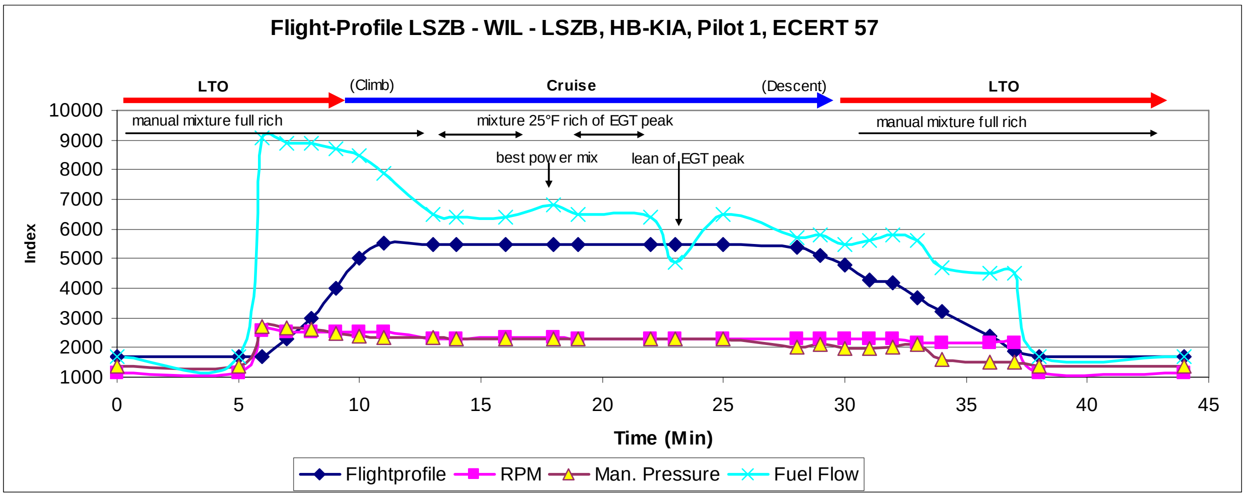


Figure 115: ECERT 57 (Defined Flight from Bern to Wilisau VOR and back to Bern, flown by pilot 1). The altitude profile is plotted in dark blue. Engine RPM, manifold pressure and fuel flow have been added to the same figure. The theoretical LTO and cruise phase boundaries are shown with red and blue darts on top of the figure.
5 Minutes after engine start up, the sharp rise in fuel flow indicates the beginning of the take off roll. After lift-off, manifold pressure is slightly reduced and the fuel flow slightly decreases (at around 6 minutes on the time axis). During level flight at cruise, the pilot was given different tasks for air/fuel mixture settings. Please note, that all variations of fuel flow (the light blue curve) during cruise level, are caused by different choice of engine operating air/fuel mixture conditions at constant RPM and constant manifold pressure (see 5.m)! At around 15 minutes on the time axis, the engine is run at slightly rich air/fuel mixture. At about 18 minutes the mixture is further enriched for best power, followed by the previous setting. At about 23 minutes, the air/fuel mixture is set to lean conditions, which is shown by a significant reduction of fuel flow. During descent and the first part of the approach, the fuel flow does not significantly fall below cruise fuel flow. This is due to the standard mixture enrichment for approach, causing the engine to run less efficiently. Because of the auto lean capabilities of the tested engine, the effect is not as pronounced as it was with HBKEZ (see figure 61).

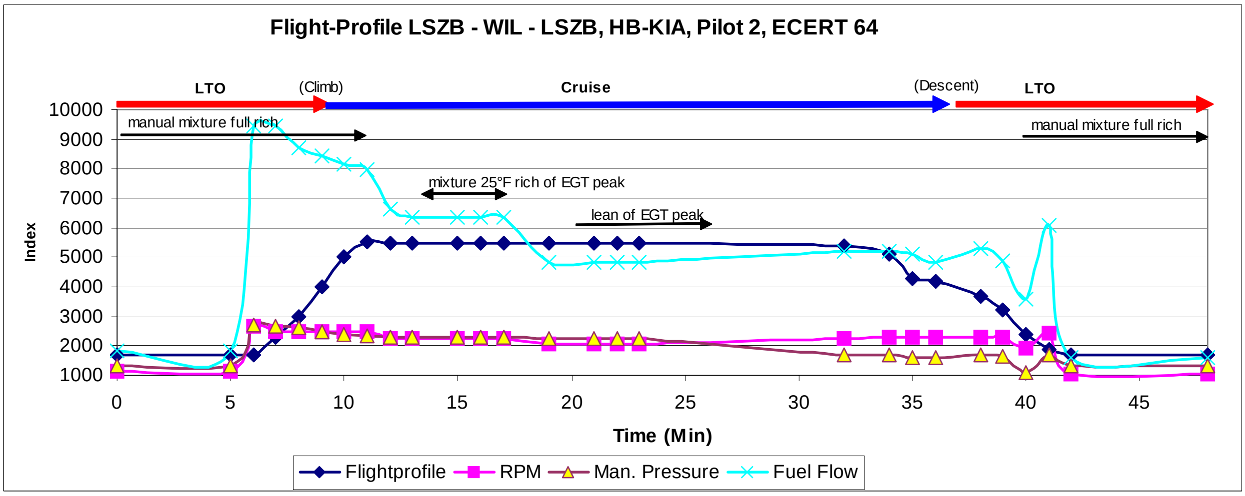


Figure 116: ECERT 64 (Defined Flight from Bern to Wilisau VOR and back to Bern, as above, flown by pilot 2). In contrast to pilot 1, pilot 2 was achieving only two different manual mixture settings during cruise: 25°F rich of peak EGT and lean of peak EGT. There is a long lean of EGT peak phase, showing significantly lower fuel consumption. The power setting during cruise and the first part of descent is slightly lower than that chosen by pilot 1. During cruise, the aircraft was flying slower than that of pilot 1, resulting in a longer flight time. The descent starts later and with higher descent rate than that chosen by pilot 1. Pilot 2 was performing rather big power corrections during landing.

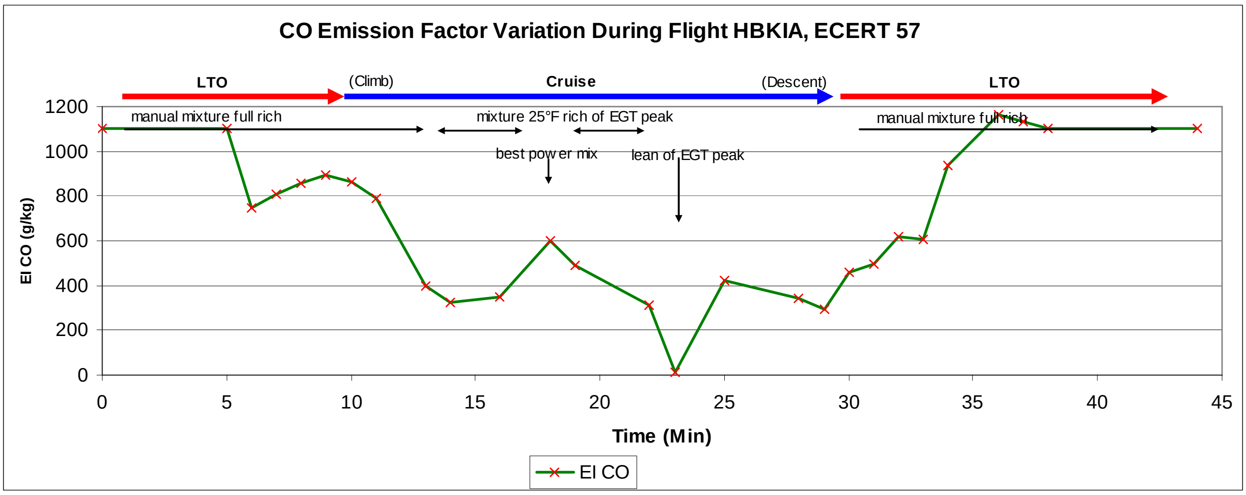


Figure 117: Variation of CO emission factor during flight. LTO and cruise phase are indicated in red and blue darts, mixture settings in black darts. (ECERT 57)

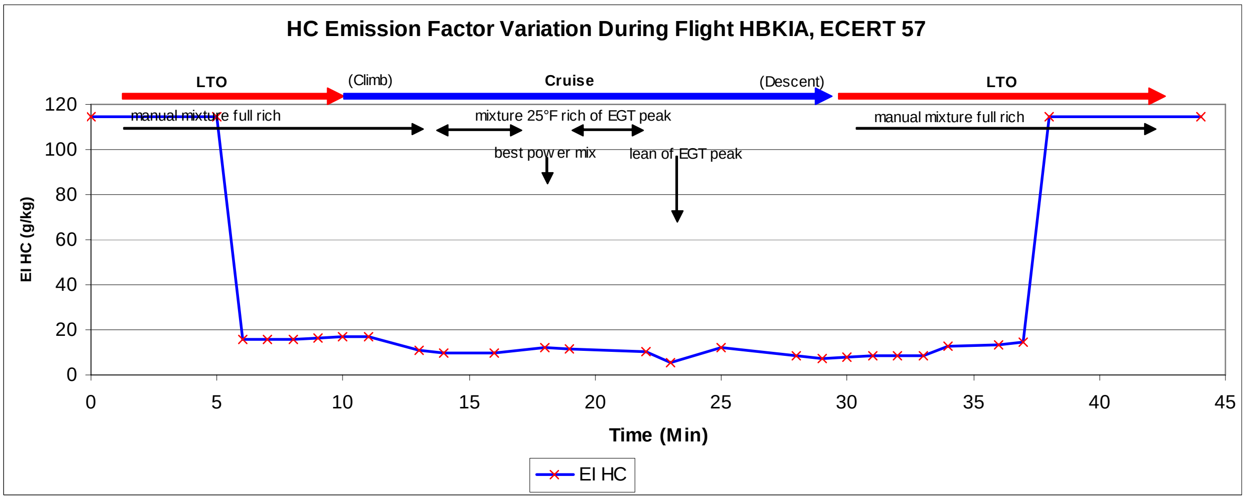


Figure 118: Variation of HC emission factor during flight. LTO and cruise phase are indicated in red and blue darts, mixture settings in black darts. (ECERT 57)

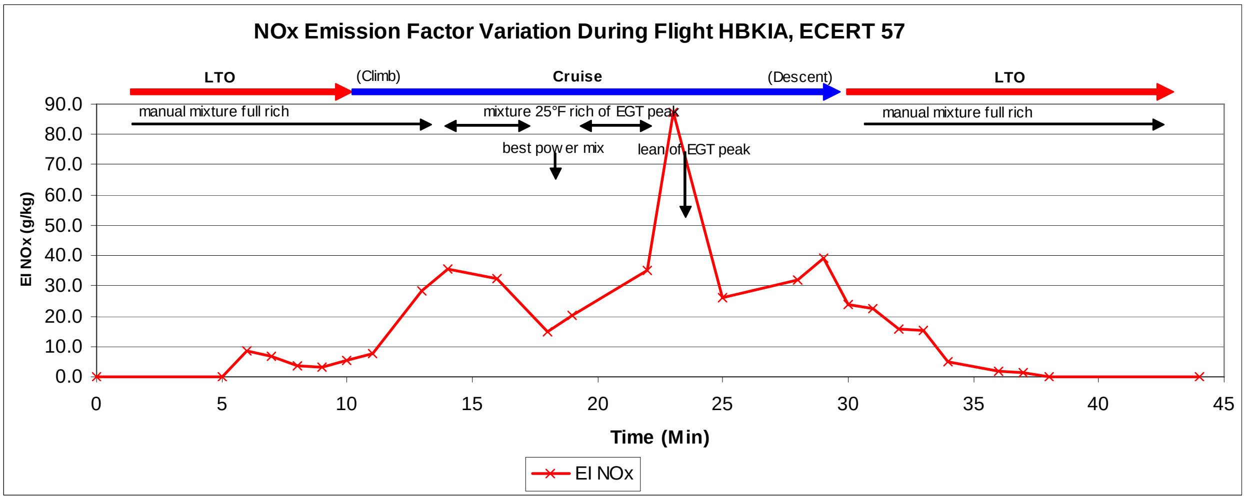


Figure 119: Variation of NO_x emission factor during flight. LTO and cruise phase are indicated in red and blue darts, mixture settings in black darts. During cruise, at a mixture setting 25°F rich of peak EGT, the EI NO_x is around 35 g/kg fuel. Please note, that at lean of EGT peak operation, the EI NO_x would decrease below rich of EGT peak value. During this flight, this does not occur: The EGT aircraft instrumentation in HBKIA does not give individual cylinder EGT. This measurement reveals that although the mean indicated EGT value has dropped with this mixture setting, at least one of the six cylinders must have been running very hot, at peak EGT, thus producing a very high EI NO_x! (ECERT 57)

For comparison of the two flights and to calculate cumulative emissions, the cruise phase values have to be generalized. The most common mixture setting with this engine is 25°F rich of peak EGT, so for both flights, the measured values for this setting have been taken for the entire level flight at cruise:

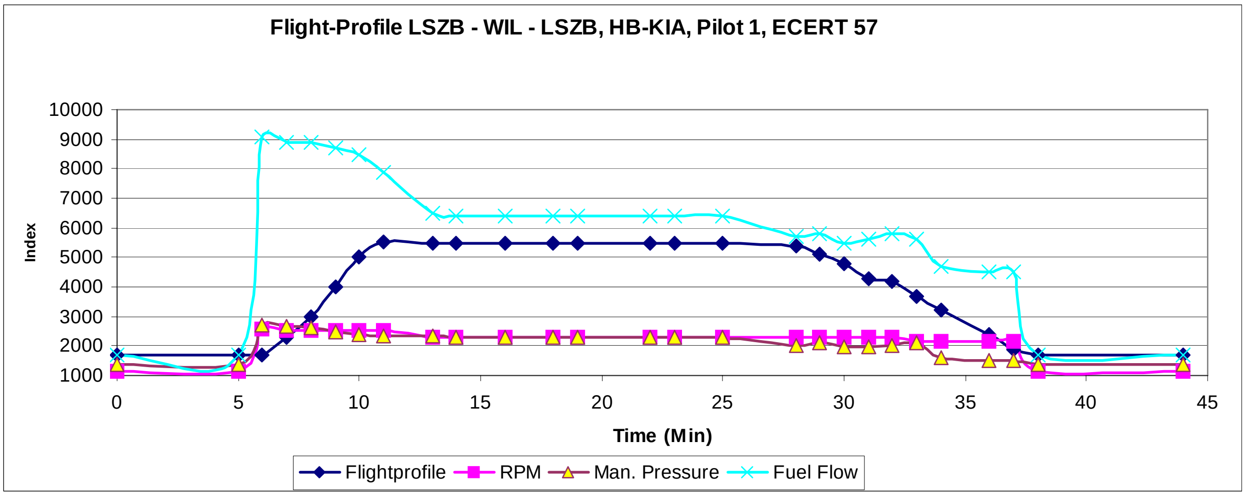


Figure 120: Pilot 1 Flight Profile, used for emission inventory. (ECERT57)

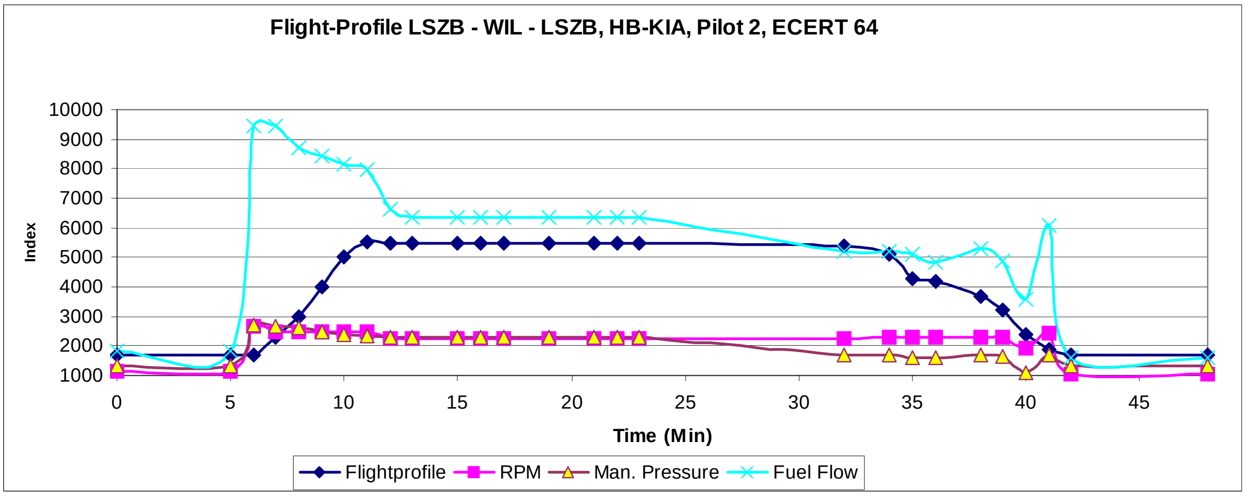


Figure 121: Pilot 2 flight profile, used for emission inventory. (ECERT 64)

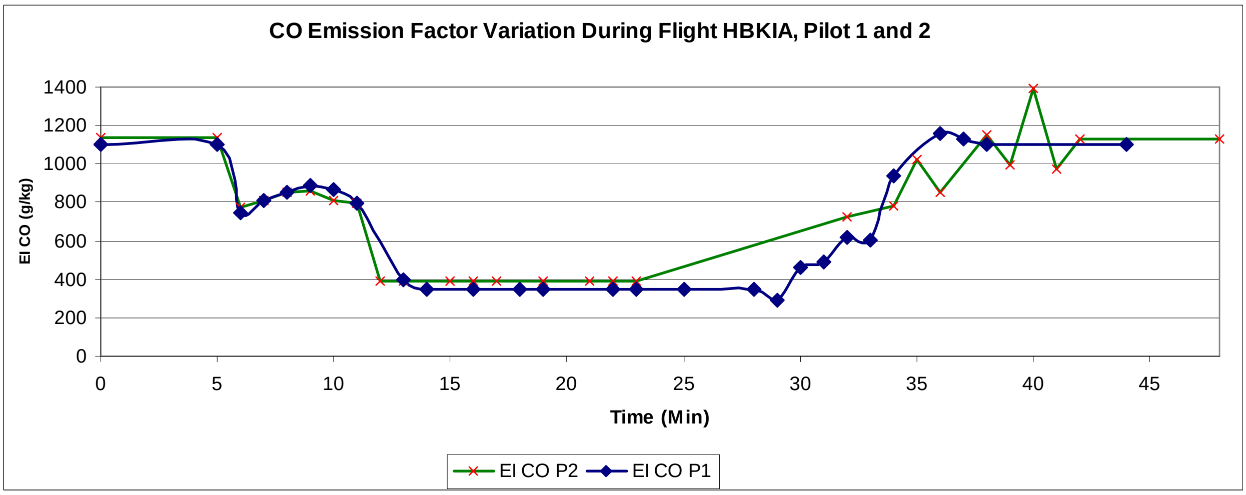


Figure 122: Comparison of CO emission factor variation during flights with pilot 1 and 2. Please note, that the increase of EI CO P2 (pilot 2) between 23 and 32 minutes after off-block is artificial, because of missing data points.

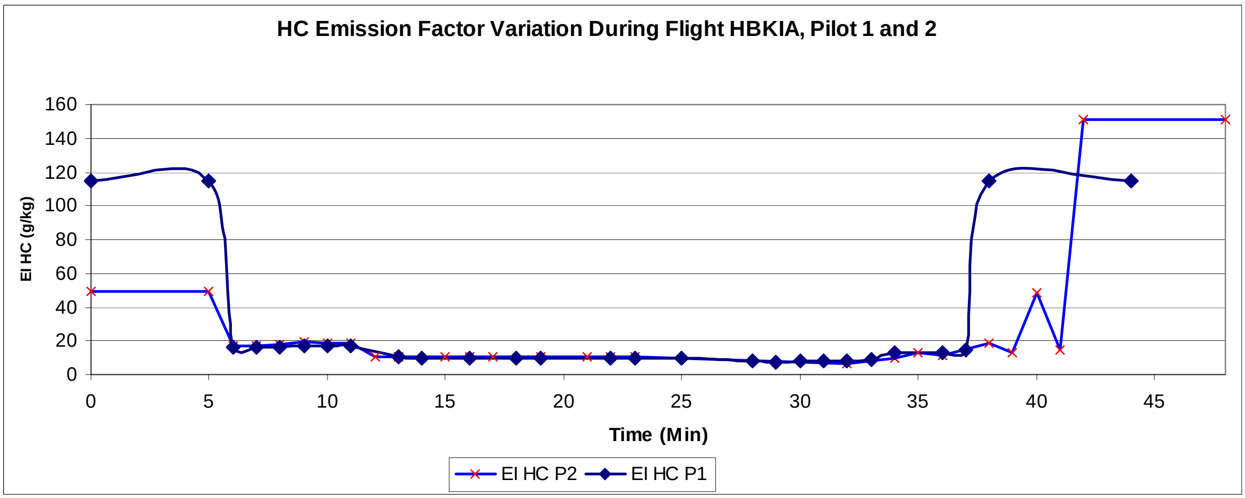


Figure 123: Comparison of HC emission factor variation during flights with pilot 1 and 2. The much higher HC emission factor during taxi (pilot 1) can be explained by lower engine RPM. At low engine RPM, EI HC drastically increases with decreasing engine RPM.

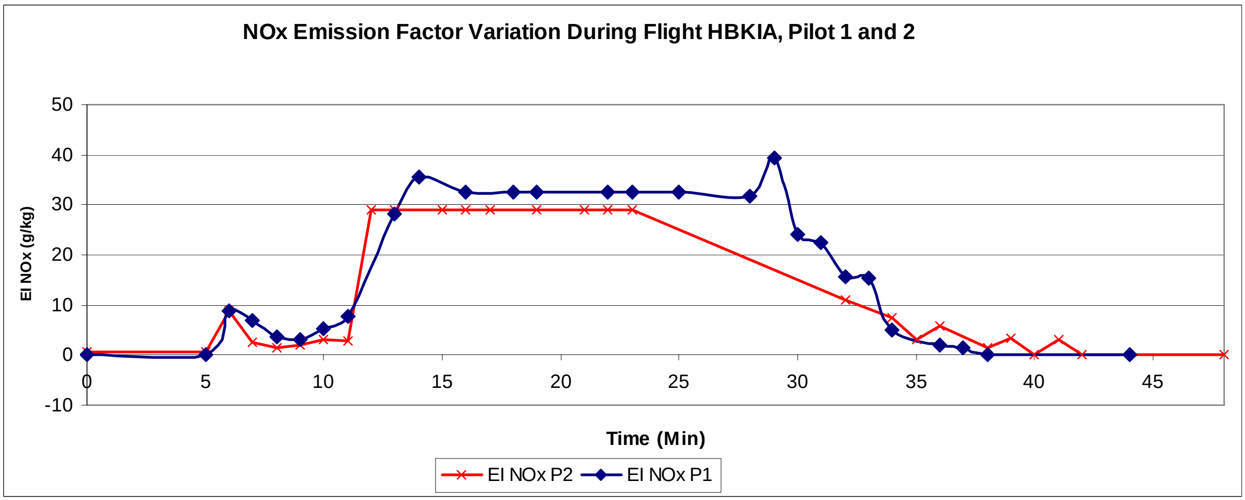


Figure 124: Comparison of NO_x emission factor variation during flights with pilot 1 and 2. Please note, that the decrease of EI NO_x P2 (pilot 2) between 23 and 32 minutes after off-block is artificial, because of missing data points, as in figure 122.

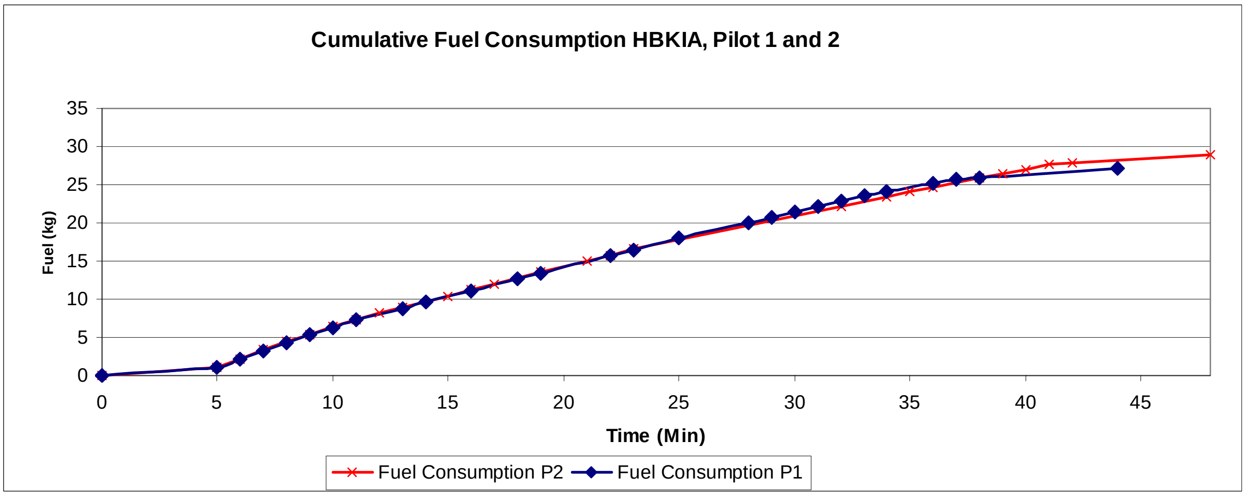


Figure 125: Comparison of cumulative fuel consumption during flight with pilot 1 and 2. In this example, pilot 2 chooses reduced cruise power. Hence the flight time is longer. Together with a suboptimal approach pattern, this adds up to higher total fuel consumption.

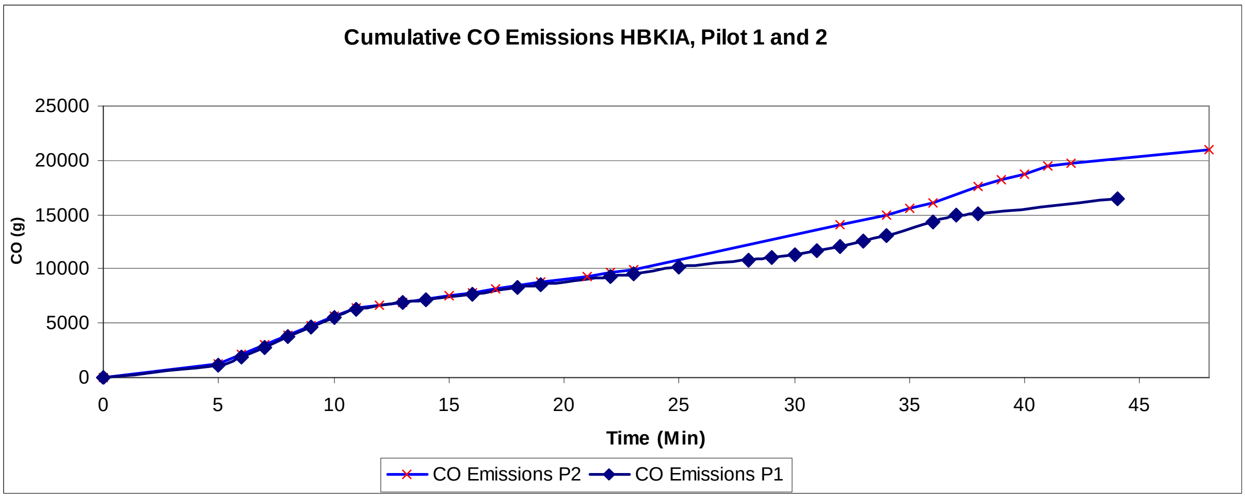


Figure 126: Comparison of cumulative CO emissions during flight with pilot 1 and 2. In this example, the lower power setting chosen by pilot 2 results in higher CO emissions. The highest portion of CO emissions occurs during taxi and take-off.

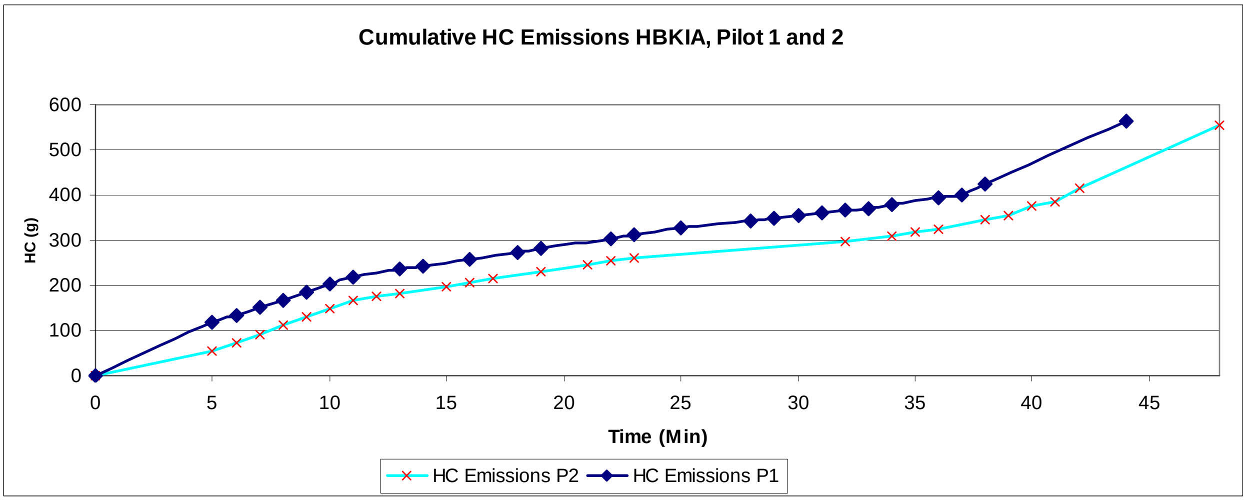


Figure 127: Comparison of cumulative HC emissions during flight with pilot 1 and 2. In this example, the lower power setting during taxi, chosen by pilot 2 results in higher HC emissions. During flight, HC emissions seem to be very similar between the two flights. The highest portion of HC emissions occurs during taxi and take-off.

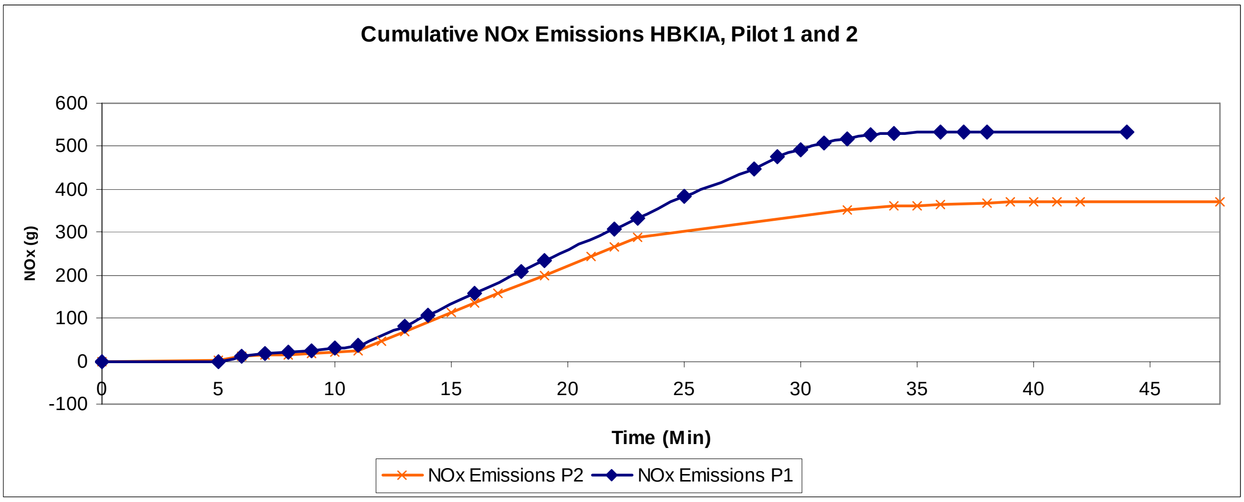


Figure 128: Comparison of cumulative NO_x emissions during flight with pilot 1 and 2. In this example, the lower power setting during cruise and descent, chosen by pilot 2 results in lower NO_x emissions. The highest portion of NO_x emissions occurs during cruise.

5.p) Emissions summary for a HBKIA mission, defined in 5.m) (300 HP injected traditional aircraft piston engine)

Table 9

HBKIA	Pilot 1	Pilot 2
LTO Fuel (kg)	11.1	11.2
LTO CO (g)	9159	10932
LTO HC (g)	384	382
LTO NOx (g)	57	30
CR Fuel (Mission kg)	17	18
CR CO (Mission g)	7325	10108
CR HC (Mission g)	180	173
CR NOx (Mission g)	476	342
CR Fuel (kg/h)	49	43
CR CO (g/(h)	20929	24259
CR HC (g/h)	514	415
CR NOx (g/h)	1360	822
Taxi Time (Min.)	11	11
Take-off Time (Min.)	1	1
Climb Time (Min.)	3.5	3.5
Cruise Time (Min.)	21	25
Approach Time (Min.)	7.5	7.5

6) HBHFX (Carburated Engine Lyc O-320 Series)

6.a) HBHFX high accuracy in-flight measurements: Installation of OBS2200

The FOCA low-cost in-flight measurement system described in Appendix 1 has some limitations for total HC and NO_x and therefore, correction factors have to be applied, as described in Appendix 5. It was not clear, how good these corrections would work for the in-flight measurements, because calibration was only possible at ground level static conditions. Until then, no system could be found in the marked, which was portable, with a potential for installation in a small aircraft and which –at the same time - was showing emission certification accuracy.
Through relations network and pure chance, HORIBA™ company got to know about FOCA in-flight measurements and presented their portable emission measurement system (PEMS), originally designed for on-road high quality measurements of diesel trucks and cars. FOCA was interested to see whether the HORIBA™ system would show comparable results to the low-cost system. HORIBA™ was interested to know, whether their system (OBS2200) was able to operate in an aircraft, facing rather quick changes of ambient conditions. At this time, the OBS2200 was not yet officially on the market. It was known from car measurements and tests in the Swiss alps, that the system would work at least down to an air pressure of about 850 hPa.
A major difference in the measurement principle between the FOCA low-cost measurement system and the OBS2200 lies in the determination of mass flow (see Appendix 1). FOCA uses actual fuel flow meters (that have to be installed in the fuel lines) and OBS2200 measures actual and ISA corrected exhaust volume flow. The HORIBA™ exhaust flow meter (which is a patented design) has to be installed in a straight part of the exhaust tube of the engine. In a first step, the OBS2200 was used for ground static measurements of HBKEZ (see Appendix 3). The calculated fuel flow from exhaust flow and exhaust carbon content measurement (OBS2200) and the actual measured fuel flow in the fuel line were compared. Those measurements matched very well (within 1 to 3% difference). Former ground based measurements and calculated emission factors of HBKEZ could be compared to OBS2200 measurements. This was part of validation work for the results that were obtained with FOCA low-cost measurement system (Appendix 3). It would have been very useful to compare also

FOCA and HORIBA™ in-flight measurements of HBKEZ and HBEYS. Unfortunately, there was no way for proper and safe installation of the HORIBA™ exhaust flow meter on the wooden and plastic covered airframe of HBKEZ and HBEYS without drilling holes and altering the airframe structure. So FOCA was looking for another aircraft with similar engine and chose the AS02 (HBHFX). The installed engine, Lyc O-320-E2A is practically identical to the one installed in HBEYS, rated at 150 HP instead of 180 HP (HBEYS). The AS02 aircraft is a full metal design, very robust, mainly used for pilot school and training. For noise reduction purposes, an additional muffler had been fitted and closer examination showed that the exhaust flow meter could be mounted instead of the muffler.

Picture 8: HB-HFX with original exhaust muffler (Gomolzig).

Moreover, the two large batteries, necessary for running the OBS2200 and the heated sampling line, could be installed below the seats, near the centre of gravity. However, zero fuel weight came close to maximum take-off weight which meant that planned flight time would be limited to half an hour per flight with a 45 minutes fuel reserve.

Details of the temporary major modification of HBHFX:

- The exhaust sample line is much thicker (40 mm diameter) than the FOCA system line. So we screwed the line directly to the airframe, using aircraft clamps and existing screw holes.
- The fixation of the exhaust probe system was a sheer replacement of the Gomolzig muffler by a stainless steel tube with the exhaust flow meter between. The exhaust system replacing the Gomolzig muffler had exactly the same weight (3.6 kg). Exhaust flow was not hindered inside the tube. We had tested the installation during a one hour ground test, also at take off power, without anything becoming loose or falling off and without any noticeable drop in engine performance. During the ground test we also rolled on the runway, without taking off and the whole measurement system fully operating.
- No existing aircraft systems were affected. Power supply was independent from aircraft.

Technical Influence

Limitations:

- Vne = 120 MPH

- Max. Altitude 7000 ft QNH
- Max. vertical acceleration = + 2g
- Neg. vertical accelerations to be avoided

Cabin Safety:

- CO detector necessary
- Emergency procedure: Emission measurement unit emergency stop button, closing down the whole system and valves immediately.
- Gas main valves have to be closed manually.

Documents Affected:

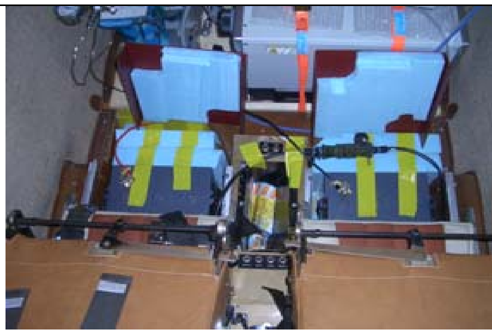
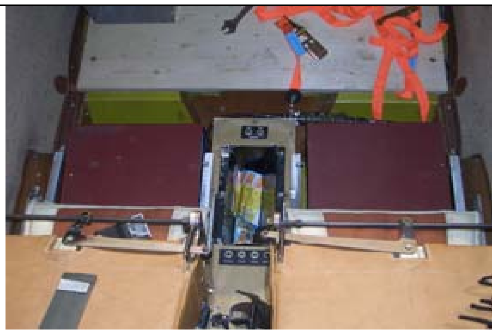
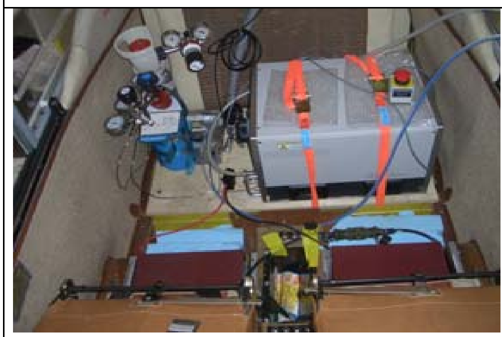
- Flight Manual (AFM) (Including weight and balance for all possible test configurations)

Applicable Airworthiness Requirements

None, restricted admission for emission measurements

Installation documentation:

	
Exhaust system installed in lieu of the Gomolzig silencer. Stainless steel pipe with D = 60 mm, wall thickness 2.5 mm. Steel support welded, identical to holder of Gomolzig silencer, including rubber suspension. With flow meter in between.	Mounting on the HBHFX. The flow meter between the supports is clamped to the pipe with a stainless steel muff. It can not fall, even if the rubber muffs were to be broken due to high temperature. The pipes have only a minimal spacing at the transition point underneath the muffs.
	
Detail of the flow meter. During the in-flight measurements, a 0,5 mm aluminium plate is clamped between the metallic bridle and the rubber muff to prevent damaging.	The connexions with the flow meter are welded. The measurement line is visible to the right on the picture. It is fixed on the fuselage by existing screws.

	
Battery with plastic cover, specially created for the installation.	Installation of both batteries underneath the front seats. They are fitting perfectly in the place and can't slide. The lids protecting the batteries' contacts are open on the photo.
	
The back seat was taken off and a 2 cm thick wooden board was fixed on the fuselage. On the left side is the metallic support for the two little gas bottles.	Batteries are mounted. Any possible upward movement of the batteries is prevented by the front seats once these are back in place.
	
Installation of the on board measurement system. The fixation is done with two clamps which are passing underneath the wooden board. The gas bottles (synth. air and He/H2) are fixed with 4 clamps to the metallic support. The pipe for He/H2 is made out of stainless steel with a reserve length of 1 m. The various links on the gas lines are tested with special gas leakage spray. A pressure drop during measurement would be signalled by the system.	Collector pipe is directly fixed to the fuselage by choke collars.

	Collector pipe is fixed with choke collars directly screwed on the fuselage. The turbulences created by the collector pipe were investigated during the rolling test on runway in LSZB and did not interfere with the controls. In emergency, the canopy can be slide backward without hindrance. The airplane wears the inscription "Experimental" on both sides of the cockpit.

AFM Supplement

1. Description

Temporary installation of a measurement system for in-flight emission measurements.

2. Operational Limits

V_{NE} is reduced to 120 MPH.

Maximum pressure altitude is limited to 7000ft.

Maximum vertical acceleration is limited to +2g. Negative vertical accelerations shall be avoided.

Load planning: With a mass of 158 kg for Pilot and Expert, maximum ramp fuel is limited to 57 liter. Therefore, measurement flights are restricted to 30 minutes duration (plus reserve). (see point 6)

3. Emergency Procedures

Supplements to the primary AFM are:
1. Push emergency stop switch of OBS2200 (By doing so, all systems are cut off, all gas valves closed immediately)
2. The main valves of the two fuel gas bottles have to be closed manually by the measurement expert.

4. Normal Procedures

No change to basic AFM.

5. Performance

No change to basic AFM.

6. Mass and Balance

Basic empty mass, after
- Removing of Gomolzig Silencer and back seat
- Mounting of Exhaust Flow Meter and wooden board

= 678 kg

Mass and Centre of Gravity:

	Mass (kg)	Moment (mkg)	Remarks
Basic empty	678	547	
System (OBS 34kg, Gas 11kg)	45	85	Back seat position
Batteries (2 peaces, 40 kg each)	80	110	Underneath front seats, position backend of pilot seats
Dry operating without crew	**803**	**742**	Lies within envelope (AFM B 5-2)

Configuration for first test flight			
Dry operating without crew	803	742	
Pilot	79	80	
Zero Fuel	**882**	**822**	Lies within envelope (AFM B 5-2)

Take-off mass for first test flight			
Dry operating without crew	803	742	
Pilot	79	80	
fuel (138 l)	100	85	
	982	**907**	Lies within envelope (AFM B 5-2)

Dry operating with full crew			
Dry operating without crew	803	742	
Pilot + Expert	158	158	
	961	**900**	Lies within envelope (AFM B 5-2)

Take-off mass with full crew			
Dry operating without crew	803	742	
Pilot + Expert	158	158	
fuel (53 l)	38	33	**Max allowable ramp fuel = 57 Liter**
	999	**933**	Lies within envelope (AFM B 5-2)

7. System Description (see Installation Documentation)

Replacement of the Gomolzig silencer by an exhaust flow meter (according picture documentation). Collector pipe fixed along fuselage, guided through the left cockpit window to the OBS2200 analyzer. Closed analyzer exhaust loop: Pumped exhaust sample and water condensate are guided outside the cockpit.
Two little gas bottles (He/H_2, synthetic air) used for the analyzer are mounted on the metallic support on the wooden board. The measurement system provides an emergency shut down switch, which is positioned within reach of the measurement expert.
The energy used for operating the measurement system and the heated sampling line is provided independently from the electrical system of the aircraft. Two pressure compensating dry batteries are fixed below the pilot and copilot seats. The batteries can not move in any direction and their contacts are covered.
Monitoring of the cabin CO concentration is done with a CO-sensor (Quantum Eye) which is placed on the right hand side of the cockpit panel, clearly visible for the crew.

8. Maintenance

No change to basic AFM.

6.b) Real time emission mass determination during flight

CO, HC, NO_x and CO_2 emission factors and the geographical coordinates from the GPS receiver have been displayed and recorded in real time during flight. The data recording interval was 1 second.

Picture 9: First departure of HB-HFX with OBS2200 fully operating.

The flight pattern used for HBKEZ and KIA had to be shortened because of the limited fuel and therefore limited flight time:

- Departure at LSZB (Elevation 1673ft)
- Continuous Climb to 5000ft (TO end at 4673ft)
- Level off at 5000ft and maintain
- Cruise phase with cruise lean at 5000ft
- Descent and approach (L begin at 4673ft)
- Landing at LSZB

Actual in- and outbound routes were chosen according to the visual approach chart (VAC), the meteorological and traffic situation.

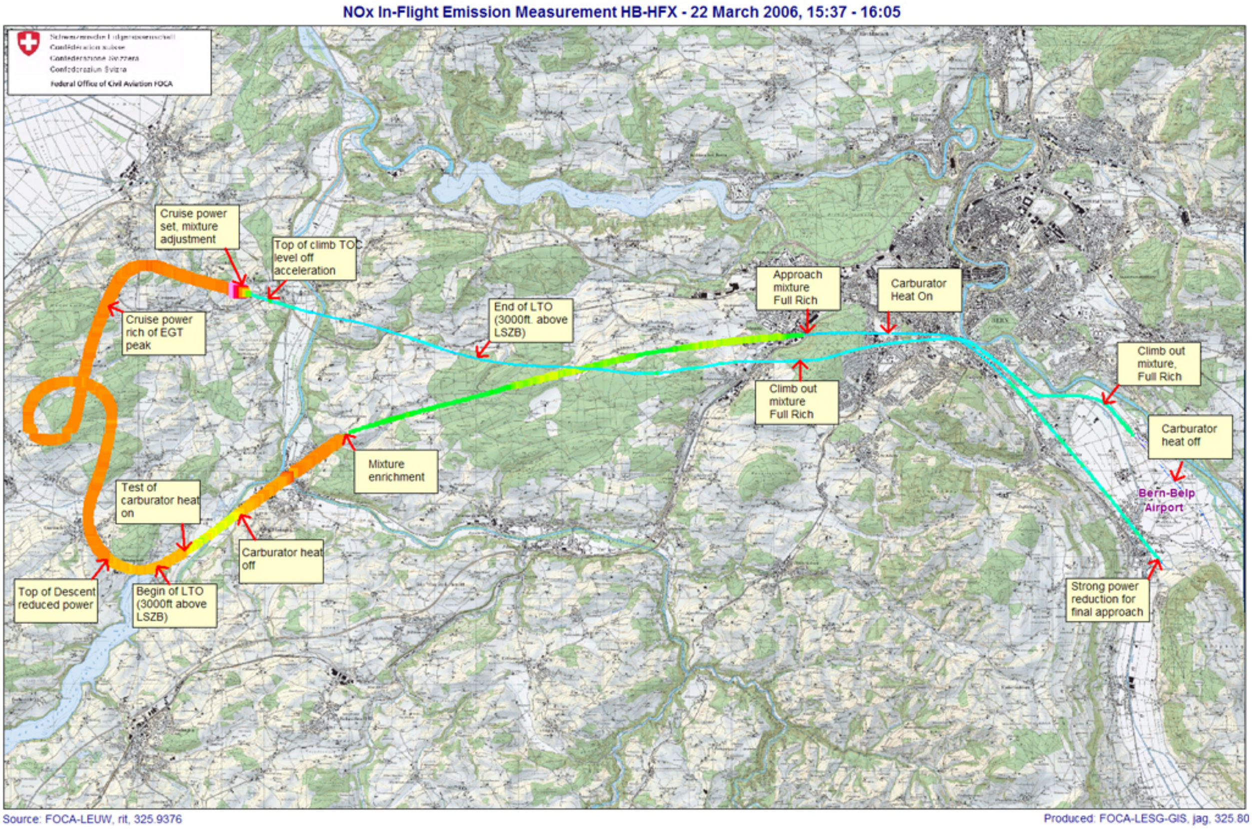
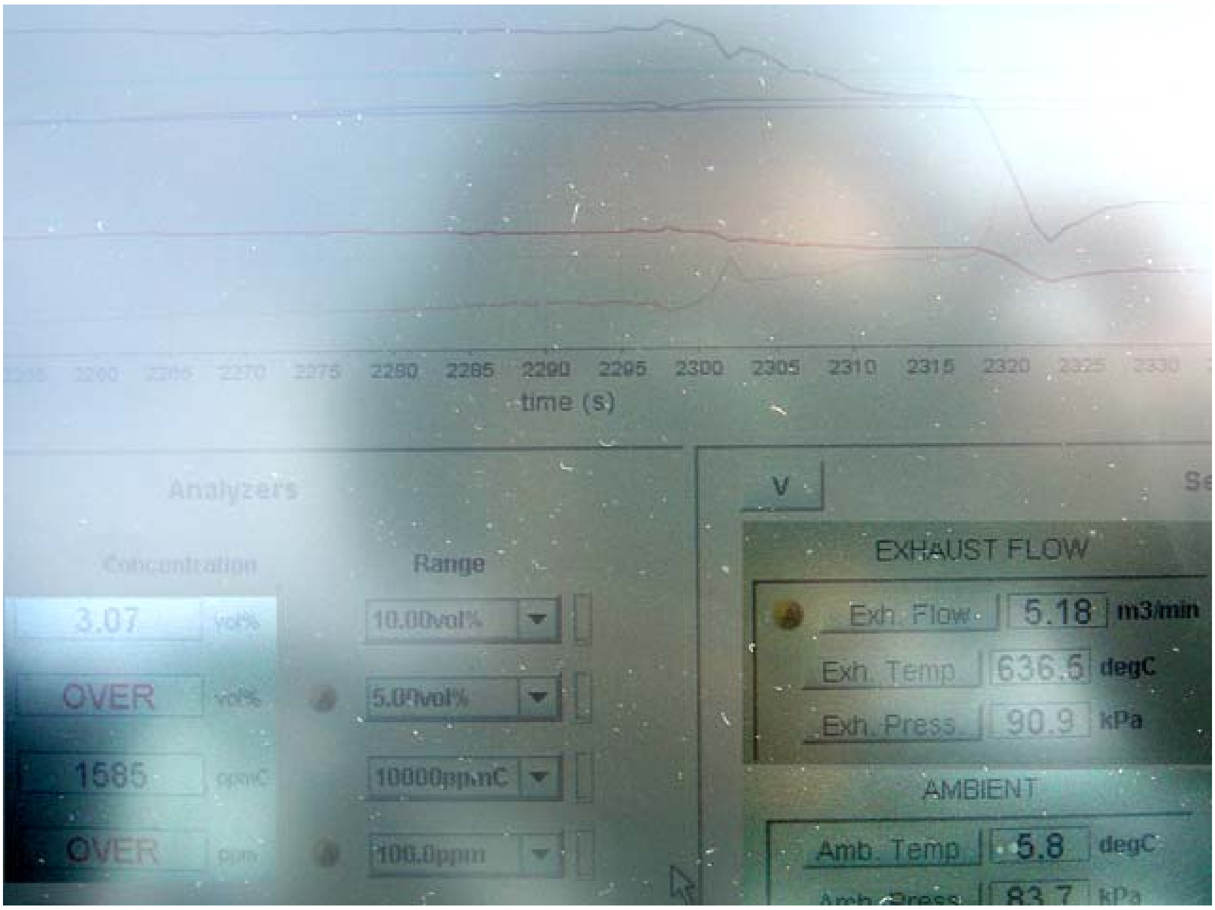


Figure 129: Visualization of the flight track and the NO_x mass from flight HBHFX 1537 (22.03.2006). Important phases of the flight and pilot operations, which affect emissions, are labelled with yellow flags. The flight begins at Bern-Belp airport (LSZB) (right hand side of the picture). The aircraft is taking off from runway 32 and departure is flown outbound route Whiskey, leading first towards Bern (the capital of Switzerland). The climb continues in westerly direction. “End of LTO” marks the point, where the aircraft reaches 3000ft above airport elevation. In this example, the coloured track indicates the amount of NO_x mass flow in grams per second. A light blue and thin track means NOx mass emissions in the order of 0.005 grams/second, a red and large track means about 0.2 grams NOx per second. At top of climb, the aircraft is levelled off and accelerates for cruise. Cruise power is set and the air fuel mixture is adjusted to less rich conditions. With the leaning procedure described in 1.c), NOx emissions get very high as peak EGT is reached (see red dot after “acceleration”). At the end of the adjustment (which is still a rich air/fuel mixture), NO_x emissions stay rather high (orange track). This is the cruise phase, with the engine running more efficient, but with rather high NO_x emissions. The orbit, which is shown on the left hand side of the picture, was only flown to demonstrate the wind situation. The aircraft was turning right with constant bank angle. The medium westerly wind produces a ground track with narrow turn, when the aircraft is turning towards the wind, and a wider turn, when the aircraft is flying with tail wind. That is why the ground track orbit is not a closed circle. Top of descent and the point where the aircraft is down at 3000ft above airport elevation are labelled accordingly. You can also see the effect of air/fuel mixture adjustments and the use of carburetor heat on the NO_x emissions during descent and approach. With the air/fuel mixture enrichment, NO_x emissions are reduced. At the end of downwind (right hand side of the picture), the NO_x emissions get very low, as the power is very low and the mixture lever in the “full rich” position.

Picture 10: HBHFX cockpit during measurement flight with cabin CO-detector (right hand side)



Picture 11: OBS2200 Laptop monitor during measurement flight with HB-HFX at 2340 seconds after engine start-up. The top line shows measured concentrations over time. At the bottom right, instantaneous values of the exhaust flow meter are displayed.

Table 10: Extract from data recording from 15:54:15 to 15:54:17 local time during take-off acceleration on the runway, showing the measured concentrations, sensor values and calculated values. (HBHFX, 1537, 22.03.2006)

FILLER_01 absolute	FILLER_02 relative [s]	ANALYZER_\ CO conc. [vol%]	ANALYZER_\ CO2 conc. [vol%]	ANALYZER_\ THC conc. [ppmC]	ANALYZER_\ NOx conc. [ppm]	ANALYZER_\ H2O conc. [vol%]	ANALYZER_\ A/F	FILLER_03 Alarm
15:54:15	440	5.59	9.46	2078.00	396.00	11.37	12.66	
15:54:16	441	5.69	9.38	2056.00	400.30	11.37	12.65	
15:54:17	442	5.74	9.35	2041.00	394.00	11.37	12.64	

SENSOR_01 Exh. Flow [m3/min]	SENSOR_02 Exh. Temp. [degC]	SENSOR_03 Exh. Press. [kPa]	SENSOR_04 Amb. Temp. [degC]	SENSOR_05 Amb. Press. [kPa]	SENSOR_06 Amb. Humid. [%RH]	GPS_01 Latitude [N/S]	GPS_02 Longitude [W/E]	GPSAV_01 Altitude [m]
5.65	491.22	97.77	12.98	94.56	61.92	N46.54.33.65	E7.30.10.656	508.90
5.55	507.67	97.71	13.00	94.56	61.91	N46.54.33.99	E7.30.10.218	508.90
5.48	518.11	97.83	12.98	94.56	61.89	N46.54.34.38	E7.30. 9.731	509.00

GPSAV_02 Velocity [km/h]	SENSOR_08 Battery [V]	ANALYZER_I CO mass [g/s]	ANALYZER_I CO2 mass [g/s]	ANALYZER_I THC mass [g/s]	ANALYZER_I NOx mass [g/s]	ANALYZER_I Fuel [g/s]	ANALYZER_I Power []	ANALYZER_MASS08 NOx corre. mass [g/s]
46.00	22.83	6.13	16.30	0.11	0.07	8.27	129.96	0.07
51.50	22.83	6.13	15.88	0.11	0.07	8.13	127.81	0.07
57.00	22.95	6.10	15.62	0.11	0.07	8.03	126.25	0.06

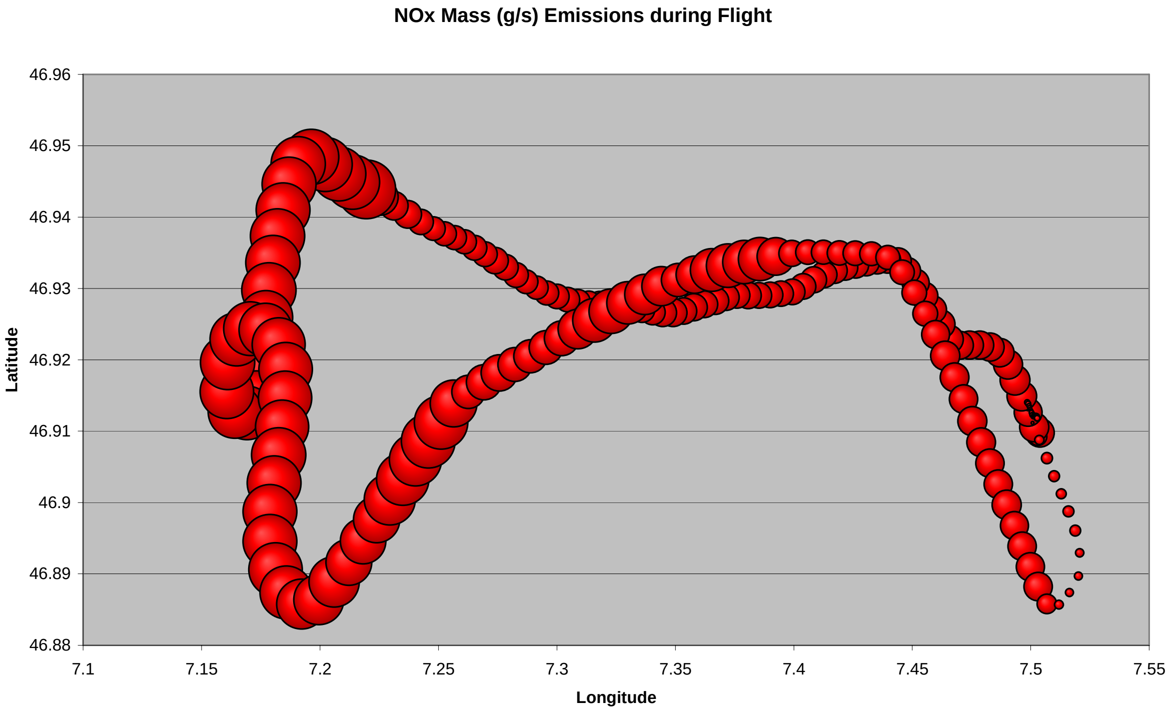


Figure 130: NO_x emissions during flight HBHFX 1537 (22.03.2006), the same flight as shown in figure 129 but without geographical background information. With this illustration (“NO_x worm”) the variation of NO_x mass emissions during the flight can be seen very clearly. One “bubble” contains the NO_x emissions integrated over 10 seconds flight time. The bubble size goes from around 0.05 to 2 grams NO_x per 10 seconds.

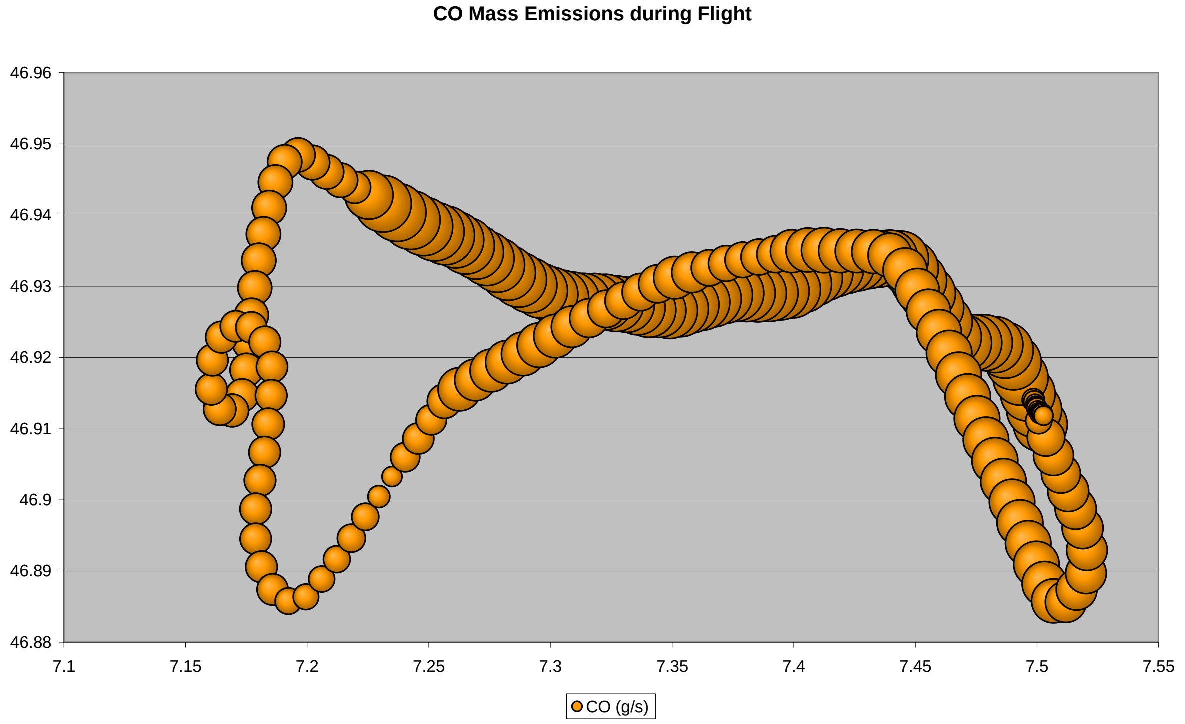


Figure 131: CO emissions during flight HBHFX 1537 (22.03.2006), the same flight as shown in figure 129 but without geographical background information. CO emissions are practically contrary to NO_x: Very high during take-off and climb, lower during cruise and high during approach. The bubble size goes from around 9 to 70 (!) grams CO per 10 seconds.

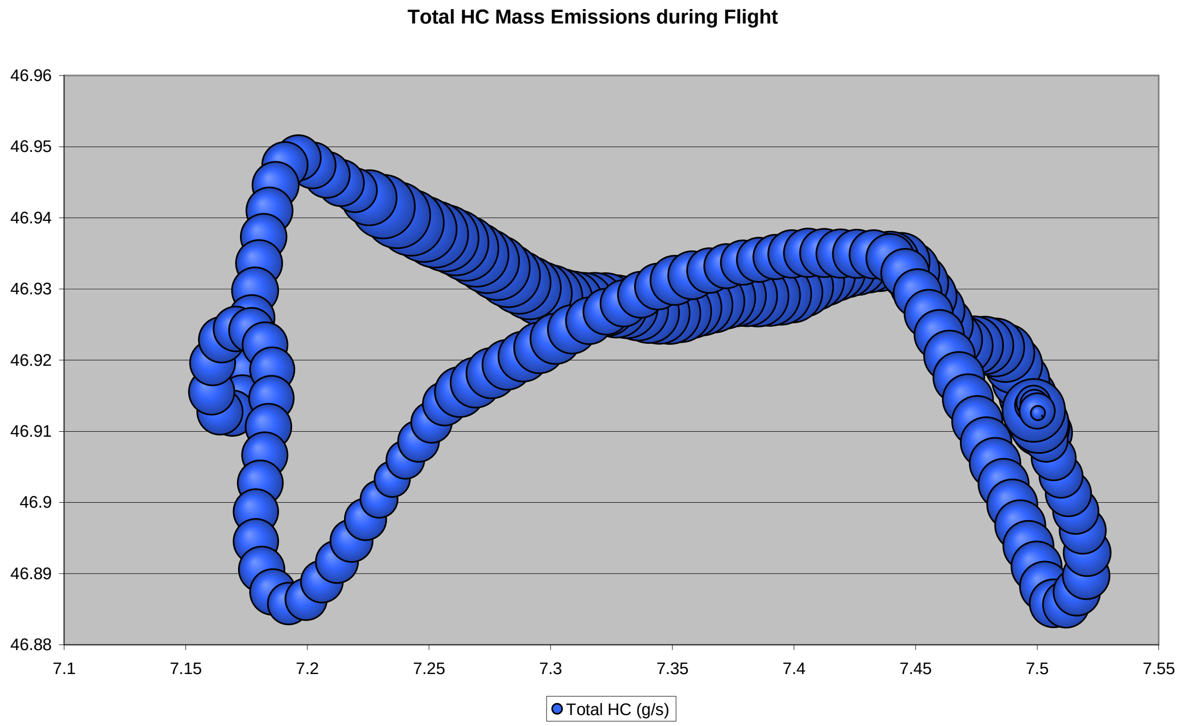


Figure 132: Total HC emissions during flight HBHFX 1537 (22.03.2006), the same flight as shown in figure 129 but without geographical background information. HC emissions are particularly high during take-off and climb, lower during cruise and higher during approach. The bubble size goes from around 0.4 to 1.2 grams HC per 10 seconds.

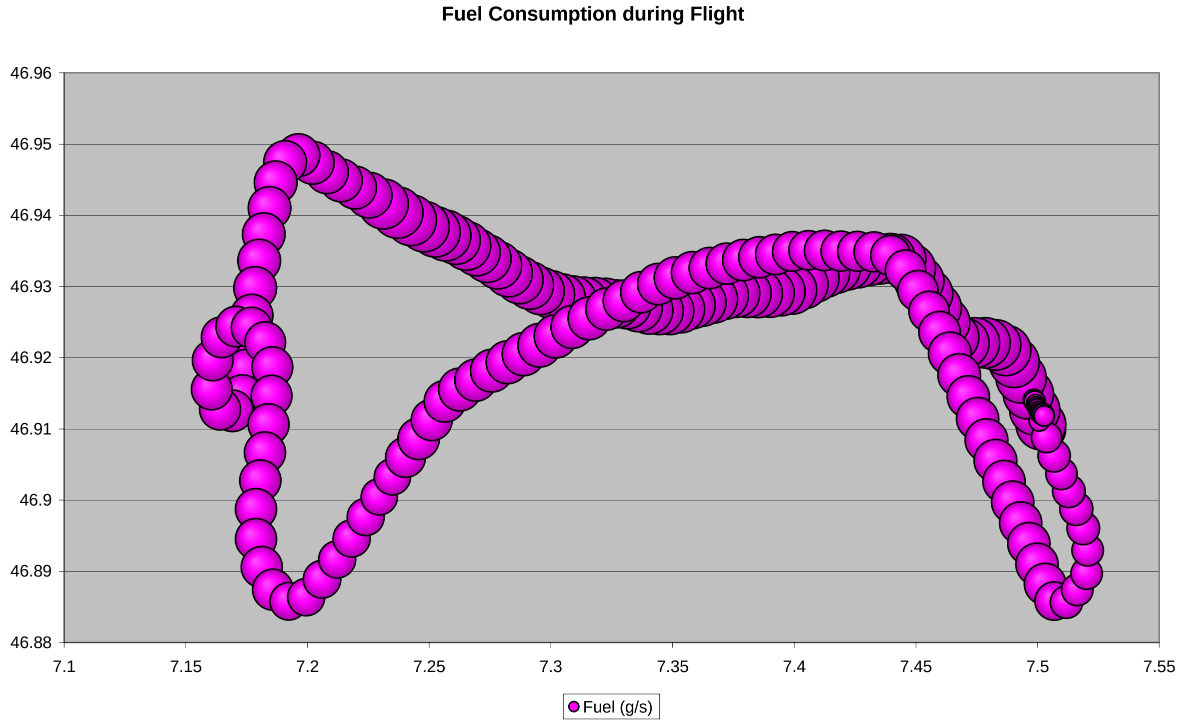


Figure 133: Fuel flow during flight HBHFX 1537 (22.03.2006), the same flight as shown in figure 129 but without geographical background information. The fuel flow is particularly high during take-off and climb, lower during cruise, stays practically the same during descent and is even increasing during approach! This can be explained by the fact, that according to the AFM, the mixture was set to full rich conditions at the end of the approach check. The bubble size goes from 83 grams of fuel per 10 seconds at take-off, to 55 grams per 10 seconds during cruise (around 27 liters per hour), 56 grams per 10 seconds during descent and 60 grams per 10 seconds in downwind before base and final turn. The final approach bubbles represent 33 grams of fuel per 10 seconds.

6.c) OBS2200 confirms typical emission factors for Lycoming carbureted engines

Table 10: Mean emission factors for Lyc O-320-A3A.

	Fuel	EF CO	EF HC	EF NOx	EF CO2
	[kg/s]	[g/kg]	[g/kg]	[g/kg]	[g/kg]
TA mean	0.0013	690	16.0	1.6	2044
TO mean	0.0083	815	12.6	6.7	1857
CL mean	0.0079	837	15.1	6.9	1816
CR mean	0.0058	410	11.6	37.0	2498
AP mean	0.0048	696	13.7	19.4	2042

In-fight emission factors obtained with HBEYS and the FOCA low-cost measurement system are confirmed with HBHFX and OBS2200.
In addition to that, the emission factor for CO_2 is calculated during the whole flights of HBHFX, in one second intervals. The low mean value of around 2 kg CO_2 per kg fuel, which is shown above, is not surprising, because of the low combustion efficiency with very high CO emission factors. The theoretical CO_2 emission factor for complete combustion and AVGAS100LL would be 3.17 kg CO_2 per kg fuel.

For LTO CO_2 calculations of typical aircraft piston engines, it is suggested to use 2 kg CO_2 per kg fuel instead of 3.17 kg CO_2 per kg fuel (see also 3.g), if CO emissions are counted separately.

6.d) OBS2200 time trend chart and confirmation of high HC emission factors at flight idle

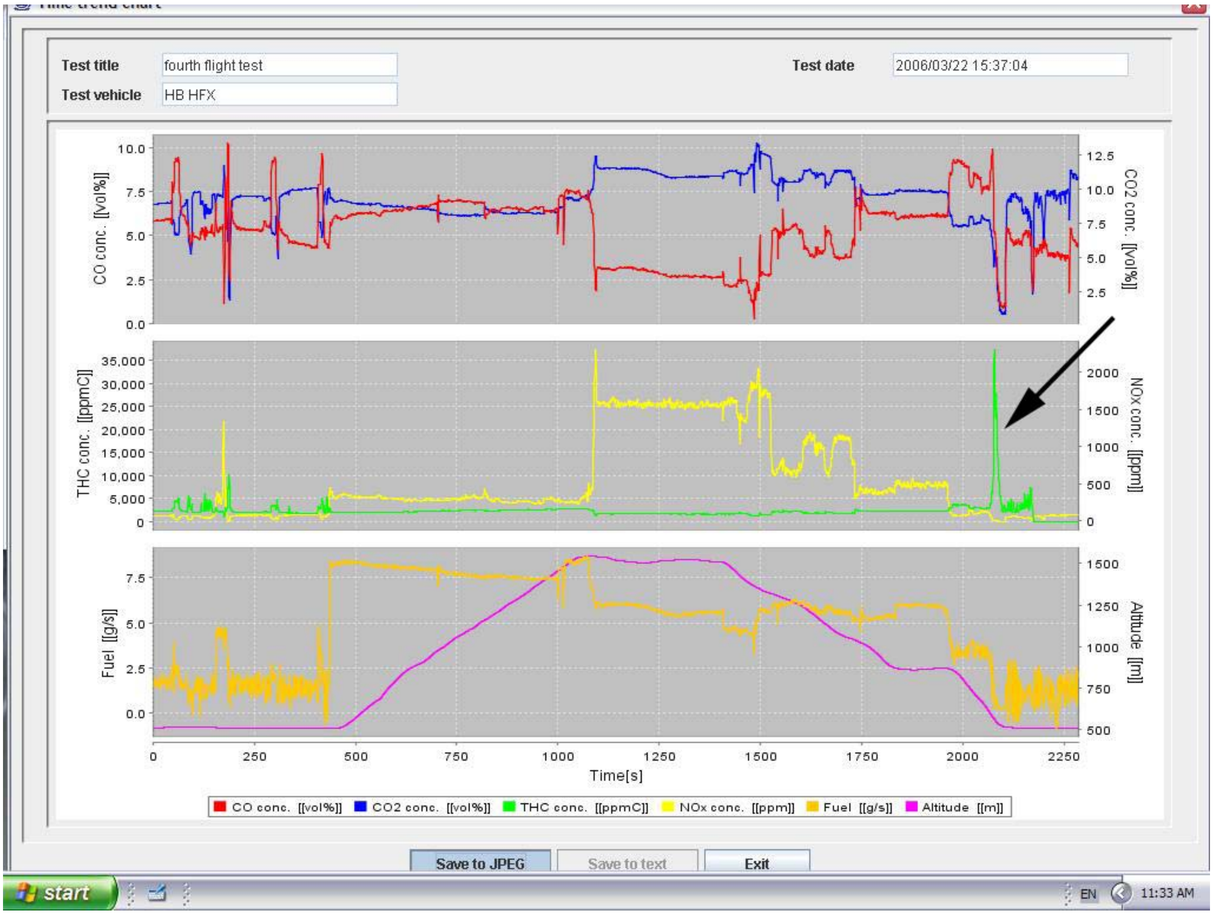


Figure 134: This is the same flight as shown in section 6.b) (HBHFX, 1537, 22.03.06) displayed as time trend chart from OBS2200. On top of the figure, you can see the CO concentration in red and the CO_2 concentrations in blue colour. In the middle, NO_x concentrations are given in yellow and total HC (THC) concentrations in green colour. The part on the bottom of the figure shows the fuel flow in orange and the flight vertical profile (GPS altitude) in violet colour.

At about 200 seconds on the time scale there is a significant NO_x, THC, CO and fuel flow peak. This is the moment, when the pilot performs the engine run-up with magneto check. The next peaks during taxi indicate a short engine RPM increase to accelerate the aircraft after a stop. At about 450 seconds, the engine goes to full power (maximum fuel flow) for take-off. During climb, NO_x concentrations decrease and CO concentrations increase due to decreasing air density and fixed mixture setting. At about 1050 seconds, the aircraft is levelled off and accelerated, which can be seen on the increased fuel flow. At about 1100 seconds, power is reduced and the air/fuel mixture adjusted to less rich conditions. There is a significant increase in NO_x and decrease in CO concentration, as shown in figures 130 and 131. THC is not reduced very much, which is also corresponding to FOCA previous results, obtained with the low-cost measurement system. Top of descent is at about 1400 seconds. As explained before, the fuel flow does not decrease significantly, because the mixture is set to richer conditions. Turning base and final approach begin at about 2000 seconds. Shortly before touch-down the engine is set to flight idle. At this point of time there is a drastic increase in THC concentration (black dart). This is a confirmation of the results obtained with FOCA low-cost measurement system (see 3.c with explanations for this effect).

Picture 12: Ready for airborne measurements

Picture 13: The HB-HFX project team