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Federal Office of Civil Aviation FOCA
Aviation Policy and Strategy
Environmental Affairs

AIRCRAFT PISTON ENGINE EMISSIONS

SUMMARY REPORT

Purpose of this paper: This paper aims to inform interested parties about the development of aircraft piston engine emission factors. These have been measured and are provided by Swiss FOCA for the primary purpose of emission inventory calculations. Furthermore, FOCA presents findings about emissions performance and in-flight operation of aircraft piston engines and recommendations for emissions reduction.

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ABSTRACT

According to Swiss aviation law (SR 748.0, LFG Art. 58), emissions from all engine powered aircraft have to be evaluated and tested. The legal requirement also incorporates aircraft engines that are currently unregulated and do not have an ICAO[1] emissions certification – like piston, helicopter, turboprop and small jet engines. Credible emissions data are necessary for emission and immission inventory purposes, environmental impact assessments and for issues directly related to environmental protection.

Up to now, there have only been few emissions data available for aircraft piston engines. This report tries to fill this gap of knowledge in a comprehensive approach. The following aspects are documented in this report and in its Appendices:

- Emissions performance for a wide range of existing aircraft piston engines.
- A methodology for cost effective standardized on ground emission measurements of aircraft piston engines.
- A methodology for the calculation of aircraft piston engine emissions.
- General principles of aircraft piston engine combustion and the effect of pilot operations on emissions.
- Research for emission reduction through optimization of pilot operations, new aircraft piston engine concepts, technological improvements and the use of cleaner AVGAS.

The presented material serves FOCA for

- Calculation of more complete aviation emission inventories in the context of legal national and international environmental requirements.
- Observation of the environmental impact of piston engine aircraft.
- Reduction of piston engine aircraft emissions.
- Pilot education.

As far as measurements are concerned, FOCA plans to increase the number of measured engines in the future. For other engine families without an ICAO emissions certification, like helicopter turbines and small jet engines, there is still a lack of emissions data and FOCA plans to work on respective packages, based on its aviation law.

June, 2007 Theo Rindlisbacher

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[1] International Civil Aviation Organization

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1. General information

1.1 Background

There are basically three propulsion concepts used for today's engine powered civil aircraft:

- Propulsion with „Turbofan“ (In everyday language, this is usually called “jet engine”),
- Propulsion with „Turboprop“ (Turbojet engine, driving a propeller) and
- Propulsion with piston engines (driving a propeller).

Turbofans (jet engines) and turboprops burn jet fuel (kerosene), aircraft piston engines primarily burn aviation gasoline (AVGAS). The highest portion of aviation fuel is consumed by large aircraft with large engines (mostly turbofans). Large turbofans and jet engines are certified for compliance with tight emissions standards.

Aircraft piston engines are mostly used for what might be called “small propeller aircraft”. On a global scale, such aircraft consume a relatively minor share of fuel. In Switzerland, the annual fuel consumption of aircraft piston engines is less than the fuel consumption for gardening activities[2]. Basically, emissions from aircraft piston engines have not been seen as a significant problem when looking at the broad picture of total emissions, and when looking at measured pollutant concentrations in a country like Switzerland. This can vary when looking at the aviation sector only, as we will see later (section 2.2.3 of this report). But assuming little to no influence, emissions from aircraft piston engines have not raised any interest, so far. Internationally, there have not been any efforts to consider work towards an emission certification for such engines. The disadvantage is that information about aircraft piston engine emissions performance is practically nonexistent. In Switzerland, this has sometimes caused problems, e.g. to produce a complete aircraft emissions inventory, or to provide credible data for an environmental impact assessment.

According to Swiss aviation law (SR 748.0, LFG Art. 58), emissions from all engine powered aircraft have to be evaluated and tested. Therefore, the Swiss Federal Office of Civil Aviation (FOCA) has been looking for efficient means, to fill the ”black emission holes“.

In autumn 2002, FOCA initiated project ECERT (Emission Certification). Although the project name incorporates the term “certification” it was clear from the beginning that the primary purpose of the project was to provide emission factors. This project would present the best available emissions data for aircraft piston engines but not necessarily at certification level, because of cost efficiency considerations.

Project planning started with estimations of the aircraft piston engine emissions contribution to the total civil aviation emissions. First estimations were based on a handful of old data and generated a surprising result: Carbon monoxide (CO) and total hydrocarbon (HC) emissions could be significant in a landing and take-off cycle, compared to large aircraft. Despite a fuel burn that was several magnitudes lower, CO and HC emissions could reach the magnitude of large aircraft. Explanations were found: The combustion in engines used for today's passenger aircraft has become exceptionally complete and clean, whereas aircraft piston engine technology – in general – has had a complete technology standstill since the 60's. Emissions reduction has never been an issue. Reliability of *simple* piston engine concepts, high power-to-weight ratio (high HP per kg), and production costs for a comparatively low number of certified engines seemed to be the main drivers. A disadvantage of such concepts was high specific emissions. Additionally, about half of the global aircraft piston engine fleet must operate on leaded fuel, due to high octane requirements.

It became clear to FOCA that it would be worth gathering a clear picture of aircraft piston engine emissions, and that new piston engine concepts would bear a high potential of emissions reduction within the aviation sector.

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[2] Swiss National Greenhouse Gas Inventory, Off Road Sector, INFRAS, January 2004.

From the beginning, the project was driven by the search for cost effective solutions. On the one hand, FOCA bought “low cost” equipment, which costs about 1/10 of a conventional certification level test equipment. This equipment was originally designed for automotive engine emissions testing (Appendix 1). For the purpose of emission factor determination, several adaptations and further developments were needed (Appendix 5). On the other hand, most aircraft used for in-flight testing belong to the Swiss Confederation, with FOCA being the responsible operator having direct access to the fleet. (Robin DR400/180 HB-EYS, Robin DR400/500 HB-KEY and HB-KEZ, Raytheon A36 Bonanza HB-KIA).
In order to measure aircraft piston engine emissions in static conditions, directly on the ground, an appropriate ground measurement methodology had to be developed (Appendix 3). A special feature which most gasoline aircraft piston engines have in common is the manual air/fuel mixture control. Knowledge, necessary for standardization of the measurements could only be gained from in-flight emission tests (Appendix 2). These measurements were also leading to an improved insight in emissions optimized operations of manually tuned engines. With growing interest in fine particle emissions, particle measurements have been integrated into the project. Finally, after the first results for particles, FOCA intensified basic research into emissions reduction of AVGAS engines (Appendix 4).

Since 2003, and through AERONET, there has been collaboration with the German Aerospace Centre (DLR), HJELMCO Oil Inc., BRP-ROTAX GmbH & Co, HORIBA Europe GmbH, TSI GmbH, ALPAIR, Swiss AIR FORCE, Prospective Concepts AG und GABUS SA.

1.2 Main scope and objectives of the project

- Development of a cost-effective ground based in-field measurement technique for aircraft piston engines (gaseous and non-volatile particle emissions) by using state of the art automotive testing equipment and by comparing in-flight to ground measurements.

- Gather absolute emissions data of a variety of piston engines for emissions inventory purposes (some helicopter – and small jet engines will follow at a later step).

- Development of operational guidelines for piston engines with manual mixture control which take engine durability and emission performance into account.

- If feasible, use the basic research for the development of an emission certification for small engines, bearing in mind that certification costs should be reasonable.

- Support basic research in order to replace leaded by unleaded AVGAS for aviation piston engines and to improve emissions performance.

2. Summary of results

2.1 FOCA data sheets and their practical application

2.1.1 General Methodology for Emission Calculation

Definition of Power Modes for Aircraft Piston Engines

Typical power settings have been established by flight testing (Appendix 2) and ground measurement comparison. Table 1 below indicates five operating modes: **Take-off, Climb out, Cruise, Approach and Taxi**. For each mode, the table indicates typical power settings used in ground static tests. (Details are given in Appendix 3.) All FOCA data, established with ground static tests, are based on the suggested modes and power settings below.

Table 1: Power Modes

Mode	% of max. Propeller HP
Take off	100
Climb out	85
Cruise	65
Approach	45
Taxi	Operator’s Manual

Calculation of emissions of an aircraft at and in vicinity of an airport (landing and take-off cycle, LTO) =

Number of engines *
(Taxi time * Taxi fuel flow * Taxi emission factor +
Take-off time * Take-off fuel flow * Take-off emission factor +
Climb out time * Climb out fuel flow * Climb out emission factor +
Approach time * Approach fuel flow * Approach emission factor)

Calculation of emissions of an aircraft during cruise =

Number of engines* (Cruise time * Cruise fuel flow * Cruise emission factor)

2.1.2 Suggested Times in Mode for Emission Calculation

Table 2 suggests standard times in mode for piston engine LTO emission calculations according to the equation above.

Table 2: Standard Times in Mode for Piston Engines

Mode	Time (Minutes)
Take off	0.3
Climb out	2.5
Cruise	-
Approach	3
Taxi	12

Remarks:

1) Part of the piston engine powered aircraft are intensely used for training and school flights, where two movements (= 1 LTO) are reduced to one circuit around the airport. The times in mode try to take a representative mixture between LTO, circuit flying and the performance variability between different aircraft into account. This can be very country dependent.
2) Cruise Time: Actual time outside LTO. In absence of such information FOCA suggests a mean cruising time of 20 minutes for small aircraft for central Europe, corresponding to a mean total flight time of 30 to 40 minutes per flight, when the LTO is included.

3) The time value for taxi (in and out) seems to be rather small but is considered appropriate for small airfields where most of piston aircraft operate. At airports, total taxi time might be higher and should be adjusted according to the local situation.
4) At climb out up to 3000ft AGL, the majority of engines below 200 HP are operated at full power. In those cases, it would be more realistic to calculate the climb segment of the LTO with take-off emission factors and take-off fuel flow.

Table 3 suggests times in mode for the LTO cycle, if circuit flying around airports is excluded. This is not suggested for full airport emissions inventories, however it can be used to compare piston engine emissions in the LTO band of 3000ft above ground level to other types of engines.

Table 3: Full LTO Times in Mode for Piston Engines

Mode	Time (Minutes)
Take off	0.3
Climb out	5
Cruise	-
Approach	6
Taxi	16

2.1.3 Cruise Emission Factors

Most of the piston engines which are dominating the market have manual air/fuel mixture control to adjust the engine to different altitudes (in fact to density altitude). This air/fuel mixture adjustment has to be done by the pilot during flight whenever the aircraft changes its power configuration and altitude. This adds a particular degree of complexity to representative emissions measurements, because emissions can vary strongly even if the same aircraft is flying at the same mass, same density altitude, same speed, configuration and attitude. The variation comes from different “leaning techniques” and is also dependent on the pilot’s experience, training and available engine cockpit instrumentation (sections 2.2, 2.3 and Appendix 2). For this reason and as a result of in-flight measurements, the cruise mode is given twice in the data sheet:

Table 4: Extract of data sheet PF01. CRUISE and CRUISE LEAN values. EI = emission factors

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

CRUISE: Measured at very rich air/fuel mixture, called “full rich”. Well defined and for comparison only

CRUISE LEAN: to be used for cruise emission calculations. The definition of the mixture comes from operator’s manuals and in-flight studies. “Cruise lean” values are the result of the most common “leaning technique”, where pilots manually adjust the air/fuel mixture to less rich conditions. ”Leaning” is a common term, however in most cases it means that the engine is run leaner than at full power but still at a rich air/fuel mixture (Details are given in sections 2.2, 2.3 and Appendix 2).
Some of the engines do not have a manual mixture control. On the datasheet this is either indicated with remarks or with the same cruise values for CRUISE and CRUISE LEAN.

2.1.4 Calculated LTO and 1 hour cruise emissions on data sheets

Table 5 (below): Extract of data sheet PF01. LTO fuel consumption and total HC, CO and NOx emissions are marked in yellow. One hour cruise fuel consumption and emissions are marked in green. All values for LTO and CRUISE are calculated based on the suggestions made in sections 2.1.1 to 2.1.3

MODE	POWER SETTING (%)	TIME (minutes)	FUEL FLOW (kg/s)	EI HC (g/kg)	EI CO (g/kg)	EI NOx (g/kg)	PM (…) (…)
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CRUISE LEAN	65	60	0.0138	5.4	473	23	
LTO TOTAL FUEL (kg) or EMISSIONS (g)			7.53	174	7327	24	
CRUISE 1HOUR FUEL (kg) or EMISSIONS (g)			49.7	268	23490	1149	

2.1.5 Data Quality and Accuracy

FOCA data sheets are primarily based on the "low cost" STARGAS 898 measurement system and the MEXA 1170 HFID (see Appendix 1). For each engine on ground static tests, a minimum of three measurements have been performed for every power mode. Data variability has been statistically checked with a T-test and 90% confidence interval (Example in Appendix 3).
The particle emission measurements have been performed in collaboration with German DLR. Primary focus were the nanoparticle and carbonyl emissions. There is presently no "low cost" for such measurements. First measurements have been made with HBKEZ. The measurement results have been reproduced one year later with the DLR measurement system and the same aircraft (see Appendix 4 for details).
Swiss FOCA sees the primary purpose of the data collection in their application in emissions inventory calculations. The measurement system that has been used so far (STARGAS 898) does clearly not represent certification standard. However, the measurement quality achieved by requirements described in Appendix 1a/b) is considered sufficient for emissions inventories. This conclusion is based on the following comparisons:

FOCA has started to use a total HC FID in parallel to the "low cost" STARGAS NDIR HC measurement and has done crosscheck measurements with a chemiluminescence (CLD) NO_x analyzer. From comparative measurements with different systems, correction factors for the "low cost" gas analyzer with NDIR HC and electrochemical NO probe have been derived. (See Appendix 5 for details.)
In addition to that, FOCA has been given the chance to use HORIBA OBS 2200. This system meets the requirements for high quality certification emissions measurements (THC FID, NO/NO_2 CLD, heated sampling line at 191°C, exhaust flow measurement etc, see Appendix 1.g) and is very compact, originally designed and tested for on board measurements in cars and trucks under real operating conditions. The system has been used for comparative ground static tests in the ECERT project. It has then been installed for the first time in an aircraft and flown successfully, providing high quality real time mass emissions data at one second intervals, together with position, altitude, speed and flight time. Complete, 4-dimensional resolved emissions inventories have been measured and recorded, from taxi out to taxi in. Those real world data have been compared to the STARGAS data and to the existing LTO-modelling data. (Details are given in Appendix 2.)

From the present experiences FOCA concludes that the results for a "low cost" measurement system described in Appendix 1a/b, as well as the calculations and corrections described in Appendix 5, would be in a systematic error band of **+-15%** for the measurement itself. This is considered acceptable because operational issues and individual engine tuning can change emission factors drastically (See Section 2.2.2 and Appendix 2) and because of the low system costs (approximately one tenth of a common measurement system, used for emission certification). In the opinion of FOCA, overall representation of emission factors mainly depends on the choice of operating points and on the real flight operations. FOCA has taken this into account by doing in-flight emission tests.

Four aircraft have been used for basic testing (Appendix 2). The first two aircraft HBEYS and HBKEZ have been tested in-flight, followed by in-field static ground tests until it was possible to reproduce useful in-flight data on ground. The third aircraft HBKIA has been first tested on ground on the basis of the ground power setting procedure developed with the HBEYS and HBKEZ measurements. Once this had been completed, HBKIA has been tested in flight in order to validate the ground test procedure (Appendix 3). The HORIBA OBS 2200 has been used for cross check of HBKEZ static ground measurement data accuracy and for in-flight measurement of HBHFX in order to produce "real world" emissions inventories.

2.1.6 Data Download

This report, as well as the full documentation (Appendices), available data and individual datasheets can be downloaded from the FOCA webpage.

Download link:

http://www.bazl.admin.ch -> for specialists -> environment -> engine emissions

List of abbreviations, used in the data sheet table:

FOCA UID: Unique identifier for piston engines which can be used as the key to link aircraft with engine data. “P” stands for piston engine, “F” stands for FOCA measurement.

Rated HP: Rated Horse Power. Manufacturer declaration. The number may vary within certain engine model variants. If a certain engine model can not be found in the table, Horsepower, Combustion Tech, Cooling System and Technology Age can give hints to choose the nearest possible representative engine.

Piston Engine Model: To simplify application of the table, only the basic model designations without derivative variants are given. Example: TCM IO-520 A, B, C, D, E, F, J, K & L are represented by TCM IO-520. In most cases the variants do not produce significant change of emission factors. The actual variant measured is indicated on the FOCA datasheet.

Combustion Technology: If a certain engine model can not be found in the table, Combustion Tech can give hints to choose the nearest possible representative engine.

Cooling System and Fuel Type: If a certain engine model can not be found in the table, Cooling System and Fuel Type can give hints to choose the nearest possible representative engine. Piston engine particle emissions are highly influenced by fuel type. Some of the engines that have been measured with AVGAS100LL are allowed to run on unleaded fuel. This has not yet been incorporated in the database.

Technology Age: If a certain engine model can not be found in the table, Technology Age can give hints to choose the nearest possible representative engine. 1960 technology engines are currently dominating the market.

Data Source: For completeness, the FAEED[3] data that Swiss FOCA has been used so far are incorporated in the table. Comparison with FOCA ECERT measurements has shown that existing FAEED data seem to be reasonable for the purpose of LTO-emission calculation. Therefore ECERT has primarily focused on missing and more modern engines to complete the picture.

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[3] FAEED = US Federal Aviation Engine Emissions Databank

2.2 General findings about aircraft piston engine emissions

2.2.1 Combustion basics

a) What goes in? Composition of AVGAS 100LL

AVGAS (aviation gasoline) is a complex mixture of hydrocarbons (HC) plus additives. The fuel must comply with the specification of the US standard ASTM D-910 which ensures safe engine operation at the whole ambient temperature and pressure range, as far as the fuel is concerned.

Additives:

- Most of the AVGAS available is AVGAS 100LL, a leaded fuel. The “LL” stands for “Low Lead” which is a relative term. AVGAS 100LL can contain up to 0.8 g lead (tetra ethyl lead) per kg fuel! The lead additive is used to get the high octane rating of 100/130. Lead additives have been introduced many decades ago, mainly to improve the power to weight ratio of aircraft piston engines by increasing the compression ratio in the cylinders. FOCA assumes that about 30% of the global gasoline aircraft piston engine fleet still needs such high octane fuel to suppress knocking or self-detonation at high compression ratios and at suboptimal air/fuel ratios and ignition timings.
- If the fuel is leaded, it contains a similar amount of ethylene dibromide. This substance is used to remove lead deposits from the combustion parts of the engine. Otherwise spark plugs can be destroyed and deposits on valves can obstruct their proper operation. As lead, the scavenger is an environmentally harmful substance, believed to be carcinogenic and contributing to stratospheric ozone depletion.
- Dyes (to colour code the fuel): The blue dye in AVGAS 100LL (1,4 – dialkylamino-antraquinone) is causing skin irritation and allergic reactions.
- Antioxidants (preventing gums and sediments)
- Icing inhibitor (optional)
- Electrical conductivity additive (optional)

Like car gasoline, AVGAS 100LL contains some amount of benzene, a toxic substance known to be carcinogenic.

Note: There are much cleaner alternatives to AVGAS 100LL, even cleaner than car gasoline. During the project, FOCA has started collaboration with Swedish Hjelmco Oil, the producer of a synthetic, very pure unleaded AVGAS, meeting ASTM-D910 specifications. (See Appendix 4 for details.)

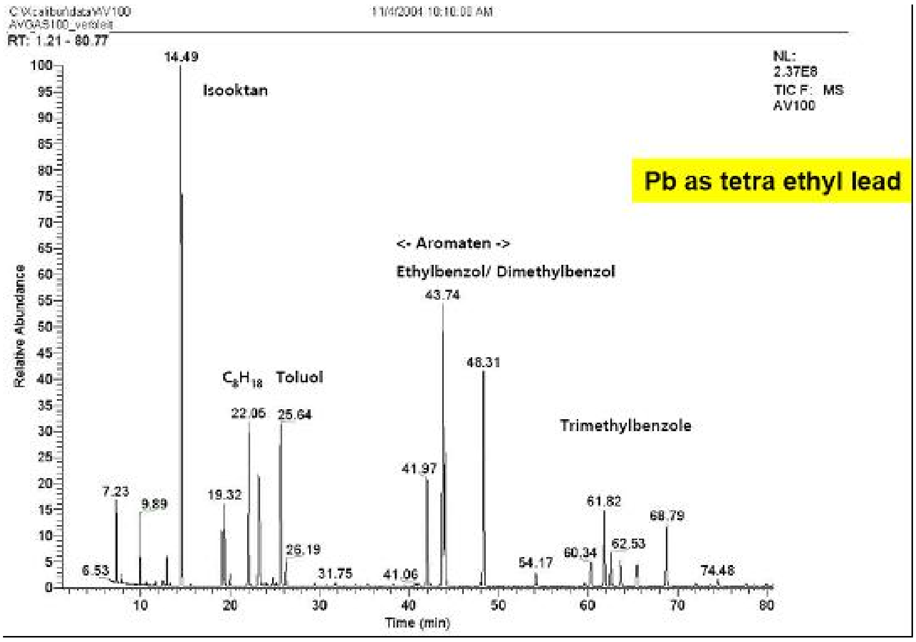


Figure 1: Composition of AVGAS 100LL, used for part of the FOCA emission tests. The composition analysis has been done with gas chromatography and mass spectrometry at DLR Stuttgart/Germany. [C. Wahl/DLR]

Some aircraft/engine combinations are certified to use motorcar gasoline (MOGAS). In Europe, this fuel is lead free but with the high bandwidth of possible composition and some alcohol content, there are limitations for its safe use. Besides this, not only the engine (which is in many cases not the problem) but also the airframe must be certified to use that fuel, which basically comes from requirements for the fuel system.

For theoretical calculations of the fuel combustion, it is useful to look at a representative AVGAS (or MOGAS) hydrocarbon molecule. Figure 2 below shows a typical distribution of the carbon number in AVGAS molecules.

A "mean" AVGAS molecule is considered to be composed of **7 Carbon** atoms and **13 Hydrogen** atoms (**C_7H_{13}**). For all standard mass emission calculations of FOCA, this molecule is used (see Appendix 5).

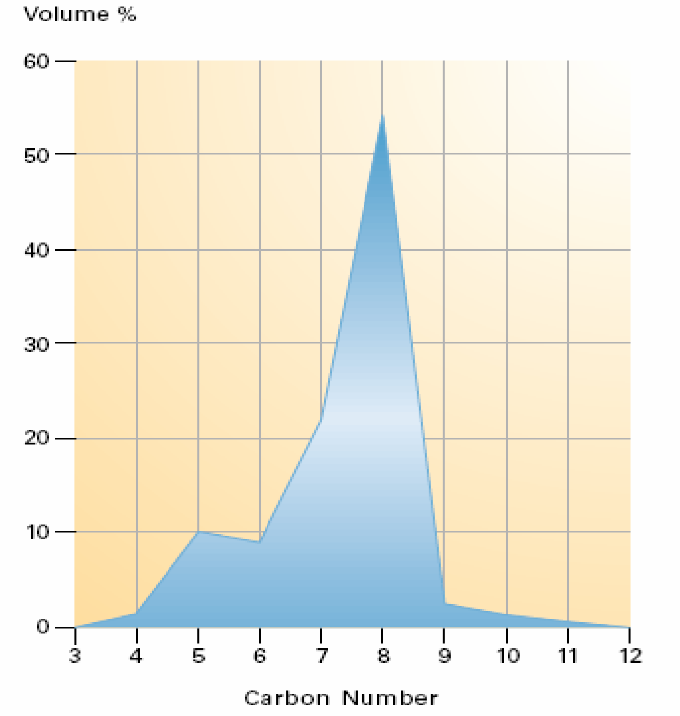


Figure 2: Carbon number distribution of the hydrocarbon molecules in AVGAS 100LL [Chevron].

b) How much air to make the fire?

Fuel **and** air are needed to ignite a fire. Generally, the more of both there is, the hotter the flame. But the combustion will only be "optimal" at certain fuel/air ratios.

The combustion conditions at which the fuel/air ratio is, such that there is neither an excess of fuel nor of air, is called the **stoichiometric mixture** within a cylinder. At this condition, all of the reactants are present in the chemically ideal amounts for combustion and the **greatest amount of total combustion heat per unit of air** is produced.

At stoichiometric mixture, the cylinder is running at "**peak EGT" (peak Exhaust Gas Temperature)**. Peak EGT mixture can be seen as the "**maximum-heat mixture point**".

In order to estimate the amount of air that is needed to burn a defined amount of fuel at stoichiometric mixture, the chemical reaction equation is used. Note, that in a combustion process the mass of all reactants going into the process is conserved. Molecules are reformulated but nothing is lost. The fuel and air have been reformed to other substances, giving heat during the formation process. Intake mass equals exhaust mass.

Calculation with reaction equation for complete combustion:

1 C_7H_{13} (AVGAS) + 10.25 O_2 (Oxygen from Air) + 39 N_2 (Nitrogen from Air) react **to ("burn" to):**

7 CO_2 (Carbon dioxide) + 6.5 H_2O (Water vapour) + 39 N_2

Taking the number of necessary molecules for the complete combustion from the equation above and multiplying them with the molar masses of the molecules, then, for 1 Mol of AVGAS the result is:

$$\textbf{97.18g } C_7H_{13} + \textbf{328.0g } O_2 + \textbf{1092g } N_2 \textbf{ react to } \textbf{308.07g } CO_2 + \textbf{117.13g } H_2O + \textbf{1092g } N_2 \qquad (1)$$

Therefore, 97.18 g fuel is reacting with 1420 g Air (O_2 + N_2). This is a mass ratio of 1 : 14.6

The conclusion is that for complete combustion of 1 kg fuel, about 15 kg air is necessary!

Fuel / Air ratio 1kg / 15 kg = 0.067 (for stoichiometric combustion)

c) What comes out?

From the chemical mass equation (1) above it can also be seen that for complete combustion:

1 kg fuel (AVGAS) produces

- 3.17 kg CO_2 (Carbon dioxide)
- 1.21 kg H_2O (Water vapour)

CO_2 and H_2O are no pollutants, but are both atmospheric green house gases due to their infrared (= heat) absorption properties. Most of the N_2 (78Vol% in ambient air) passes combustion unchanged.

Hot air: N_2, CO_2 and H_2O are dominating the exhaust gas.

Besides hot air, pollutants are formed.

Causes for the production of pollutants can be:

Oxygen deficiency:
There is too little oxygen to react the C from the fuel to CO_2 (Carbon dioxide). It will react to **CO** (Carbon monoxide) only.
The fuel can not react completely to CO_2 and H_2O (water) and a complex mixture of hydrocarbon molecules (C_xH_y) will be exhausted, also named **HC.**

High combustion temperatures and pressures with short chemical reaction times:
The nitrogen (N_2) contained in ambient air (78Vol%) together with the oxygen (O_2) from ambient air (21Vol%) start to react in the combustion chamber (cylinder) to form nitrogen oxides (NO and NO_2, named as **NO_x**)

Pollutants: CO, HC, NO_x, soot, lead bromides (AVGAS 100LL)

FOCA measurements concentrated on CO, total HC and NO_x emissions, which are reported in FOCA data sheets. Soot and other particles were measured by DLR Institute of Combustion Technology, Stuttgart, in collaborative projects (Appendix 4).

d) Properties of pollutants

Carbon monoxide (CO):

- Toxic gas, e.g. blocking oxygen transport in blood.
- Chemically unstable, normally converted to CO_2 after a few days in the free atmosphere.

Hydrocarbons (HC):

- Hundreds of possible H-C-molecules (e.g. formaldehyde) with different health impacts, some carcinogenic.
- Some are converted with sunlight (UV) to radicals, contributing to ground level ozone production. In the troposphere, ozone is able to strongly react on different substances. Ozone is able to “clean” the troposphere (+), but it is itself toxic with increasing concentrations (-).

Nitrogen Oxides (NO_x):

- NO converts to NO_2 within minutes to hours in free atmosphere.
- NO_2 (yellowish colour) is toxic for the respiratory system.
- With sunlight (UV), NO/ NO_2 contributes strongly to the low level ozone production

2.2.2 Air/fuel mixture adjustments

a) Dominant “old tech” engines require manual air/fuel mixture control

Around 70% of all aircraft piston engines which can be found in the global market have the following general concept:

- Opposed cylinders in boxer configuration
- Big cylinder volume, relatively low RPM, no reduction gear for the propeller
- Air cooled (direct air cooled cylinders, indirect via oil cooler)
- Carburettors without ambient conditions or combustion sensing devices
- Most injection systems without ambient conditions or combustion sensing devices
- Injection systems not timed with cylinder valve movements
- Constant ignition timing, not taking into account engine RPM (except for start-up)
- Everything mechanical, no electronic devices

This general concept, which is called here “**old tech**” or **“conventional”,** has not changed for many decades. Contributing factors were the very good power to weight ratio, the “simplicity” (compared to a modern car engine) and very good reliability and durability of such engines. Keeping in mind that aircraft engines have to pass an airworthiness certification process, it must be understood how costly it is, to certify a complex engine. At the same time, the market of aircraft piston engines is rather small. This situation is completely different from that of car engines, which are sold in millions with less demanding requirements. In addition to that, as long as leaded AVGAS can not be completely replaced, it is difficult to install electronic mixture control devices.

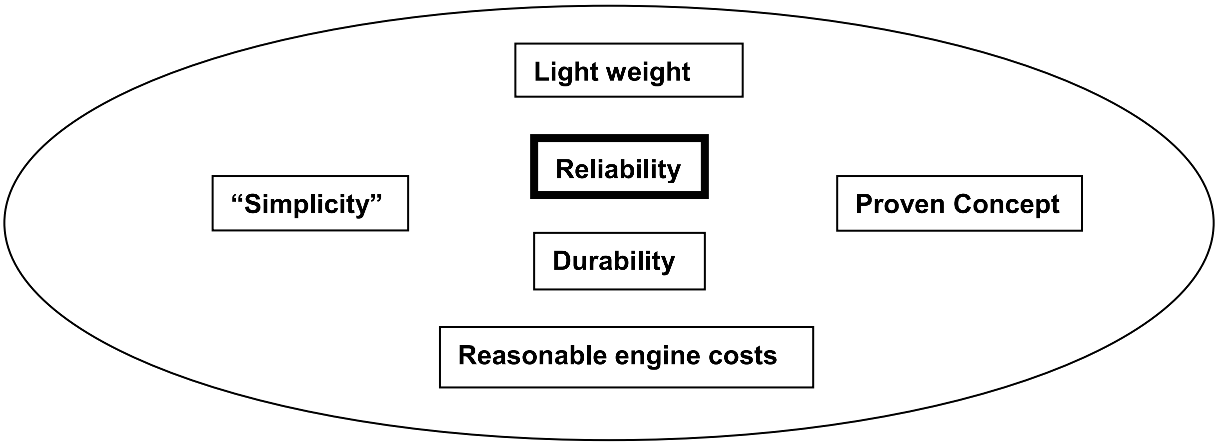


Figure 3: Basic design parameters of an “old tech” aircraft piston engine

The disadvantage of the “old tech” engine is:

- **High specific fuel consumption** (at least at high power settings)
- **High specific emissions**

Increasing flight altitude (decreasing air density) increases the fuel/air ratio (of normally aspirated engines.)

Because carburettors and fuel injectors of “old tech” aircraft piston engines can not sense air density and resulting fuel/air ratio, the **air/fuel mixture has to be adjusted manually**. Without correction, the engine runs increasingly richer, the lower the air density is, and besides waste of fuel and excessive emissions, it may finally quit.

Picture 1: Throttle (black), propeller (blue) and mixture handle (red).

In addition to the throttle, the mixer handle controls

- **Engine power**
- **Engine temperature**
- **Emissions performance**
- **Specific fuel consumption**

The mixer position plays a vital role for the resulting emissions. That is why any measurement of aircraft piston engine emissions requires proper investigation of mixer operation.

b) Rich and lean mixture definition with lambda (λ)

It is convenient to indicate actual air/fuel mixtures, obtained with a certain setting of the mixer handle at certain ambient conditions, by comparison with the stoichiometric air/fuel mixture. The term “lambda probe” is known from gasoline car engines with catalyst .The word “lambda” comes from the greek letter λ. The “lambda probe” (“λ – probe”) actually measures the oxygen content in the exhaust. The probe signal is used to control the air/fuel mixture in the injection system of a car engine to be near stoichiometric. If the air/fuel mixture is stoichiometric, λ equals 1. If there is too much fuel for the combustion (oxygen deficiency), λ is smaller than 1. If there is excess oxygen for the combustion, λ is bigger than 1.

Definition of λ :

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

$$for\ \mathbf{AVGAS:}$$

$$\lambda = \frac{Airmass : Fuelmass \qquad (measured)}{14.6 \qquad (stoichiometric)}$$

$$Note:$$

$$\lambda > 1 : \mathbf{lean\ mixture} \qquad \lambda < 1 : \mathbf{rich\ mixture}$$

“lean” = poor in fuel (excess oxygen), “rich” = fuel excess (oxygen deficiency)

Example: If a carburettor is mixing air and fuel in a ratio of 10 kg to 1 kg, then

λ = (10 : 1) : (14.6 : 1) = **10 : 14.6 = 0.68** -> The engine is running rich, with oxygen deficiency.

c) Mixer = lambda control

Figure 4 below shows lambda values in function of percent maximum continuous power for a TCM IO-550B engine. The grey shaded area shows the “full rich” lambda region for that engine. This is the lambda region, obtained at mixture “full rich” for sea level ISA conditions. At taxi power, the engine runs at about lambda = 0.70, getting richer up to 20% power. With increasing power, if the mixer is left at “full rich”, the engine runs slightly less rich (lambda = 0.78) and towards maximum continuous power again richer with lambda around 0.74.

If the mixer handle is pulled back at a certain throttle setting, for example at 45% power (as shown in figure 4, red line), **lambda increases** (in most cases while reducing the fuel pressure). **The engine runs less and less rich**. Still rich, the best power point is passed. Pulling the mixer handle further back, the stoichiometric mixture is reached, which gives the highest exhaust gas temperature (EGT peak). If that point is trespassed, the engine runs lean and the best economy point is approached. As the pilot pulls further, the engine may run rough and quit. At the maximum pulled position of the mixer handle, fuel is cut off and the engine will definitely quit.

It must be noted that during the mixer operation, the engine power changes. So, for the measurement shown below, also throttle corrections had to be made, in order to maintain constant power. FOCA chose a low power setting for this measurement to keep engine temperatures of the air cooled engine well below the limit, as the aircraft was standing. But the variations of lambda with the mixer positions are valid for all possible power settings and are not limited to the measured engine (example).

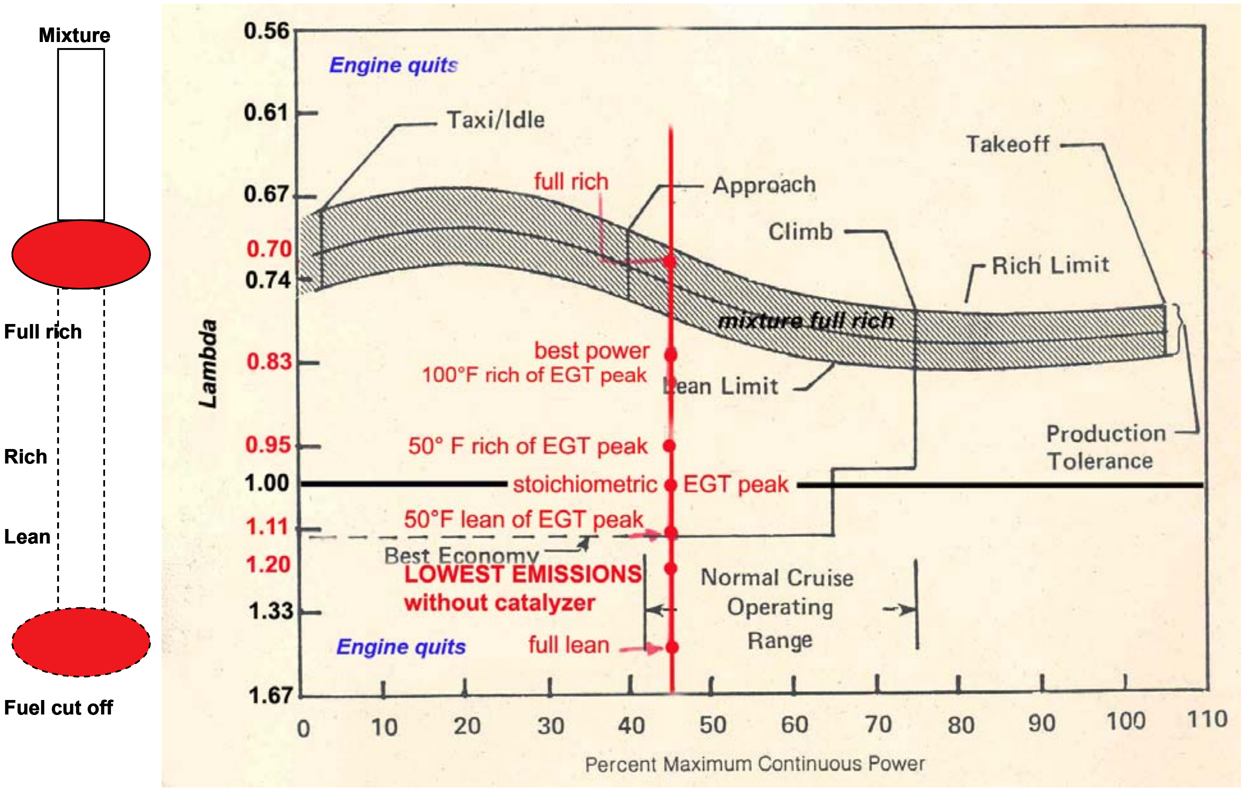


Figure 4: Lambda values in function of the mixer handle position, from full rich to lean, measured with TCM IO-550B engine at 45% maximum continuous propeller power. The measurement of lambda is described in Appendix 5. EGT = Exhaust Gas Temperature.

d) Typical values for lambda

λ = 1	EGT peak (maximum-heat mixture point)
λ = 0.85	approx. 100°F rich of EGT peak (maximum-pressure mixture point, best power)
λ = 0.95	approx. 25 - 50°F rich of EGT peak (still a rich air/fuel mixture)
λ = 1.15	approx. 50°F lean of EGT peak (lean mixture, lowest specific fuel consumption)

e) Influence of mixer settings on engine temperature and power

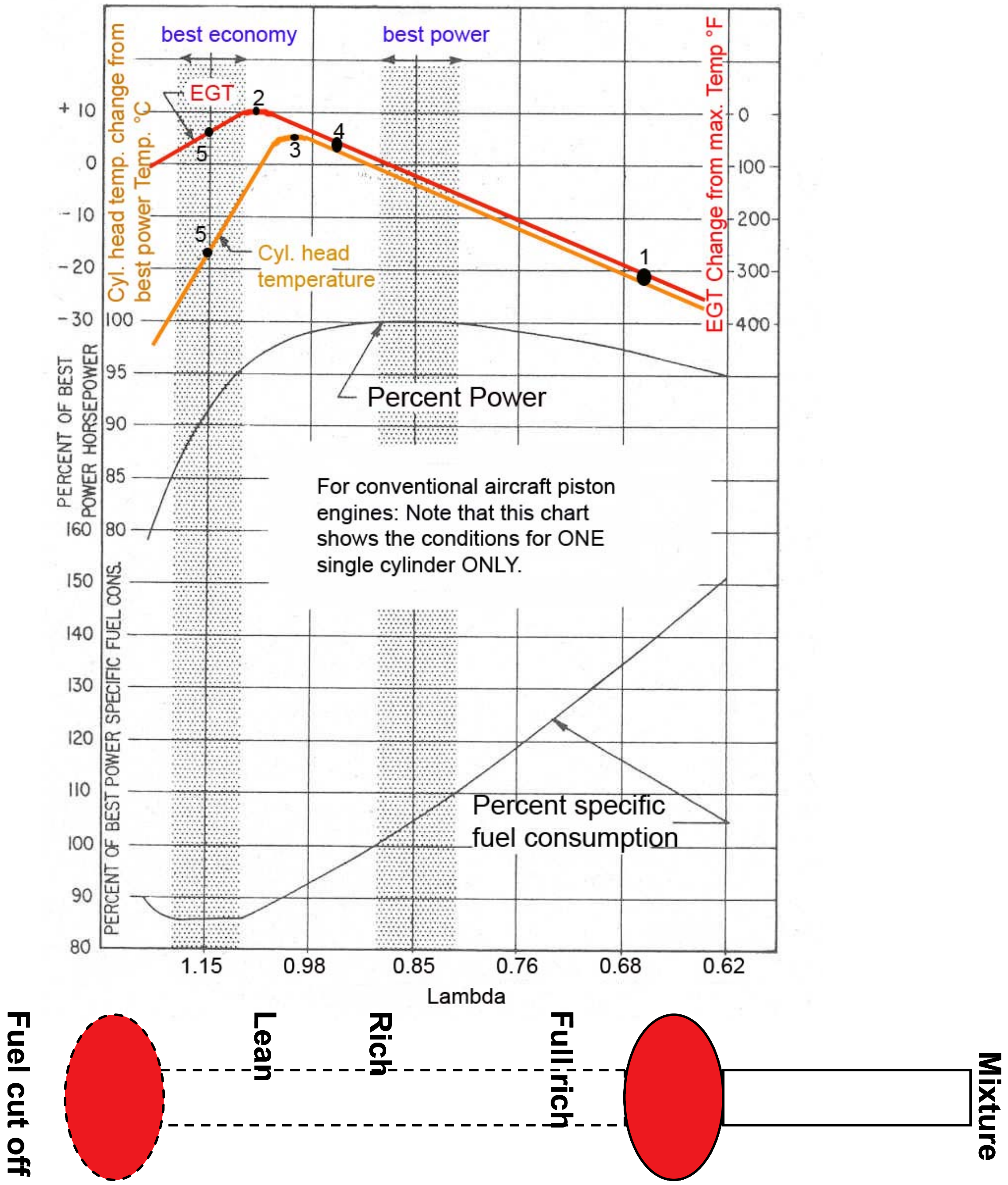


Figure 5: Influence of mixer position (lambda) on engine temperature, power and specific fuel consumption for a certain fixed throttle setting. Note: This chart has to be read for one single cylinder and not for the whole engine. 1 = full rich, 2 = peak EGT, 3 = peak CHT, 4 = standard cruise mixture, 5 = lean mixture setting. CHT = Cylinder Head Temperature. [Adapted from Textron™ Lycoming™]

Discussion:

At a fixed throttle setting, pulling the mixer from “full rich” (Position 1) first increases CHT, EGT and power and improves SFC (Specific Fuel Consumption).

At EGT around 100 °F rich of EGT peak, the best power mixture is obtained.

With further pulling the mixer, with still rich air/fuel mixture, EGT and CHT further increase. **At 50° to 25°F rich of EGT peak point (Position 4), the CHT is around the maximum (Position 3) for the given throttle setting.** Interestingly, this is the most common cruise power mixture setting for conventional “old tech” aircraft piston engines (also obtained with the “feel-the-RPM-drop-and-push-back-the-mixture-1cm-rule”[4] for fixed pitch propeller aircraft, see section k).

With further pulling the mixer, the air/fuel mixture gets stoichiometric (λ =1) and peak EGT is reached (Position 2). CHT has already fallen a little bit. Power and SFC are both decreasing.
Past peak EGT, with further pulling the mixer, the air/fuel mixture gets lean (λ > 1). EGT is decreasing, **CHT is significantly decreasing,** power is decreasing and SFC reaches the minimum value. This drop of CHT at lean conditions seems to be contradictory to practical experience of pilots and mechanics, reporting engine overheat damage, when operated at lean conditions. This will be discussed in section j).

Best power:

- Best power is obtained at a fuel/air mixture with slight oxygen deficiency (**at about 100°F below and rich of peak EGT.**
- At this condition, from incomplete combustion, an excess of combustion gases is produced (mainly CO).
- The extra gas produced increases the pressure in the cylinder which contributes more to piston movement.
- **“Best power mixture”** can be seen as the **“maximum-pressure mixture point”**
- Remember: Piston movement, not heat *per se* is what results in power.
- Best power is generally about 5 to 7% above power at “full rich” (sea level) mixture.
- At best power, the mixture is giving the most power per unit of air, not per unit of fuel.

Best economy:

- **When the mixture is leaned past EGT peak, fuel consumption drops off faster than power production, up to a certain point.**
- This point is called the best-sfc point or **best economy mixture** and **occurs at or near 50°F lean of EGT peak**

- Note: At best economy setting **the fuel consumption can be 40% lower than at “best power”!**

f) Influence of mixer settings on emissions

The FOCA instrumentation for measurement and calculation of emission factors is described in Appendix 1 and 5. Based on this instrumentation, in-flight testing with different mixer settings has been performed. In order to get emissions (in mass units), measured emissions concentrations (respectively emission factors) have to be multiplied with the fuel burn, as explained in section 2.1.1 of this report. Figure 6 below shows the exhaust CO_2 and pollutant concentrations in function of the mixer position at a fixed throttle setting. The concentrations have been measured on a TCM IO-550B engine of the aircraft HB-KIA.

Note:
1) The shapes of the curves in figure 6 are representative for **all** combustion engines (piston engines, jet engines (turbofans), etc.).
2) If on the one hand, the concentration (respectively emission factor) of a certain pollutant in the exhaust **and** the fuel burn are both high, resulting emissions are high. On the other hand, a fuel burn reduction can reduce emissions, even if the concentration (or emission factor) of a pollutant is not lowered.

Taking the concentrations shown in figure 6 and the decreasing fuel flow from right to left into account:

- At mixture “full rich”, CO is extremely high, HC high, NO_x low. Direct CO_2 is fairly low, but taking the later recombination of pollutants (mainly CO) to CO_2 into account, total CO_2 will be very high (corresponding to the very high fuel burn).

---

[4] This is a standard rule, taught in many flight schools, applied for engines without EGT probe. With fixed pitch propeller, any change in engine power will be noticed by an engine RPM change.

- At mixture “best power”, CO and HC become lower, NO_x becomes higher with increasing engine efficiency, total CO_2 high.

- At “standard cruise mixture” (rich of EGT peak), CO and HC are further reduced, **NO_x sharply increases** and total CO_2 is still high.

- At “peak EGT”, CO is very low, HC low and NO_x near the maximum value (complete combustion with NO_x “trade-off”). Total CO_2 starts to decrease.

- At “mixture lean” (around $\lambda = 1.15$), CO and HC are very low, NO_x relatively low and CO_2 is lower. The engine is at its best specific fuel consumption. Low pollutant concentrations and low fuel burn lead to lowest possible emissions. If not highest possible power is needed, then this would be the preferred mixture setting.

In conclusion, the preferred mixture setting

- **For lowest emissions**
- **For lowest fuel consumption per flight distance (in many cases)**
- **For reasonable cylinder operating temperatures (see also figure 7)**

Would be 50°F Lean of EGT peak, at λ around 1.2

It is known from AFM and engine operating manuals that this mixture setting

- **Must not be applied with most of “old technology” engines**
- **Does not work with most of “old technology” engines**

The reason and possible solutions will be discussed in section j)

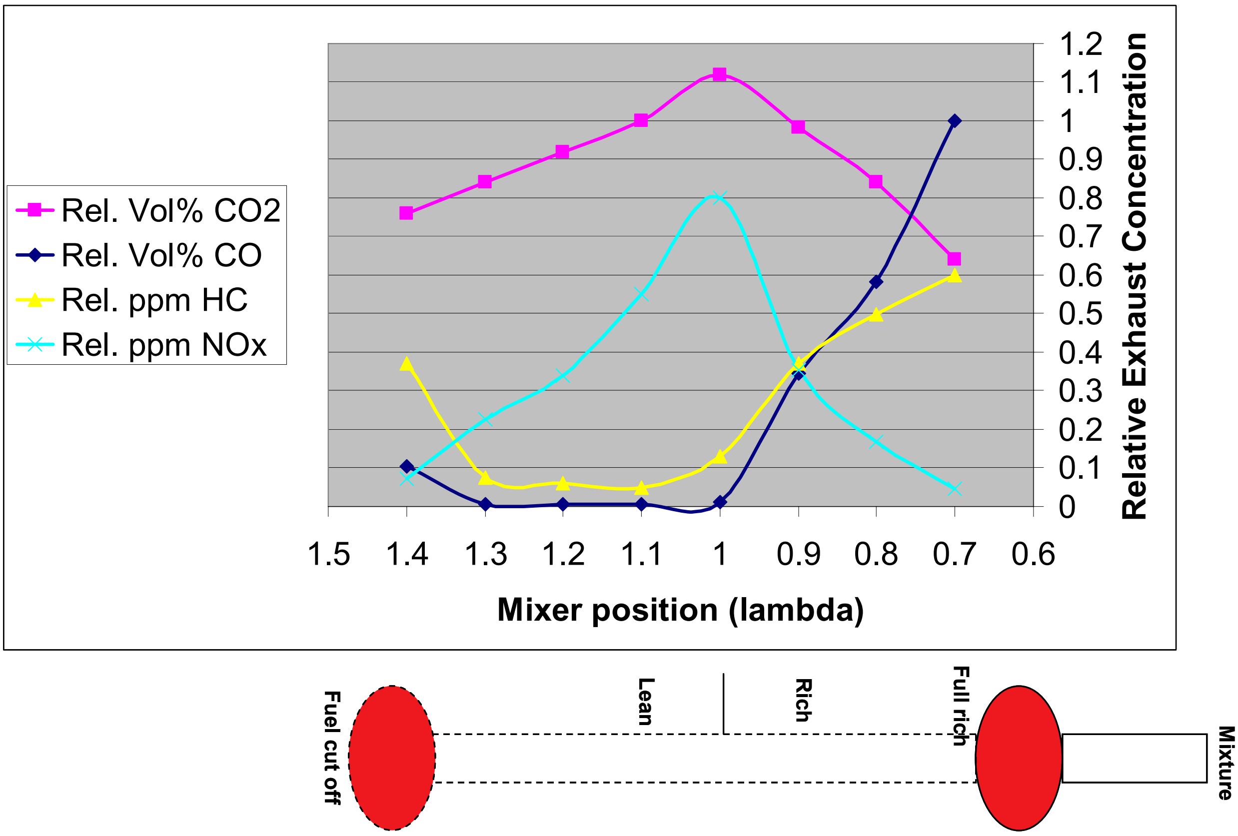


Figure 6: The figure shows the change of exhaust CO_2 and pollutant concentration in function of the mixer position (lambda). The concentrations are given in a relative scale in order to show them all in the same figure.

g) Influence of mixer settings summary

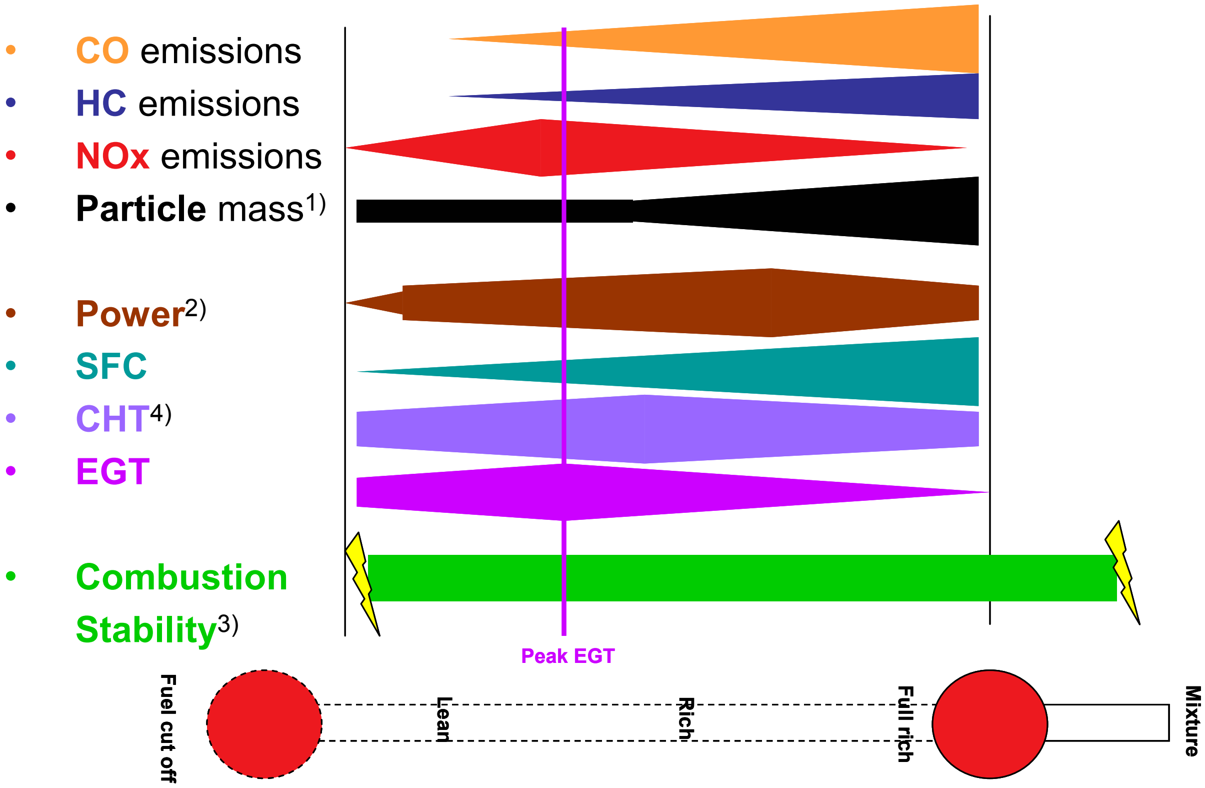


Figure 7: Influence of mixer position on emissions, power, specific fuel consumption, engine temperatures and combustion stability at a fixed throttle setting for one cylinder.

Note$^{1)}$: Particle mass (and number) emissions are generally high. Emissions are at the same magnitude as a car diesel engine without particle filter, mainly for two reasons: Extremely rich mixtures at high power (black carbon emissions) and leaded fuel, producing a lot of lead bromide particles. With unleaded AVGAS, at lean conditions, particle mass emissions would be very low (Appendix 4).
Note$^{2)}$: At lean conditions, there is a significant power drop, if the throttle is fixed. In the times of piston engine driven airliners, after lean mixture had been established in the cruise, throttle was increased to compensate for the power drop. This changed the mixture and temperature distribution again and in an iterative process, the lean mixture at the same power level as the rich mixture was established. This technique can still be used today, if the engine and instrumentation allow.
Note$^{3)}$: Combustion stability is lost, if the mixture is too rich (engine flooded with fuel) or too lean (combustion temperature too low and combustion reaction too slow). The combustion stability range is wide for rich mixtures and narrow for lean mixtures.
Note$^{4)}$: Lean mixture in the cylinder is not only beneficial for lowest emissions but also for lower CHT.
Final note: Diesel piston engines always run lean on steady-state conditions over the whole operating range.

h) Why “full rich” at high power for “old tech” engines?

- Most “old tech” aircraft piston engines are air cooled.
- **At full power, the cooling performance of air cooled engines is often too weak.** There is generally less cooling air flow in climb than in cruise or descent, because the aircraft flies slower and has a different attitude. But in climb, the engine is working at the highest load. Therefore, **additional cooling is required:** Incomplete combustion at **very** rich mixtures (lambda 0.7) reduces combustion temperatures, thus keeping cylinder head temperatures relatively low. This is **internal combustion cooling by wasting fuel.**
- **At high power settings, some excess fuel may be necessary to suppress detonation** also due to invariable ignition timing.

Note: Lean mixtures reduce combustion temperatures as well, but with greater loss of power.

i) Why “rich” near idle power?

- “Rich mixture” ensures safe engine operation in **engine transient conditions**:
  When the throttle is opened, the engine experiences a sudden inrush of air. Therefore, a transient lean mixture condition exists. The mixture must be rich enough, so that suddenly opening the throttle does not kill the engine.

- “Rich mixture” (λ around 0.7) is necessary for cold-weather starting ability.

- Air-cooled engines need a “fudge factor” for possible too lean conditions of single cylinders under worst case conditions.

Note: “Rich mixture” can be any mixture with $\lambda < 1$ (mixture rich of EGT peak). It is not necessarily the “full rich” carburettor setting.

j) Uneven distribution of mixture and temperature in “old tech” engines

From measurements and investigation, the author thinks that the primary cause for problems with running “old tech” piston engines lean in cruise is the uneven mixture and temperature distribution in the different cylinders. Figure 8 shows, what temperature and mixture distribution would be required, in order to be able to run the engine lean as a whole. All cylinders would have their temperature peaks at exactly the same mixer position. In that case, 50°F lean of EGT peak would be a clearly defined operating point for the engine, with all cylinder head temperatures lower than for the same power at rich mixture. If the cylinders run like this, the engine can be run lean at low temperature, low SFC and lowest emissions!

Note: The temperature can vary in absolute terms from cylinder to cylinder, due to differences in cylinder charge and piston compression.

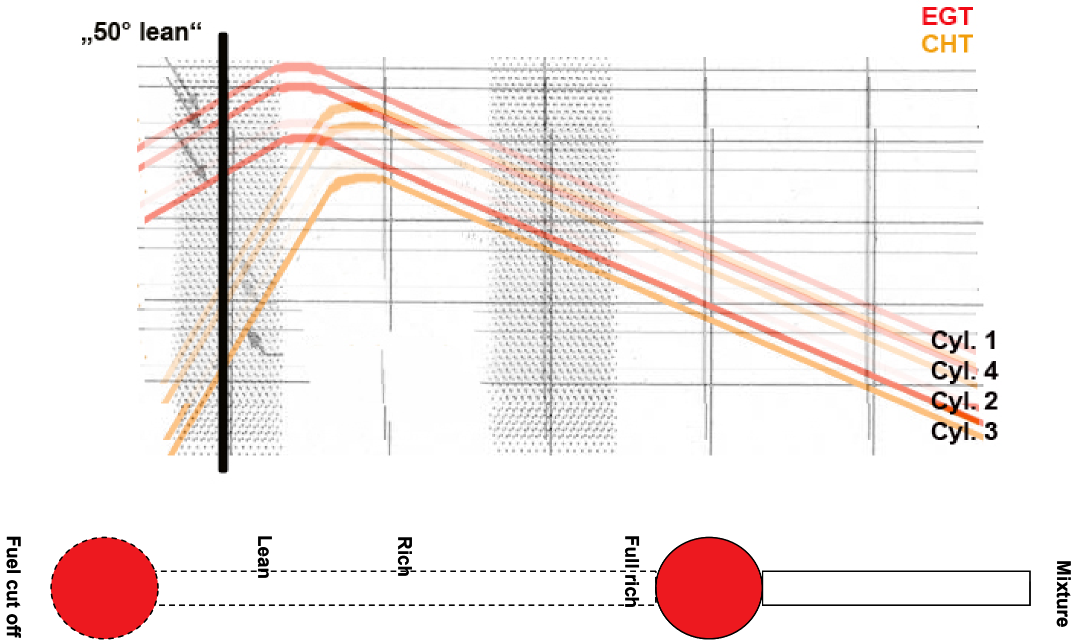
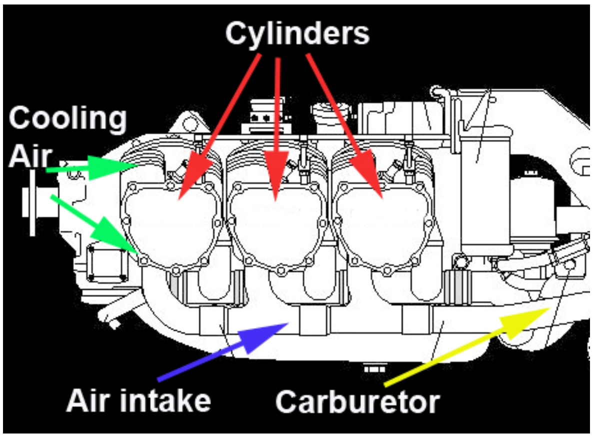


Figure 8: Requested mixture distribution in four cylinders for a certain mixture position. All four cylinders pass peak temperature at the same mixture position.

In reality, all cylinders of “old technology” aircraft piston engines normally have their individual peak temperature at different mixture settings (figure 9)! Additionally, peak temperature can vary significantly from cylinder to cylinde**r.**

Reasons for this (not to be considered complete):



- Different distances from carburettor to cylinders
- Cooling air distribution causes cooling differences.
- Fuel droplets that have to travel “uphill”, against gravity in the induction system tend to reach the nearer cylinder more easily.
- Fuel injectors: Bad nozzle tuning
- Airflow anomalies

Many intake systems are so poorly tuned that lean misfire begins in the leanest cylinder(s) well before peak EGT is reached in the richest cylinder(s).

- Recall: It takes fuel **and** air to make the fire. **The more fuel and air, generally, the hotter the flame.** This can be expressed by the term “cylinder charge”. Cylinders normally are **differently charged.**
- Also, **the more compression a cylinder has during combustion, the higher the final temperature.**
- As the mixture handle is pulled back, the richest cylinder will be the last one to reach the peak EGT (figure 9). It is well possible that this cylinder can reach the highest EGT of all cylinders:

It is possible for the richest cylinder to give the highest peak EGT.

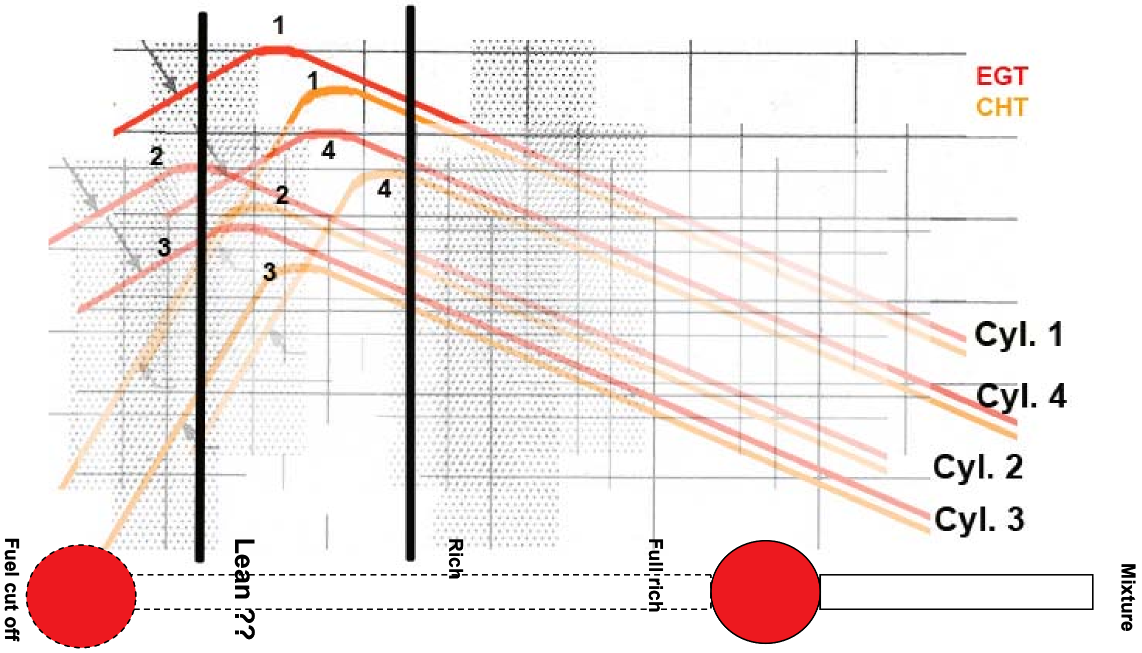


Figure 9: Uneven distribution of mixture and temperature in an “old tech” engine. At a certain mixture position, all cylinders have a different lambda and different temperatures!

In the **example** of figure 9 above, it is assumed that mixture is set to 50°F lean of EGT peak (left black line) **with reference to cylinder 1.**

The **leanest cylinder is that one, which first reaches "EGT peak"**, when the mixer is pulled. In the example, it is **cylinder no. 4**.
At the selected mixture setting (for cylinder 1), the cylinder 4 can already be so lean that it reaches the **lean misfire condition**. In practice this can sometimes be noticed by a slightly rough running engine. Of course, this condition is negative for engine life. And note in this example, no 4 is running cooler than cylinders 1 and 2.
The **richest cylinder is no 2**. All other cylinders have passed EGT peak and this one just reached it. The coolest cylinder, in absolute terms, is cylinder no 3, despite the fact, that it is running near EGT peak.
The **hottest cylinder**, in absolute terms, is **cylinder no 1**. This one has e.g. the best charge and/or compression of all four cylinders.

Do not confuse "leanest" and "hottest" cylinder.

- The **leanest cylinder is that one, which first reaches "EGT peak"**, when the mixer is pulled back

- The **richest cylinder is that one, which last reaches "EGT peak",** when the mixer is pulled back

- The **hottest cylinder**, can be the richest e.g. if combined with best charge and/or compression.

Conclusions

- **If** all cylinders together are running **lean, temperatures can be lower** than with rich of EGT peak or best power point.
- At lean mixture, the combustion process is slowed down and the combustion pressure on the piston and on the cylinder head is distributed over a longer period of time, **reducing material stress**.
- At lean mixture**,** the engine reaches the **lowest specific fuel** consumption and the **lowest possible emissions.**
- Rich mixtures have a much larger bandwidth of lambda for engine operations than lean mixtures (figure 7). Lean mixtures require better mixture control.
- Altitude changes (e.g. descent) are sometimes less critical with rich mixtures.
- For engine transient power conditions, rich mixtures are needed.

- Most **"old tech"** engines have a higher risk of one ore more cylinder(s) being at high internal temperatures, without noticing it. Therefore such engines **must not** be run lean.
- Going very lean with "old tech" engines can cause one ore more cylinder(s) to reach the lean misfire condition. Therefore such engines must not be run lean.

Picture 2: Running lean for thousands of hours is nothing new: The Wright R-3350 engine (DC7 etc.) has been operated on lean mixture during cruise (historical example). As explained above, lean mixture requires better mixture control. In former times this was assured e.g. by symmetrical engine design (equal distances for air intake, symmetrical cooling air flow etc) and a fuel flow and power based leaning technique. A flight engineer was looking after the engines all the time during flight.

In a modernized piston engine aircraft, lean operation is possible by use of a fuel injection system with carefully tuned injection nozzles and/or with FADEC, controlling each cylinder separately.

k) Investigated manual mixture setting procedures

Setting the air/fuel mixture without EGT: Many “old tech” piston engine aircraft with fixed pitch propeller do not have any exhaust gas temperature instrumentation. Therefore no information about exhaust gas (and internal combustion) temperatures is available. To handle the mixer of such aircraft, pilots are often instructed to adjust the mixture with a "rule of thumb": At a fixed throttle setting, the pilot pulls the mixture lever slowly back 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 forward (about 1 cm) and the **engine is running slightly rich**. After a while, the pilot checks cylinder head and oil temperature.

Rule for fixed pitch propeller engines without EGT for cruise below 75% propeller power: “feel-the-RPM-drop-and-push-back-the-mixture-1cm”. This mixture adjustment for cruise should be done at **every** altitude with engine propeller power not exceeding 75% (refer to AFM).

The effect of the rule was studied with FOCA aircraft HB-EYS (In-flight measurements with application of the above rule are documented in Appendix 2, sections 1 and 3). The measurement system showed the resulting lambda for a certain mixer setting on a small TV-monitor. In doing so, during the flight, the effect of a certain mixer setting on lambda and emissions could be immediately observed.

With a fixed pitch propeller engine, without EGT and the aircraft at constant climb angle, best power mixture is obtained with the mixer position giving the highest engine RPM. Usually, from this mixer position, the mixture is slightly enriched for better engine cooling. For a normally aspirated engine, this adjustment should usually be done in climb above 5000 ft density altitude (refer to AFM).

General findings for the rule:

- If the pilot applies the rule slowly and tries to sense possible engine vibrations[5] with feet on the floor, the resulting lambda is around 0.93 to 0.95 which corresponds quite nicely to a 50°F rich of EGT peak setting.
- With increasing density altitude, the “rule of thumb” leads to increasingly richer mixture.
- Adjusting the mixture in static aircraft condition, e.g. prior to take-off at high density altitude (mix for highest static RPM (best power) and enrich) leads to a richer mixture than applying the rule during flight.
- Strictly speaking, the rule is only applicable for cruise but can be used to a lesser extend to climb. For descent, at a fixed mixer position, the mixture gets leaner, and eventually, the engine may quit. Therefore many AFM call for mixture “full rich” in the descent, which is very far from optimum for the engine (see 2.3.1 c).

Setting the air/fuel mixture with EGT:
The standard setting is often 25 to 50°F rich of EGT peak during cruise.

Some engines may – according to AFM – run lean of EGT peak. In fact, the engine installed on HB-KIA, does not seem to have an extremely uneven mixture distribution and it is not surprising as the AFM describes lean of peak operation. But in spite of that, during an in-flight measurement at lean conditions with HB-KIA, one or more cylinders were clearly running hot (high NO_x emissions) without being noticed by cockpit instrumentation (see previous section j and Appendix 2, section 5)!

General findings for EGT mixture setting:

- Proper mixture adjustment with EGT needs time (5 minutes easily). The temperature probe (which is a thermocouple in many cases) is reacting slowly and the engine needs time to stabilize temperature at a certain throttle/mixer setting.
- Most EGT leaning techniques start with finding EGT peak. This means that at least the measured cylinder has to run on EGT peak for a certain time, which may in fact not be beneficial for cylinder life, if by chance, this is the hottest cylinder.

---

[5] Additional vibrations can be caused, if one or more cylinders are in a very different mixture state compared to others, as shown in section j) of this report. A mixer position with increased engine vibrations should be avoided.

- A single probe for EGT (and CHT!) on a four or six cylinder “old tech” piston engine is considered not sufficient for proper mixture adjustment (see previous section j). Certified instruments, showing all cylinders and exhaust temperatures simultaneously, would be preferred.

General findings for all “old tech” engines:

- For every change of power configuration and altitude (air density change), the mixer position should be changed.
- Applying “carburettor heat” at a fixed throttle position enriches the mixture. The hotter air in the intake is less dense and this has the same effect as flying higher. Therefore, the mixture should be adjusted to less rich conditions after applying carburettor heat.
- Mixer adjustments, if done properly during flight, can consume a considerable amount of pilot concentration and can distract considerably from primary tasks (fly the aircraft, look out, etc.), especially, if pilots are not well trained.

l) Mixture adjustment technique with fuel flow

- Whenever possible, install (certified) EGT and CHT on every cylinder exhaust and cylinder head.
- Whenever possible, install a (certified) fuel flow transducer in the fuel line(s) and a corresponding fuel flow instrument.

Fuel flow method:

Fuel flow method:

This method is based on setting fuel flow as a function of set power (MP and RPM) and of altitude according to tables of graphs.

The author suggests using existing cruise performance tables and graphs in aircraft AFM as a starting point to set fuel flow for certain power and ambient conditions. However, practical experience showed that individual differences in engine and cockpit gauge indications between one and another aircraft of the same type can exist. It may therefore be advisable to generate a table, which is related to the actual individual aircraft. The fuel flow values for such a table can be obtained with the following simplified approach:

- Choose a day with moderate ambient temperatures on ground and with no significant temperature inversion. Record the indicated fuel flow for defined power settings at different flight pressure altitudes[6], with the engine perfectly leaned according AFM. Use, if possible, EGT for all individual cylinders

.

- Once this table is ready, the engine is leaned at a defined throttle (and RPM setting) **based on the fuel flow.** Example for a variable pitch propeller aircraft:

For 65% power at 5500 ft PA the setting may be 22.5 InHg and 2350 RPM,
The corresponding tabulated fuel flow for 50°F rich of EGT peak is 9.5 GAL
➔ Pull back the mixer handle to read 9.5 GAL on the fuel flow instrument instantly
➔ Check EGT (instantly and after a couple of minutes) and CHT (after a couple of minutes).
Note: Checking EGT is necessary to fine tune mixture, especially if flying at outside air temperatures which differ strongly from the temperatures, when the fuel flow table was generated.

Setting the mixture by fuel flow goes very fast, does not distract too much from primary tasks. It may also be an advantage for engine life: There is no need to go to peak EGT values every time leaning starts.

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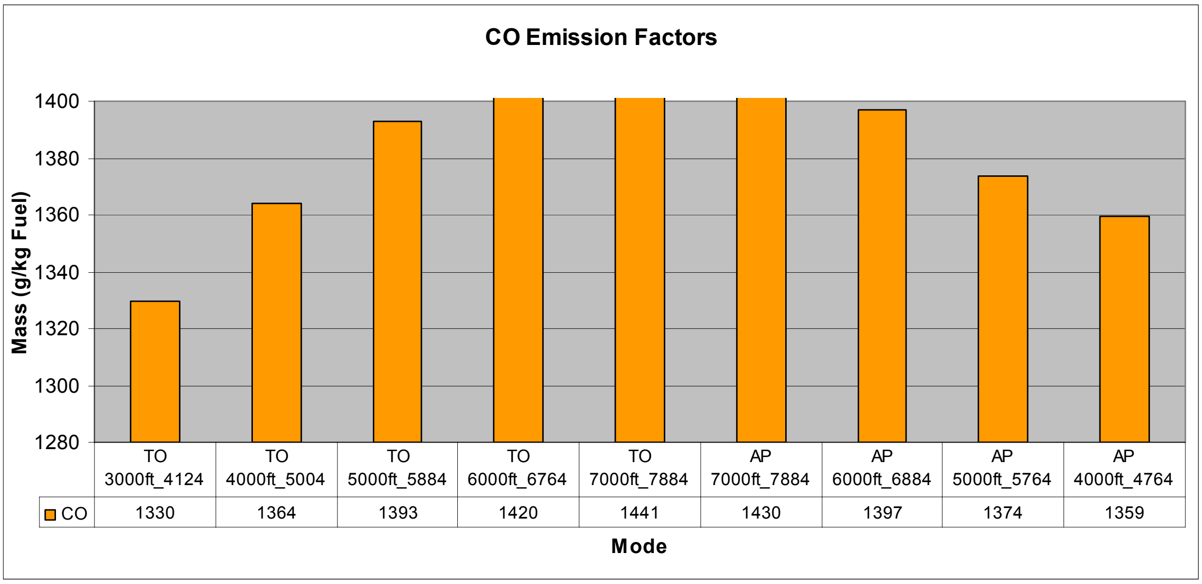
[6] Strictly speaking, the engine should be leaned according to the prevailing air density and the aircraft should be flown at defined density altitudes. For practical reasons, temperature deviations from ISA conditions are neglected at this stage. EGT check after setting the fuel flow takes possible variations into account.

2.2.3 Typical emission factors and magnitude of emissions

a) Pollutants of “old tech” engines during landing and take-off cycle (“full rich” mixture)

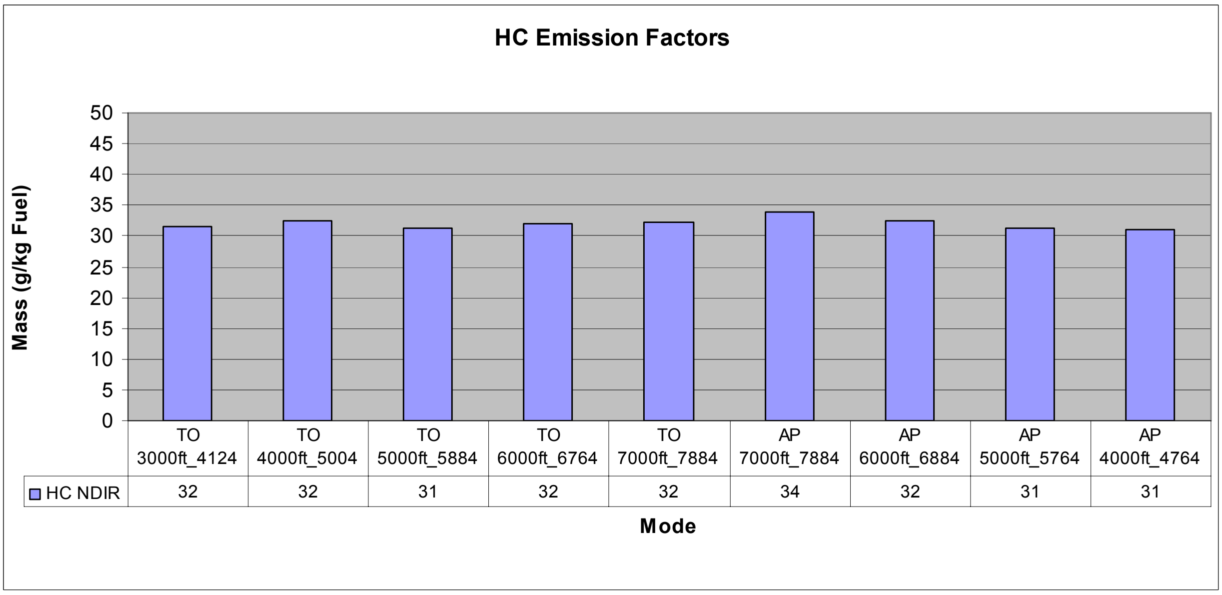
In most cases, “full rich” is set **during the whole landing and take-off cycle (LTO)**. Because of oxygen deficiency, the fuel combustion is very incomplete with a lot of CO, HC and particle emissions.



	TO 3000ft_4124	TO 4000ft_5004	TO 5000ft_5884	TO 6000ft_6764	TO 7000ft_7884	AP 7000ft_7884	AP 6000ft_6884	AP 5000ft_5764	AP 4000ft_4764
🟧 CO	1330	1364	1393	1420	1441	1430	1397	1374	1359

Figure 10: Example of CO emission factors, measured in-flight at full throttle between 3000 and 7000ft pressure altitude and at approach power (about 45% of maximum propeller power) between 7000 and 4000ft pressure altitude. The second number to the right of the pressure altitude indicates the density altitude. The measurements were made with HB-KEZ and a Lyc IO-360 engine, which has an extremely rich “full rich” mixture. It can also be seen from the figure that increasing altitude leads to higher CO emission factors, which means that the engine gets increasingly richer, if it is not leaned.

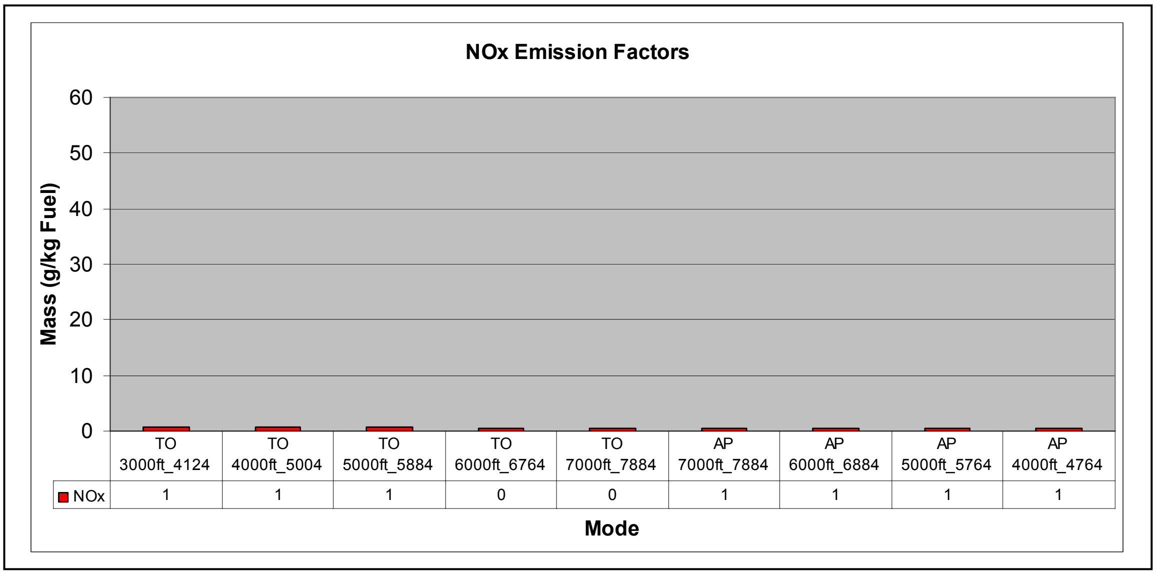
Generally, “old tech” engines will produce **between 600 and 1200 g CO per kg fuel** under “full rich” conditions. Note: The CO emission factor of a jet engine is generally a factor of 1000 lower!



	TO 3000ft_4124	TO 4000ft_5004	TO 5000ft_5884	TO 6000ft_6764	TO 7000ft_7884	AP 7000ft_7884	AP 6000ft_6884	AP 5000ft_5764	AP 4000ft_4764
🟪 HC NDIR	32	32	31	32	32	34	32	31	31

Figure 11: Example of HC emission factors, measured in-flight at full throttle between 3000 and 7000ft pressure altitude and at approach power (about 45% of maximum propeller power) between 7000 and 4000ft pressure altitude. (Example HB-KEZ)

Generally, “old tech” engines will produce **between 12 and 30 g HC per kg fuel** under “full rich” conditions. Note: The HC emission factor for a jet engine at high power is around zero! (Complete combustion). Only at taxi/idle it will be higher and be of the same magnitude.



	TO 3000ft_4124	TO 4000ft_5004	TO 5000ft_5884	TO 6000ft_6764	TO 7000ft_7884	AP 7000ft_7884	AP 6000ft_6884	AP 5000ft_5764	AP 4000ft_4764
🟥 NOx	1	1	1	0	0	1	1	1	1

Figure 12: Example of NOx emission factors, measured in-flight at full throttle between 3000 and 7000ft pressure altitude and at approach power (about 45% of maximum propeller power) between 7000 and 4000ft pressure altitude. (Example HB-KEZ)

Generally, “old tech” engines will produce **only a few g NOx per kg fuel** under “full rich” conditions. Note: The NO_x emission factor of current jet engines at high power is in the order of 20 to 30 g / kg fuel, because of high efficiency and slightly rich mixture at the fuel nozzle. At taxi/idle the NO_x emission factor is down at a few g / kg fuel.

Non-volatile particles and soot emission factors:

Figure 13 shows a typical example of a particle number - size distribution from an aircraft gasoline piston engine, running on AVGAS 100LL (leaded fuel) under full rich air/fuel ratio at approach setting (HB-KEZ).

For the different power modes,

- the **mean particle diameter**[7] varied between **49 and 108 nm** and
- the total particle **concentration** varied between 5.7 to 8.6 times **10 million particles per cubic centimetre.**

With an assumed specific density for soot of 1.2,

- the estimated particle **mass concentration** was around **10 000** $\mu g/m^3$ (**micro grams per cubic meter**).

Generally, particle emissions of aircraft gasoline “old tech” piston engines, running on leaded AVGAS at “full rich” conditions, seem to be comparable to diesel car engine particle emissions (see figure 14). Details of these measurements are given in Appendix 4.

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[7] Most of the particles are ultra fine: 100 nm = 0.00001 mm

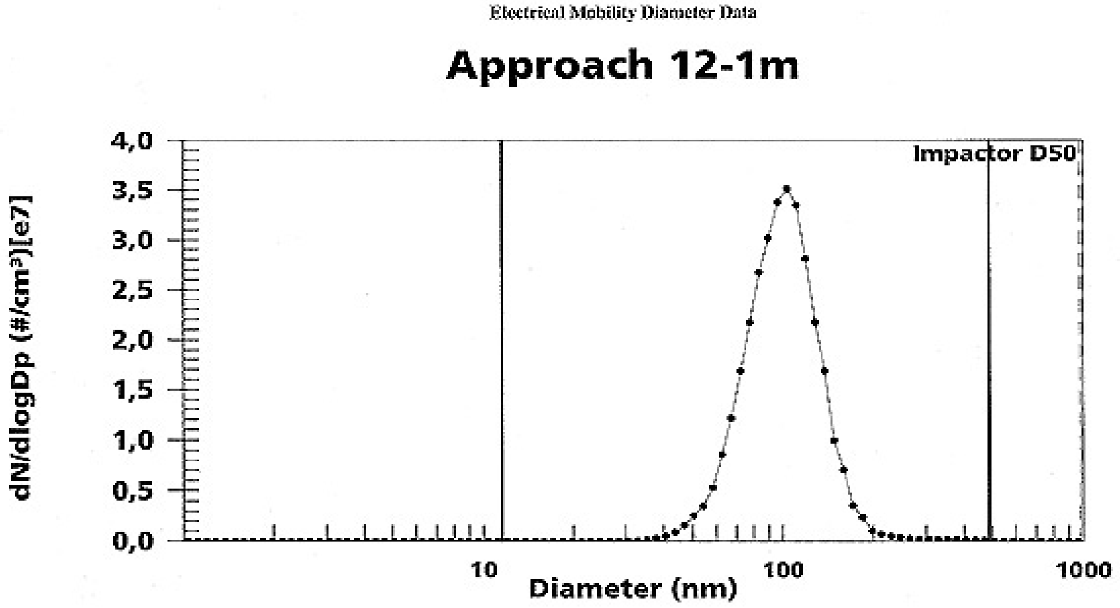

Figure 13: Number-size distribution of HB-KEZ engine at approach mode. The mean particle diameter is around 100 nm and the total concentration is in the order of 10 million particles per cubic centimetre (cm^3).

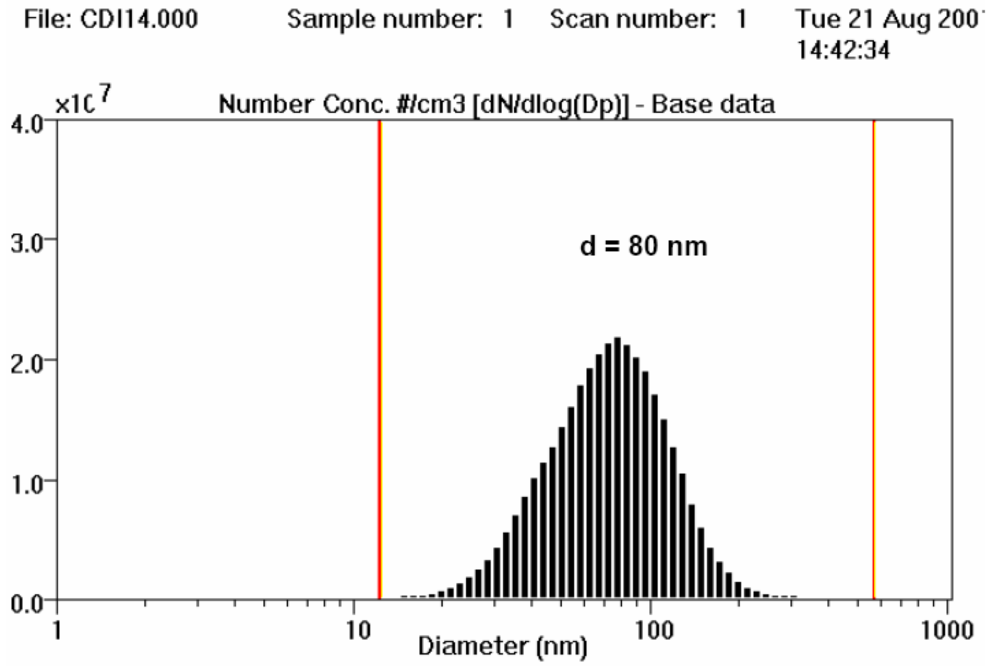

Figure 14: Number-size distribution of a typical diesel passenger car (CDI) at 2000 RPM (increased idle) for comparison to the HB-KEZ measurements [C. Wahl/DLR 2004l]

Based on the measurement of two typical “old tech” aircraft gasoline piston engines (150 and 180HP) the following soot emission factors are suggested (Appendix 4):

	Soot Emission Factors (mg soot / kg fuel)			
Fuel	TA	AP	CL	TO
AVGAS 100LL (leaded)	50	40	70	100
AVGAS 91/96UL (unleaded)	1	1	2	3

b) Pollutants during cruise (at or near “peak EGT”)

In most cases, a mixture setting near peak EGT is chosen for **cruise conditions**. At peak EGT, the combustion is complete and theoretically, no partially burned fuel products should be produced. In reality, because of inhomogeneous mixture and temperature distribution in a cylinder, there are still **small amounts of CO** (carbon monoxide) and **HC** (hydrocarbons) in the exhaust gas.

Due to maximum combustion heat and short reaction time at peak EGT, the nitrogen from air (N_2) reacts with the oxygen from air (O_2) in the combustion chamber to form **NO (and to a lesser extent NO_2),** called **nitrogen oxides NO_x,** as explained in section 2.2.2 f). This is the classical “fuel burn – NO_x“ trade-off: Increased engine efficiency (less fuel burn) can lead to higher NO_x emissions. The trade-off is normally discussed in the context of aircraft turbofan engines, but of course it exists also for piston engines, if they are run more efficiently. Automotive engines have exhaust after treatment systems with catalysts to reduce NO_x. For aircraft gasoline piston engines, this would also be an option – if the fuel was not leaded.

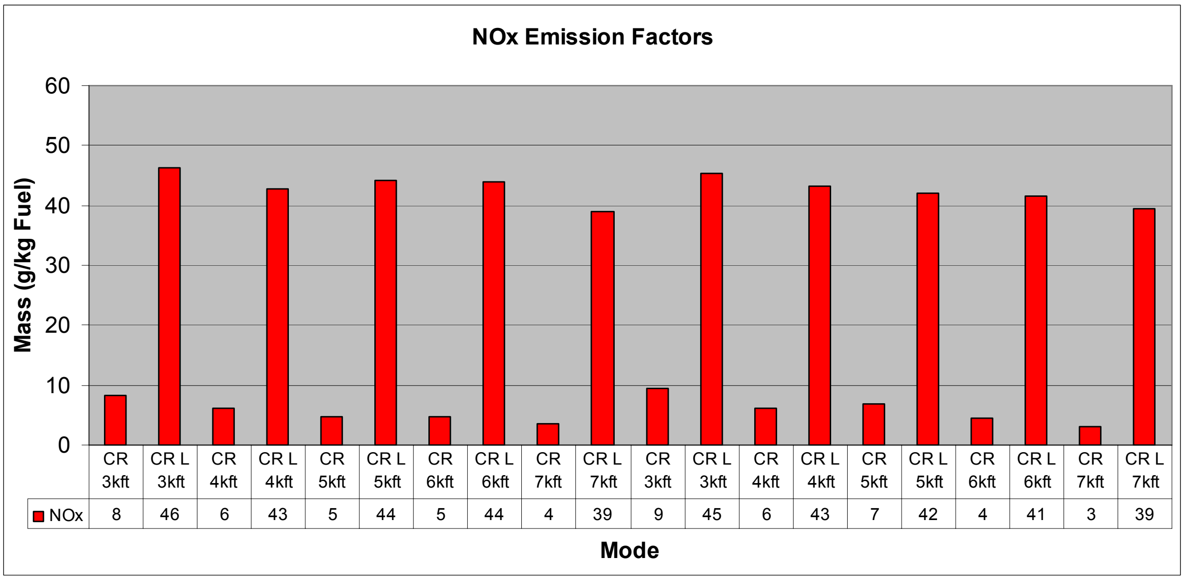

Figure 15: Example of NO_x emission factors, measured in-flight during cruise between 3000 and 7000ft pressure altitude and at about 65% of maximum propeller power. The measurements have been repeated between cruise “full rich” (indicated with CR, low NO_x) and cruise peak EGT mixture (indicated with CR L, high NO_x). At “full rich”, NO_x emission factors decrease with increasing altitude. The measurement also shows reproducibility of the results (Example HB-EYS).

Generally, “old tech” engines will produce between 30 and 40 g NO_x per kg fuel near “EGT peak” conditions during cruise.

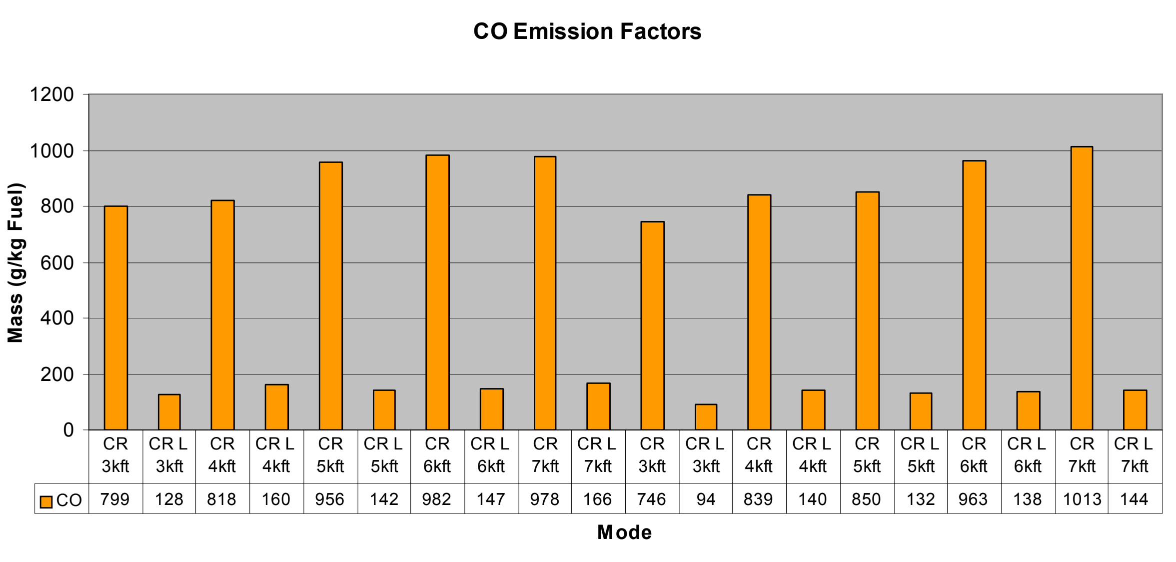

Figure 16: Example of CO emission factors, measured in-flight during cruise between 3000 and 7000ft pressure altitude and at about 65% of maximum propeller power. The measurements have been repeated during cruise “full rich” (indicated with CR, low NO_x) and cruise peak EGT mixture (indicated with CR L, high NO_x). At “full rich”, CO emission factors increase with increasing altitude. The measurement also shows reproducibility of the results (Example HB-EYS).

Generally, “old tech” engines will produce around 200 g CO per kg fuel near “EGT peak” conditions during cruise.

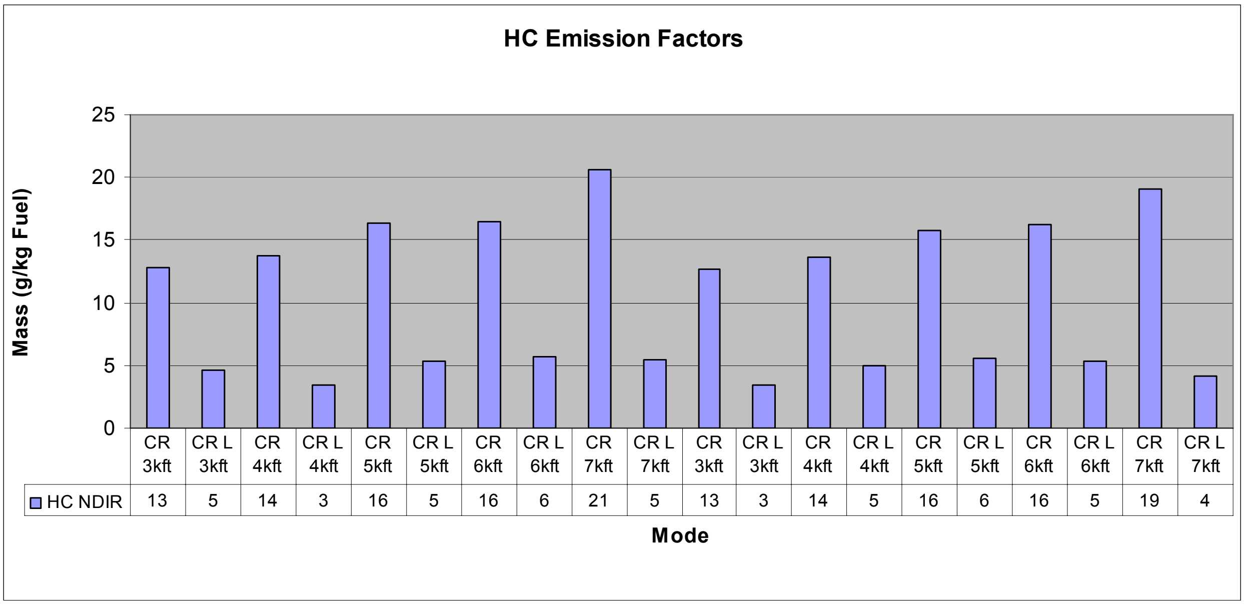

Figure 17: Example of HC emission factors, measured in-flight during cruise between 3000 and 7000ft pressure altitude and at about 65% of maximum propeller power. The measurements have been repeated during cruise “full rich” (indicated with CR, low NO_x) and cruise peak EGT mixture (indicated with CR L, high NO_x). At “full rich”, HC emission factors increase with increasing altitude. The measurement also shows reproducibility of the results (Example HB-EYS).

Generally, “old tech” engines will produce between 6 and 12 g HC per kg fuel near “EGT peak” conditions during cruise.

Based on the measurement of two typical “old tech” aircraft gasoline piston engines (150 and 180HP) the following soot emission factors for cruise are suggested (Appendix 4):

Soot Emission Factors (mg soot / kg fuel)	
Fuel	CR
AVGAS 100LL (leaded)	40
AVGAS 91/96UL (unleaded)	1

c) Emissions for aerodrome circuits (“old tech” engines)

A circuit is a flight pattern that is flown at an airport e.g. for aircraft doing a sequence of landings for training purposes. A high percentage of piston engine aircraft are flying in aerodrome circuit patterns, because those aircraft are often used for pilot basic training and education.

For a typical 4 seat piston engine aircraft, circuit emissions for low level circuits (1500 ft PA) and high level circuits (5600ft PA, with mixture adjustment) are given in tables 1 and 2 (from Appendix 2, section 3 g). For a high performance single engine piston aircraft, suggested mean values are given in table 3.

Normally, for CO_2 emissions calculation, complete combustion is assumed, which means to multiply the kg fuel by 3.17 to get kg of CO_2 (section 2.2.1.c). As shown before, “old tech” piston engine have an extremely incomplete combustion during circuit flying. In Tables 1 and 2, this has been taken into account with a lower value for CO_2 emissions. So it is possible to sum up all emissions of different species to get the total emissions.

However, in emissions inventory work, the general principle is to calculate the mass of CO_2 (and H_2O) **as if they were resulting from complete combustion.** The **pollutants** have to be seen as **part of CO_2 and H_2O mass emissions.** This makes a certain sense in the context of climate impact assessments, because most CO and HC pollutants will later be transformed in CO_2 and H_2O after being released into the atmosphere.

Tables 1 and 2: Circuit emissions for a **typical 4 seat single engine piston aircraft (180HP)**. (Appendix 2, section 3 g). Please note: CO_2 emissions have been indicated here as measured directly in the exhaust gas (see text above for explanation).

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

Table 3: Circuit emissions for a **typical high performance single engine piston aircraft (300HP)**, fitted with automatic mixture adjustment (best power mixture). (Appendix 2, section 5 h). Please note: CO_2 emissions have been indicated here as measured directly in the exhaust gas (see text above for explanation).

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

d) Emissions for landing and take-off cycle

Emissions in the landing and take-off cycle (LTO) are based on the suggestions of section 2.1.2 and on the data contained in the individual FOCA engine data sheets.

Table 4: LTO fuel and emissions for a typical **microlight aircraft (Switzerland: Ecolight)**, if fitted with a four stroke engine. Note: No lead and no bromide emissions. The soot value is estimated.

ECOLIGHT (MICROLIGHT 4 - STROKE)	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
LTO TOTAL FUEL (kg) or EMISSIONS (g)	1.4	47	940	33	0.002	0.0

Table 5: LTO fuel and emissions for a typical **flying school single engine piston aircraft (150HP)**. The soot value is estimated.

SINGLE EGINE PISTON AIRCRAFT 150HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
LTO TOTAL FUEL (kg) or EMISSIONS (g)	3.2	47	2397	28	0.17	2.5

Table 6: LTO fuel and emissions for a turbo **diesel single engine piston aircraft (135HP)**. The soot value is estimated.

SINGLE ENGINE TURBO DIESEL 135HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
LTO TOTAL FUEL (kg) or EMISSIONS (g)	1.6	5	19	30	0.09	0.0

Table 7: LTO fuel and emissions for a typical **4 seat single engine piston aircraft (180HP)**. The soot value is estimated.

SINGLE EGINE PISTON AIRCRAFT 180HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
LTO TOTAL FUEL (kg) or EMISSIONS (g)	3.9	71	3930	12	0.20	3.1

Table 8: LTO fuel and emissions for a **single engine piston high performance aircraft (300HP)**. The soot value is estimated.

SINGLE EGINE PISTON AIRCRAFT 300HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
LTO TOTAL FUEL (kg) or EMISSIONS (g)	7.5	174	7327	24	0.39	6.0

Table 9: LTO fuel and emissions for a **twin engine piston high performance aircraft (2 x 325HP)**. The soot value is estimated.

TWIN EGINE PISTON AIRCRAFT 2 X 325HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
LTO TOTAL FUEL (kg) or EMISSIONS (g)	21.6	244	19330	46	1.12	17.2

e) Emissions for cruise

The tables below show fuel consumption (in kg) and gaseous pollutants mass emissions for cruise during one hour flight. The cruise setting has been chosen according to engine technology as described in Appendix 3.

Table 10: One hour fuel and emissions for a typical **microlight aircraft (Switzerland: Ecolight)**, if fitted with a four stroke engine. Note: No lead and no bromide emissions. The soot value is estimated.

Ecolight Aircraft (Microlight 4-Stroke)	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
CRUISE 1HOUR FUEL (kg) or EMISSIONS (g)	8.7	67	1090	243	0.009	0.0

Table 11: One hour fuel and emissions for a typical **flying school single engine piston aircraft (150HP)**. The soot value is estimated.

SINGLE ENGINE PISTON AIRCRAFT 150HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
CRUISE 1HOUR FUEL (kg) or EMISSIONS (g)	20.9	243	8557	772	1.09	16.6

Table 12: One hour fuel and emissions for a turbodiesel **single engine piston aircraft (135HP)**. The soot value is estimated.

SINGLE ENGINE TURBO DIESEL 135HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
CRUISE 1HOUR FUEL (kg) or EMISSIONS (g)	14.1	22	91	373	0.8	0.0

Table 13: One hour fuel and emissions for a typical **4 seat single engine piston aircraft (180HP)**. The soot value is estimated.

SINGLE ENGINE PISTON AIRCRAFT 180HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
CRUISE 1HOUR FUEL (kg) or EMISSIONS (g)	23.0	197	6743	903	1.20	18.3

Table 14: One hour fuel and emissions for a **single engine piston high performance aircraft (300HP)**. The soot value is estimated.

SINGLE ENGINE PISTON AIRCRAFT 300HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
CRUISE 1HOUR FUEL (kg) or EMISSIONS (g)	49.7	268	23490	1149	2.58	39.5

Table 15: One hour fuel and emissions for a **twin engine piston high performance aircraft (2 x 325HP)**. The soot value is estimated.

TWIN ENGINE PISTON AIRCRAFT 2 x 325HP	Fuel (kg)	HC (g)	CO (g)	NOx (g)	Soot (g)	Lead (g)
CRUISE 1HOUR FUEL (kg) or EMISSIONS (g)	106.0	766	60088	1648	5.51	84.2

f) Emissions of modern turbo diesel engines – a comparison

By design, diesel engines are lean burn engines, working with a lot of excess air (= a lot of excess oxygen)! The TAE-125-01 Centurion 1.7 engine, which FOCA has measured, had a minimal λ of at least 1.3. In every continuous operating condition (take-off, climb, cruise, approach), the FADEC controlled engine is running lean. With section 2.2.2 f) it is directly understandable, what this means in terms of gaseous emissions: **Emissions are minimal in comparison to "old tech" gasoline piston**

engines of the same power. Depending on the operating conditions, the emissions of the diesel can be a factor of 100 lower, compared to "old tech"! (See tables 6 and 12, figures 18 and 19).

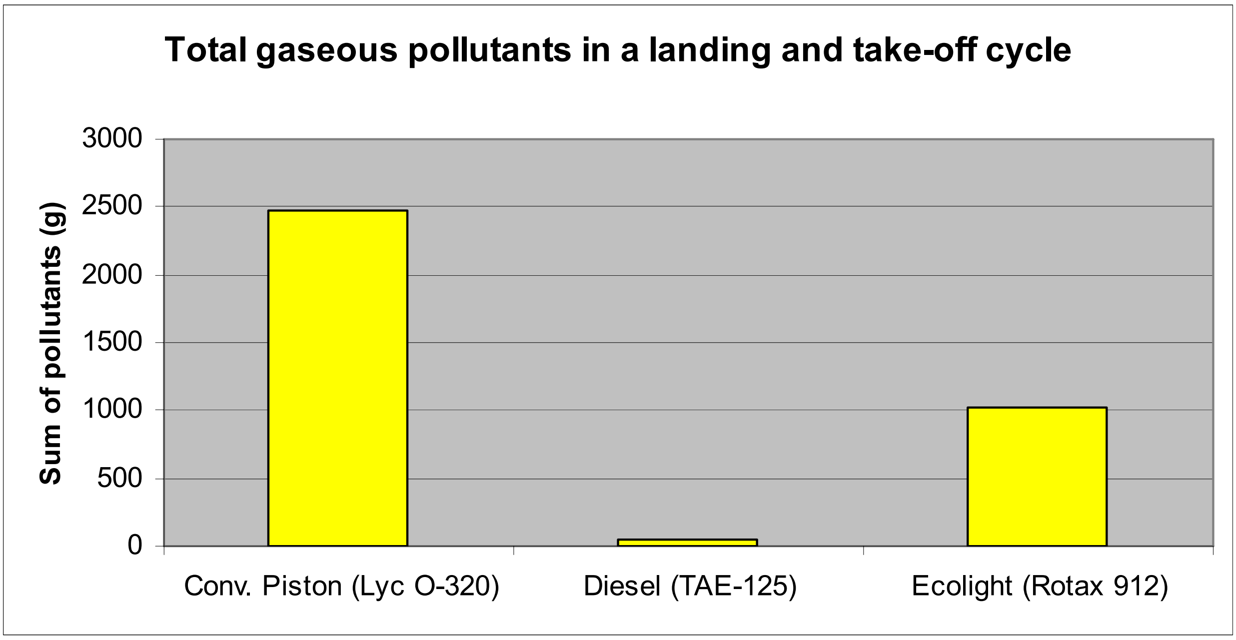

Figure 18: Sum of gaseous emissions during a landing and take-off cycle, based on FOCA measurements, for a conventional "old tech", a turbo diesel of similar power and a four stroke microlight engine (Swiss microlight = Ecolight).

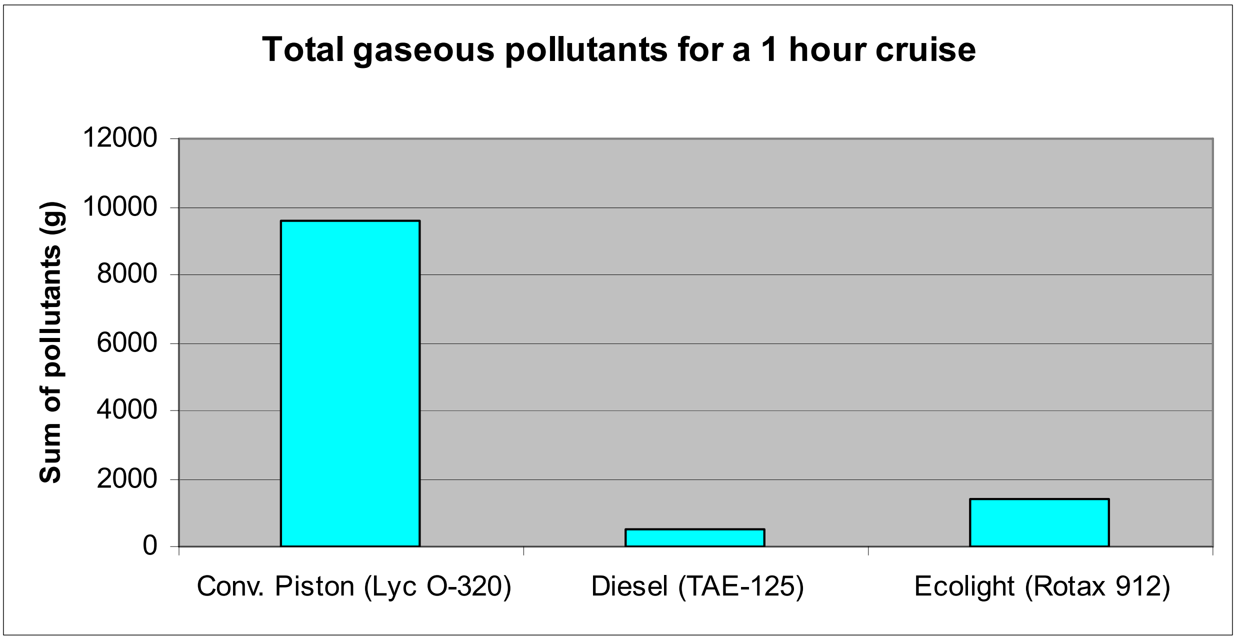

Figure 19: Sum of gaseous emissions during one hour cruise, based on FOCA measurements, for a conventional "old tech", a turbodiesel of similar power and a four stroke microlight engine (Swiss microlight = Ecolight).

Particle Emissions: At approach (full rich), the mean diameter of emitted particles from an "old tech" engine (an aviation gasoline engine) was around 100 nm and the concentration around 10 million non-volatile particles in 1 cubic-centimetre (cm^3) of exhaust air. This is very similar to a diesel engine without particle filter (see section 2.2.3 a).

From present knowledge it is concluded that the size, number and mass of emitted particles from the measured turbo diesel engine is not worse than with the rich burn gasoline aircraft piston engine, using leaded fuel. However, the chemical composition of the particles can be different with possibly different health effects, if particles are directly inhaled.

g) Contribution of piston engines to total aviation emissions

FOCA is providing aircraft emissions data to external bodies e.g. for environmental impact assessments. FOCA is legally bound to calculate annual emissions inventories based on different principles, and has developed advanced models, taking every aircraft movement and destination into account, with actual flying engines .

One of the models calculates the fuel (CO_2) and emissions for all flights from A to B in Switzerland and all flights from A in Switzerland to the first destination B abroad during one year. This modelling corresponds approximately to the fuel sold in Switzerland during one year, which is used as a quality control for the bottom up calculated fuel consumption. This model has been used for the comparison below.

For total CO_2 emissions, based on the fuel sold, no modelling would be necessary, as for aviation fuel, every kg of fuel translates approximately into 3.15 kg CO_2 (This is the value for jet fuel, not for AVGAS). Pollutants emissions depend on engine technology and therefore on the actual engines that are flying. From point of view of fuel burn (CO_2), piston engines can be completely neglected. In Switzerland, AVGAS consumption is lower than fuel consumption for gardening (off road sector). Even in comparison with jet fuel only, the AVGAS consumption is not significant (see below). But from point of view of pollutants emissions, for the first time, FOCA was able to generate a clear picture of the contribution from aircraft piston engines to total aviation emissions in Switzerland.

The results of pollutants mass emissions have been generated based on the computation of around 700’000 flight records of the year 2004, using actual engine data as far as possible for all operations that took place in Switzerland during that year.

Piston aircraft emissions have the following shares on civil aviation emissions in Switzerland:

- **Less than 1% share on total aviation fuel and CO_2**
- **1% share on NO_x**
- **10% share on HC**
- **40% share on CO**
- **100% share on lead and bromides (the only lead source!)***

*about 5 metric tons of lead and a similar amount of bromides per year in Switzerland

2.3 Optimization of fuel burn and emissions

2.3.1 “Old tech” gasoline engines

a) Use of unleaded AVGAS

FOCA and DLR measurements have proven a significant reduction of gasoline piston aircraft emissions by use of the unleaded Swedish AVGAS 91/96 UL. Besides this, the fuel meets the same aviation standard as the leaded AVGAS. The engine manufacturer Textron Lycoming has included AVGAS 91/96UL as an approved alternate aviation gasoline for a large number of its engines already since 1995. The engines with type numbers are listed in service instruction No. SI 1070. Bombardier-Rotax explicitly recommends the use of this fuel for its engines.

b) Power setting, choice of speed and altitude for lowest possible CO_2 emissions in cruise

Lowest possible CO_2 emissions will be the result of lowest possible fuel burn (section 2.2.1 c). If CO_2 emissions shall be minimized, a mission has therefore to be optimized for best range. In order to find an optimal speed and altitude for best range in cruise, a theoretical approach is outlined below. Please note that distances, speeds and forces are in fact vectors. Because of parallel vector situations, the notation of vectors is simplified with the size of the scalar.

Definition of terms for theoretical considerations:

$$FF = \text{fuelflow} = \frac{\text{fuelmass}}{\text{time}} = \frac{m_f}{t} \quad (1) \qquad and \quad TAS = \text{true airspeed}\ (2)$$

$$S_R = \text{specific range} = \frac{\text{distance}}{\text{fuelmass}} = \frac{d}{m_f} = \frac{\frac{d}{t}}{\frac{m_f}{t}} = \frac{TAS}{FF} \quad (3)$$

$P =$ engine power

$P_{req} =$ required power (for airframe) $=$ required thrust $\cdot$ true airspeed $= F_{req} \cdot TAS$ (4)

$P_{avail} =$ available power (from engine at full throttle)

$$SFC = \text{specific fuel consumption} = \frac{FF}{P} = \frac{\frac{m_f}{t}}{P} = \frac{m_f}{t \cdot P} \quad (5)$$

The speed for best range (v $_{best\_range}$) is the speed, where the ratio between forward speed (a true air speed TAS) and the fuel flow (FF) is the best possible (equation 3).

The term $TAS : FF$ is called specific range. The specific range for a given aircraft depends on

- power management
- cleanness of the airframe
- aircraft mass
- density altitude

At v $_{best\_range}$, the specific range is highest.

How can v$_{best\_range}$ be found?

One practical solution is the permanent automatic computing of $TAS : FF$ (or better: *Ground Speed : FF,* which takes wind into account). This can be done with a fuel flow measurement unit, which is coupled to GPS and constantly provides the nautical miles (NM) per fuel ratio. With experience, the NM per fuel ratio can be maximized, adjusting engine power and altitude accordingly (therefore *Ground Speed)* during flight.

Theoretical approach:

For the usual power range of an aircraft piston engine, the fuel flow is proportional to the (propeller-shaft) power P_{avail}. With (5), the fuel flow can be written as:

$$FF = \frac{FF}{P} \cdot P = SFC \cdot P \quad (6)$$

Equation (6) in (3) gives the following specific range formula:

$$\boxed{S_R = \frac{TAS}{SFC \cdot P} \quad (7)}$$

The term SFC describes engine resp. propulsion efficiency. The term $TAS : P_{req}$ is an expression for the aerodynamic efficiency of the airframe. More precisely, the maximum specific range will be obtained at highest TAS with lowest SFC and minimum required engine power.

$$\boxed{S_R\ \text{max.} = \text{max.} \frac{TAS}{SFC \cdot P_{req}} \quad (8)}$$

In order to make things easier, the considerations are made step by step:

1) Looking at aerodynamic efficiency and aircraft mass (keeping propulsion efficiency constant)
2) Looking at propulsion efficiency alone
3) Altitude considerations
4) Summary and “Rules of Thumb”

1) Aerodynamic efficiency term, with equation (4)

$$\frac{TAS}{P_{req}} = \frac{TAS}{F_{req} \cdot TAS} = \frac{1}{F_{req}} \qquad (9)$$

Equation (9) expresses the fact that aerodynamic efficiency is best, if the required thrust is least. In steady state conditions, level flight at constant speed, the required thrust exactly compensates drag. Therefore, the number of Newtons for the required thrust equals the number of Newtons of the drag. Hence, for best aerodynamic efficiency, drag must be minimal. Besides others, the drag of a given aircraft is dependent on the aircraft mass. During cruise, the aircraft burns fuel and gets lighter, which reduces the mass, therefore reduces the necessary lift (reduces the lift coefficient) and the resulting drag.

From the lift and drag equations (which we are not writing down here), it follows that the minimum drag occurs at the maximum lift-to-drag ratio. The true air speed for minimum drag, v_{min_drag}, , can be found (theoretically) by using the function of required power to fly at a certain TAS for a given aircraft and mass:

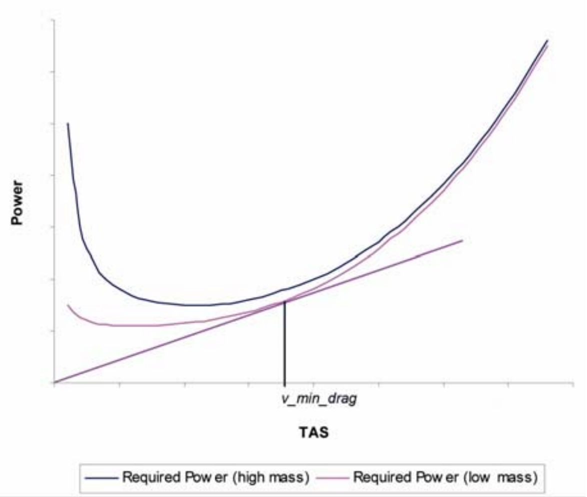

Figure 20: Required power for a given aircraft in function of TAS for two different aircraft masses. The highest possible value for equation (9) is given with the tangent from the origin to the power required curve. This represents the minimum for $P_{req} : TAS$ which is the same as the maximum of $TAS : P_{req}$. The corresponding speed for minimum drag is $v_{\_min\_drag}$. The two power curves have been plotted based on a generic airframe. The tangent in the figure shows the example for $v_{\_min\_drag}$ determination in the lower mass case.

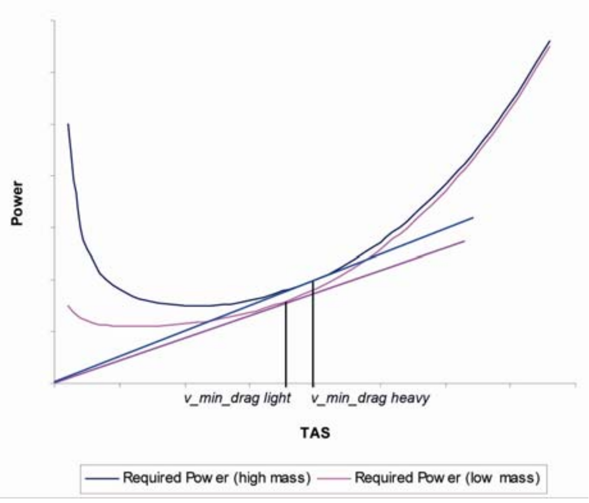

Figure 21: Required power for a given aircraft in function of TAS for two different aircraft masses. With increasing mass, $v_{\_min\_drag}$ increases.

- For best range (at constant SFC), $v_{best\ range}$ is equal to $v_{min\ drag}$.
- With decreasing aircraft weight, $v_{min\ drag}$ decreases.
- With headwind, $v_{min\ drag}$ increases. (The origin of the tangent in figure 20 moves to the right.)
- $v_{min\ drag}$ is a very low cruising speed compared to “conventional” cruising speeds.
- Drag reduction in general is not only achieved by approaching $v_{min\ drag}$, but also by cleaning the airframe and the propeller from insects and dirt, reducing edges between engine cowling and airframe, etc.

2) Propulsion efficiency

In general, aircraft piston engines will run more efficiently (SFC gets smaller, improves):

- If the required power to fly at a certain TAS is generated with the throttle fully open.
- If engine RPM are as low as possible to generate the required power.
- If the engine runs with more than 40% and less than 70% of the maximum sea level power.
- If the air/fuel mixture is properly adjusted (summary in next section c).

At low engine RPM, cylinder charge with air/fuel mixture is better and there are less friction losses. At full throttle, the intake system works more efficiently. However, there is a lower limit for efficient engine power generation, as well.

Low engine RPM can be achieved with a variable pitch propeller. In fact, the propeller efficiency of a variable pitch propeller is very good at low RPM, which can combine to a good efficiency of the whole propulsion system at relatively low RPM.

Output of the required power at low RPM needs relatively higher Manifold Pressure (MAP), respectively torque. For many engines, the MAP (in InHg) must not exceed engine RPM/100. The limitations are given by engine manufacturers and/or stated in the AFM/EOM and must be known.

Apart from a better achievable SFC at lowered RPM (not lowest power), the propeller noise can be significantly reduced. A drop of only 100 RPM will reduce the propeller tip mach number with an impressively positive effect on noise reduction. This is an environmental win-win situation (noise and emission reduction).

For a fixed pitch propeller aircraft, to fly on lowest possible RPM is normally not feasible. The effects depend on the chosen fixed propeller pitch and are therefore extremely aircraft dependent.

3) Altitude considerations

Before talking about altitude effects, it is worth understanding, that the speed indicator in most piston engine aircraft is essentially a pressure gauge, calibrated in speed units. The speed is called “Indicated Air Speed” IAS. At sea level standard conditions IAS will equal TAS. TAS is the only speed in the narrow sense.

- With increasing altitude, IAS will be less than TAS. If IAS is kept constant during climb, TAS will increase.
-

The dynamic pressure used for moving the needle of the speed indicator is the same as the dynamic pressure in the drag formula. Therefore,

- if IAS is kept constant during climb, the drag will remain the same, but TAS will increase. From equation (4) follows, that the required power increases.
- If TAS shall be kept constant with increasing altitude, IAS has to be reduced. At higher altitude, the drag and the required power will then be less.

With increasing density altitude, normally aspirated piston engines lose power, due to the lower oxygen partial pressure. Flying at high density altitudes can reduce the available power at full throttle down to 55% or even below. With medium available power at full throttle, properly mixed and at reduced RPM, the engine is at best SFC. Despite lower drag and higher achievable TAS at higher altitude, the relatively low available power (around 50%) holds the TAS at a relatively low level, not very far above $v_{min\ drag}$. This means that the airframe is near to its best aerodynamic efficiency. Both effects, good SFC and TAS near $v_{min\ drag}$ combine to best specific range.

During cruise, the aircraft gets lighter by fuel burn. Figure 22 suggests reducing TAS accordingly. This can be done by successively climbing higher, as the loss of power will eventually reduce TAS, despite a lower drag at higher altitude.

In turbocharged engines, at higher altitude, a relatively high air pressure (enough oxygen per volume) can be maintained in the manifold. For turbocharged engines, the altitude for best specific range could be further increased compared to the normally aspirated engine, because the engine provides the required power at higher altitude. The lower ambient air density causes less drag, with the effect of a higher achievable TAS, which increases specific range (equations 4 and 8).

High cruising altitude does not necessarily result in best specific range for a piston engine aircraft. The fuel for a climb to higher altitudes and the wind components have to be taken into account. Additionally, the SFC of the piston engine is not very altitude and speed dependent, compared to a jet engine. Therefore, high specific range can be obtained also at lower altitudes with sufficient power reduction at maximum allowed MAP and low RPM (around 50% of maximum sea level power), which results in a TAS not very far above v_{min_drag}

4) Summary and "Rules of Thumb"

The speed for best range is not very far above $v_{\_min\_drag.}$. In any case, the AFM has to be consulted. Additionally, the following "rules of thumb" may be considered:

The least CO_2 emissions during cruise may be achievable with:

- $v_{\_best\_range}$ (no wind) = TAS *for best rate of climb* + 15%
- $v_{\_best\_range}$ + 1/4 of head wind component (for headwind)
- $v_{\_best\_range}$ – 1/5 of tail wind component (for tailwind)
- $v_{\_best\_range}$ – 4% for every 100 kg below MTOM
- Required power not below 45% and seldom above 55%
- Required power at lowest possible RPM with highest allowed MAP
- Proper mixture adjustment (High contribution, Appendix 2, summary in section c below)

”Holding position” during flight

If an aircraft has to hold position during flight (e.g. during an approach), the best range criteria is not important. In this case, the aircraft should burn the fuel at the slowest rate possible, in order to minimize CO_2 emissions. This is a power setting for *best endurance*. As explained before, the fuel burn for a piston engine is practically proportional to the power. The least fuel burn per time can therefore be achieved with a speed that requires the least power to keep the aircraft flying. This speed is at the minimum of the required power:

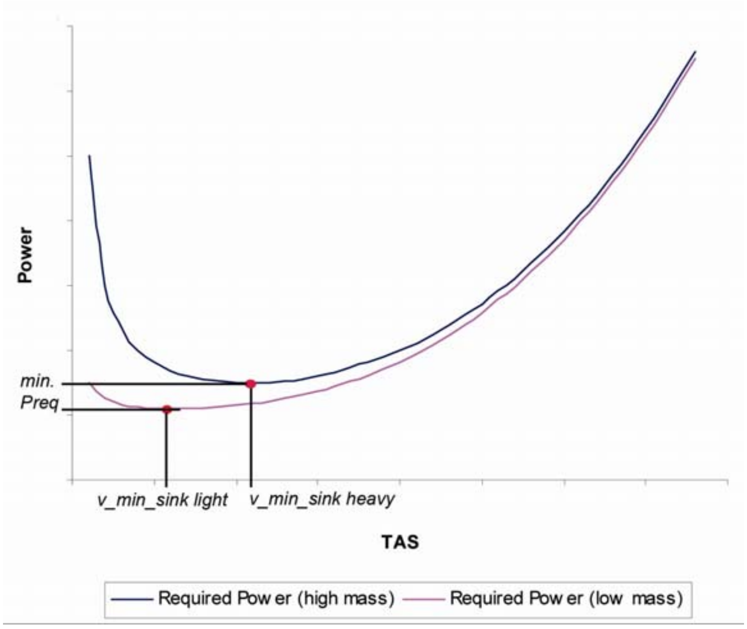

Figure 22: Determination of speed for maximum endurance. It is the speed at minimum required power (the lowest point of the curve), shown for two aircraft masses. With increasing mass, the speed for maximum endurance increases. The lowest required power equals the lowest energy consumption per time to keep the aircraft flying. The speed where this occurs corresponds to the speed for minimum sink rate with engine off ($v_{\_min\_sink}$).

Usually, $v_{\_min\_sink}$ is not directly indicated in a piston engine aircraft AFM. But it is very near v_y, the speed for best rate of climb. The best rate of climb will be achieved at a speed where the difference between available power and required power for the climb will be biggest. Because the required power is lowest at $v_{\_min\_sink}$, the best rate of climb will usually be around that speed.

The least CO_2 emissions in a holding may be achieved with:
- Flying slightly higher than or at v_y (AFM restrictions may apply)
- Required power at lowest possible RPM with highest allowed MAP

c) Manual mixture management (Climb, Cruise, Descent/Approach)

Climb

- At climb, the engine may be leaned according to AFM to **best power if AFM/EOM allows and CHT limits can be maintained.** Again, the fuel flow method (as described in section 2.2.2 l) may be useful.

Cruise “rich of EGT peak”

- At cruise, flying slightly “rich of EGT peak” is still better than flying best power or very rich from point of view of emissions, although there will be more NO_x emissions. There will be less fuel consumption (less total CO_2), less CO and HC emissions and less particle mass emissions.

Cruise at “50°F lean of EGT peak”

- Flying lean would be the optimum from point of view of emissions. With the specific fuel consumption at the minimum for a certain power setting, range can be maximized and at the same time, all emissions will be minimized as shown in section 2.2.2 f). In addition, the engine can run cooler. Minimum requirements for safe engine operation at this condition are considered like:
  - The engine manual and AFM explicitly describe lean mixture setting as an option.
  - The engine has a well balanced mixture and temperature distribution between the different cylinders.

Descent / Approach

- During descent at a fixed mixer position, the engine will normally get less rich (or leaner) due to increasing air density. If the mixture is set slightly rich before descent, the cylinders are approaching peak EGT when the aircraft descends. With a lean setting before descent, the cylinders are approaching lean misfire condition and may flame out during descent. Therefore, pilots are told to go to “full rich” for descent or approach. This makes operation simple.

- FOCA measurements have shown that with the simple “full rich” operation, more fuel per distance is burnt during descent and approach than during cruise! The combination with a very incomplete combustion at “full rich” often leads to higher total emissions during descent than during cruise (Appendix 2).

- Instead of going standard “full rich”, the author tested alternatives: Engine propeller power is down at around 45%. If the mixture is set to 100°F rich of EGT peak (best power, safety margin) just before descent, and if the 100°F during descent are maintained by stepwise enriching the mixture, **considerable amounts of fuel and emissions can be saved.** The 100°F have proven to be practical also for the case, when a sudden increase of power is required during descent. “Full rich” is set later, at mid downwind and checked in the final check, because “full rich” is necessary in the event of a go around.

2.3.2 Choice of engine technology

a) FADEC for gasoline engines

In the opinion of the author, certified FADEC systems for “old tech” fuel injected aircraft gasoline piston engines are a valuable means of significantly reducing emissions (including fuel burn). A FADEC system is able to control the air/fuel mixture of every single cylinder and therefore, the engine can be run lean during cruise.

b) Turbo Diesel engine

At the time of completing this FOCA report, the turbo diesel engine has shown by far the lowest gaseous emissions per unit of power. From point of view of emissions, the turbo diesel technology brings the greatest reduction of aircraft piston engine emissions. This includes CO_2 and pollutants. From point of view of particle emissions, the turbo diesel is not considered worse than the “old tech” gasoline piston engine, running on AVGAS100LL.

3. Outlook – planned future work

3.1 Number of measured aircraft piston engines

3.1.1 “Old tech” engines and new engine concepts

Some of the FOCA data are based on the measurements of one particular engine of a certain engine type. Significant variations between one and another engine of the same type exist and therefore FOCA plans to improve data representation with more measurements of different engines of a particular engine type. The database will also be completed with engine emissions data for still missing engines.

3.1.2 Modernized “old tech” engines with FADEC

During the last couple of years, options for fuel injected engines have been brought into the market and have been certified for certain airframe/engine combinations.
From present knowledge, the author concludes that FADEC equipped aircraft piston engines (with individual cylinder control) can have substantially improved emissions performance. More measurement data are needed.

3.2 Unleaded AVGAS

In Europe, AVGAS 100LL is the **only leaded fuel** in the market. Besides lead-tetraethyl, this fuel contains bromides which are harmful to the stratospheric ozone layer. The scientific research programme documented in Appendix 4 has revealed that the use of an unleaded fuel like AVGAS 91/96 UL can dramatically improve emissions performance of existing aircraft piston engines. Therefore, whenever feasible and applicable, FOCA supports the transition from leaded AVGAS to a cleaner unleaded AVGAS for aircraft piston engines. Unfortunately, AVGAS 91/96 UL can not yet replace AVGAS 100LL in any case, due to the slightly lower octane rating. Tested unleaded AVGAS with still better environmental performance than 100LL, like type C and G (Appendix 4) are alternatives that will be evaluated in the future.
Unleaded motor gasoline (MOGAS) has strong limitations for use in aircraft. Existing “old tech” piston engine aircraft designs – if possible at all - require a supplemental type certificate (STC) to ensure safe operation when using MOGAS. For safety reasons, such a STC normally prescribes very low ethanol content. The increasing ethanol content in motor gasoline may lead to difficulties in aircraft MOGAS supply in the future. Besides this, instead of lead components, MOGAS can contain substances, which create a certain risk for contamination of drinking water[8].

Picture 4: Research on unleaded AVGAS, St. Stephan, Switzerland, May 2006. From left to right: C. Wahl, M. Kapernaum (both DLR), L. Hjelmberg (Hjelmco), T. Rindlisbacher, W. Bula (both FOCA)

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[8] MOGAS sold in Switzerland and analyzed in 2006 contained quite large amounts of MTBE.

3.3 Emissions data for helicopter turbines and small turbofans

For other engine families, like helicopter turbines and small jet engines, without an ICAO emissions certification, there is still a lack of emissions data and FOCA plans to work on two respective packages, based on its aviation law (SR 748.0, LFG Art. 58):

- **Hel**icopter **en**gine emissions, project **HELEN** (starting mid 2007)
- **S**mall **tu**rbo**f**an engine emissions, project **STUF** (planned to start in 2008).

A first feasibility study for application of the FOCA “low cost” measurement system has been done on a typical business jet turbofan in summer 2006. Measurements of gaseous exhaust components have been combined with a sophisticated particle measurement system (as described in Appendix 4, section 4). Measured gaseous emissions have been compared to certification level data kindly provided by the engine manufacturer. The data matched quite nicely.

3.4 International activities

Due to environmental legislation of different countries, and also to the increase of interest at international level, the improvement of knowledge about non-certified engine emissions data has become more and more important. FOCA is supporting the further development of ICAO guidance material for the calculation of emissions caused by the aviation sector and for calculations in relation to environmental impact assessments.

- END -

4. List of acronyms and abbreviations

AFM	Airplane Flight Manual
AMSL	Above mean sea level
AP	Approach mode
ASTM	American Society for Testing and Materials, one of the largest voluntary standards development organizations in the world
AVGAS	Aviation gasoline
AVGAS 100LL	leaded AVGAS with 100/130 aviation octane rating
AVGAS 91/96 UL	unleaded AVGAS with 91/96 aviation octane rating
BHP	Brake Horse Power
°C	Temperature in degrees Celsius
CAEP	Committee on Aviation Environmental Protection
CHT	Cylinder head temperature
CL	Climb mode
CLD	Chemiluminescence
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation Particle Counter
CR	Cruise mode
CR L	Cruise mode with adjusted mixture to lambda = 0.95
CR LL	Cruise mode with adjusted mixture to lambda = 1.3
CR R	Cruise mode at mixture "full rich"
Density Altitude DA	Height in the International Standard Atmosphere at which the prevailing air density occurs. Key parameter for aircraft and engine performance
DLR	German Aerospace Centre
DWD	Downwind (part of the approach pattern at the airport)
EEPS	Engine Exhaust Particle Sizer
EF	Emission Factor (sometimes also indicated as EI, emission index)
EGT	Exhaust Gas Temperature
ELT	Emergency Localizer Transmitter
EOM	Engine Operating Manual
°F	Temperature in degrees Farenheit
FADEC	Full Authority Digital Engine Control
FF	Fuel Flow
FID	Flame Ionization Detector
Final	Final approach (last segment of approach before touchdown)
FOCA	Federal Office of Civil Aviation (the Swiss Civil Aviation Authority)
ft	feet
FT	Full Throttle
GPS	Global Positioning System
H_2	Hydrogen
H_2O	Water(vapour)
HBEYS	FOCA aircraft Robin DR400-180 with Lycoming O-360 series engine
HBHFX	Aircraft AS 2002 Bravo with Lycoming O-320 series engine
HBKEY	FOCA aircraft Robin DR400/500 with Lycoming IO-360 series engine
HBKEZ	FOCA aircraft Robin DR400/500 with Lycoming IO-360 series engine
HBKIA	FOCA aircraft Bonanza A35 with Teledyne Continental IO-550 series engine
HBWAD	Aircraft Ikarus C22-B with Rotax 912S engine
HC	(total) hydrocarbon emissions
HC6NDIR	NDIR HC reading in Hexane ppm
He	Helium
HP	(Propeller) Horsepower
ICAO	International Civil Aviation Organization
InHg	Pressure Unit in inches of mercury column, e.g. 23 InHg = 779 hPa
ISA	International Standard Atmosphere
λ	Number, expressing how rich or lean an air/fuel mixture is
Lambda	Number, expressing how rich or lean an air/fuel mixture is
Lean	Air/fuel mixture which is poor in fuel (excess oxygen) in relation to stoichiometric mixture
LTO	Landing and take-off cycle
M	Torque
MAP	Manifold Air Pressure

Mixer	Lever in the cockpit to adjust air/fuel mixture
Mixture	Air/fuel mixture
Mode	Flight phase and attitude with certain power setting
MOGAS	Motorcar Gasoline
MPH	Miles per Hour
MTBE	Methyl tert-butyl ether
N_2	Nitrogen
Nanoparticles	Ultra fine combustion particles with diameters between 10 and 500 nanometers
NDIR	Non-Dispersive Infrared Sensor
NO_x	Nitrogen oxides
"Old tech"	Market dominant aircraft piston engine concept
P	Power
PM	Particle Mass
Pressure Altitude PA	Height in the International Standard Atmosphere at which the prevailing air pressure occurs, obtained by setting the subscale of a pressure altimeter to 1013.2 hPa
QNH	Ambient air pressure corrected to sea level with ISA temperatures
Rich	Air/fuel mixture which is rich in fuel (oxygen deficiency) in relation to stoichiometric mixture
RPM	Revolutions per Minute
RWY	Runway
SEKEI	Aircraft Piper PA-28 Warrior with Lycoming O-320 series engine
SMPS	Scanning Mobility Particle Sizer
STC	Supplemental Type Certificate
stoichiometric	Combustion condition at which the air/fuel ratio is such that there is neither an excess of fuel nor of air
TA	Taxi mode (aircraft taxi out and in at the airport)
THC	Total hydrocarbon emissions (often simply indicated as HC)
TO	Take-off mode
UV	Ultraviolet radiation
VFR	Visual Flight Rules
Vne	Never-exceed speed

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