

Aircraft NO_x-Emissions within the Operational LTO Cycle



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1 Executive Summary

Emission inventories of aircraft in the vicinity of airports are traditionally calculated by using ICAO engine exhaust emission data and the ICAO reference LTO cycle, the latter sometimes adapted to airport specific taxi times. Initially intended for certification purposes, the LTO cycle cannot sufficiently take operational issues (de-rated take-off, climb profiles) into account.

Within this context, Unique (Flughafen Zürich AG) initiated this study in cooperation with Swiss to evaluate flight specific data, aiming at defining an operational LTO cycle, deriving operational times in mode, fuel flow and emissions data and compare the results with previous inventories.

Swiss evaluated aircraft data from 9 aircraft-engine combinations, ranging from A319 to A340-300 and including B757 and B767.

The evaluated data suggested to have an operational LTO cycle defined with 4 phases similar to the ICAO reference cycle:

Take-off:	Average thrust setting from take-off brake release to the point of main engine throttle back.
Climb:	Thrust setting from the point of throttle back to the mixing height altitude, or more generally 3000 feet.
Approach:	Average thrust setting from mixing height altitude (or 3000 ft) over the touch down point to the end of the rollout on the runway.
Taxi / Ground Idle:	Average thrust setting from engine start to the point of take-off brake release for taxi-out and from the end of rollout after landing to parking and main engine turn-off for taxi-in.

The overall averaged fleet results show reduced fuel flow (-38%) and NOx emissions (-31%):

Table 1-1: Overall Results LTO Assessment using 9 aircraft/engine-combinations from A319 to A340

Parameter	Mode	ICAO Reference	Operational ZRH	Difference
Time (min)	Take-off	0.7	1.6	+130%
	Climb	2.2	0.5	-77%
	Approach	4.0	4.4	+10%
	Idle/Taxi	26.0	14.8	-43%
Fuel	LTO ¹	100%	62%	-38%
NOx	LTO ¹	100%	69%	-31%

¹Average of all evaluated nine aircraft-engine combinations and their LTO cycles.

While this methodology returns a first good estimate on operational fuel consumption and NOx-emissions, another option could be to use non-sensitive, static aircraft, engine and airport information alike to derive a methodology based on performance to calculate alternative emissions on an individual aircraft basis.

2 Background

2.1 Reference Conditions for Engine Certification

Gaseous emissions of jet engines whose rated output is greater than 26.7 kN and whose date of manufacture is on or after 1 January 1986 are regulated under the provisions as set out in the ICAO Annex 16, Volume II, Aircraft Engines Emissions. These provisions have been established by ICAO to guarantee that engines do not exceed certain regulatory environmental limits. The engine is tested at specified thrust settings. Furthermore, the reference emissions LTO cycle for the calculation and reporting of gaseous emissions shall be represented by the following time in each operating mode:

Table 2-1: ICAO Reference LTO Cycle

Operating Mode	Thrust setting	Time in operating mode, minutes
Take-off	100 % F_{oo}	0.7
Climb	85 % F_{oo}	2.2
Approach	30 % F_{oo}	4.0
Taxi/ground idle	7 % F_{oo}	26.0

The LTO cycle basically covers emissions of self-moving aircraft from the ground up to 3,000 ft above ground. The different modes are not described in more detail.

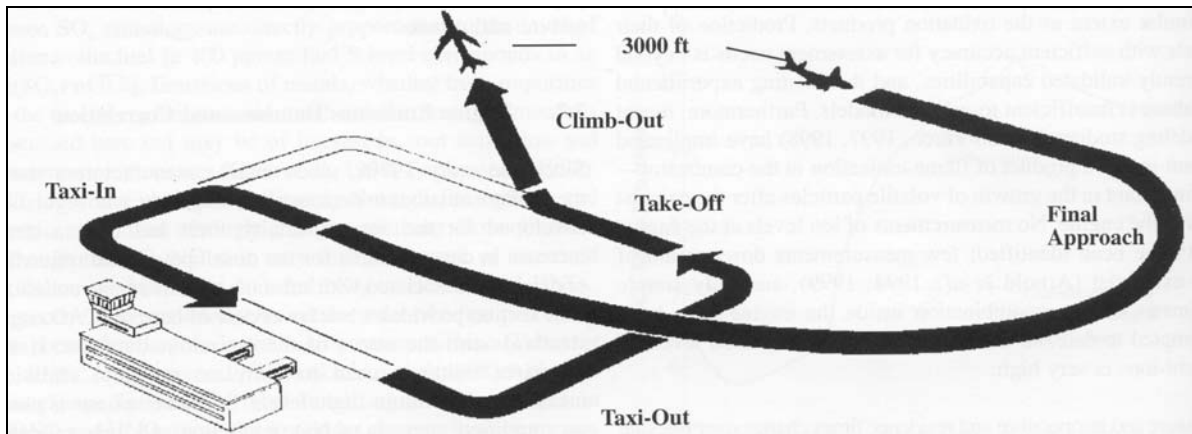


Figure 2-1: ICAO reference LTO-cycle

2.2 ICAO Engine Emission Data

Detailed engine data of turbo-jet and turbofan engines with a rated output greater than 26.7 kN is provided by ICAO through its assigned contractor. The standard engine data sheet contains data on the engine identification, the test environment and detailed fuel flow and emission indices for different substances. The data base is updated regularly and the information is publicly available.

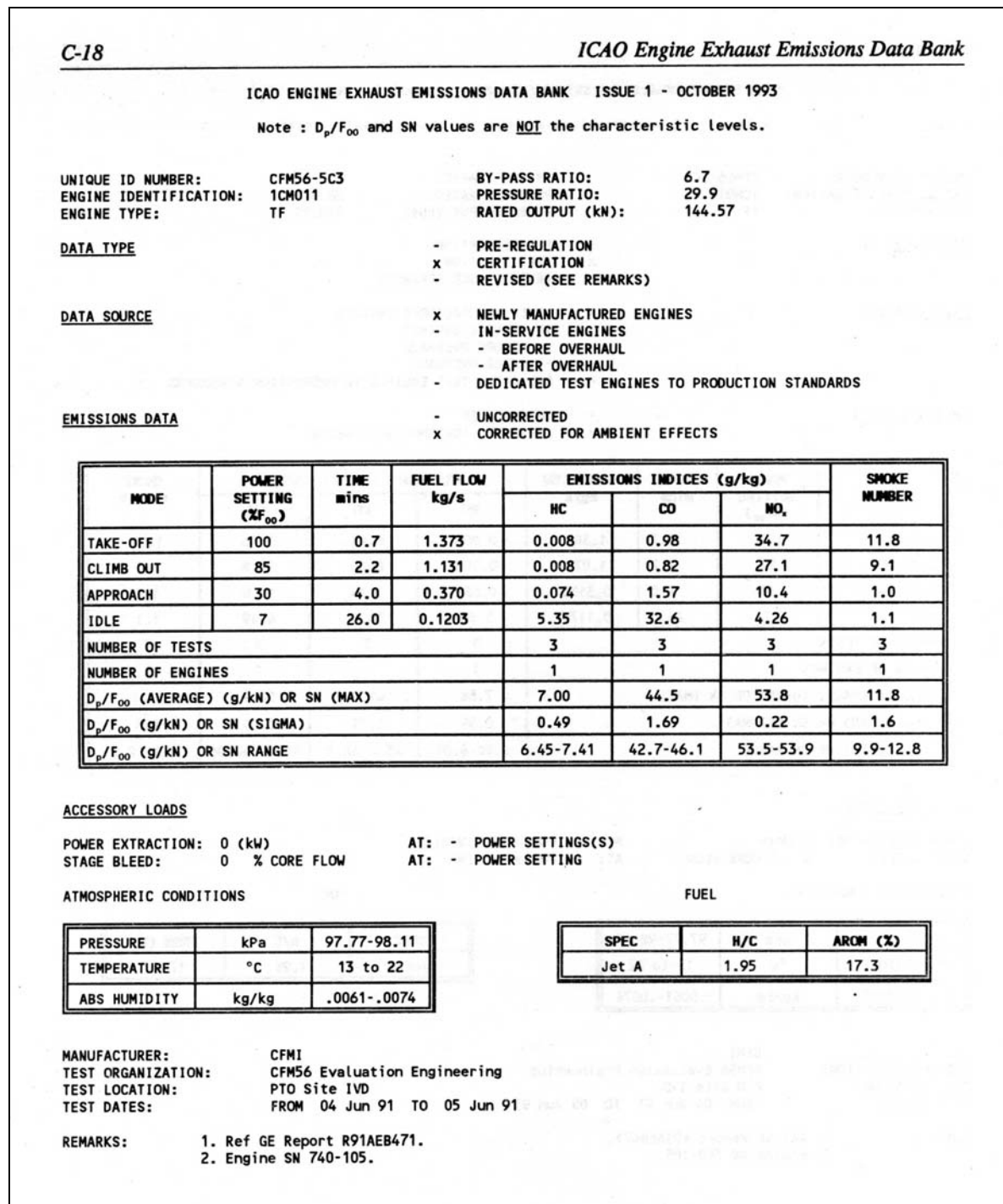


Figure 2-2: ICAO Engine Exhaust Emission Data Bank

2.3 Unregulated Engines

Since ICAO provisions only regulate part of all aircraft engines in operations, all other engines need to be considered through an alternative methodology. The engine types that are not regulated are turbojet and turbofan engines with 26.7 kN thrust or less, propeller turbines, piston engines and gas turbines. In order to respond to requests for emission inventories, additional reference LTO-cycle and emission data sheets had to be developed. One is the US EPA default time in mode table for various aircraft categories:

Table 2-2: US EPA Default time-in-modes¹

Aircraft Category	Time in Mode (Minutes)			
	Take-off	Climbout	Approach	Taxi/Idle
Commercial Carrier:				
Jumbo, long and medium range jet	0.7	2.2	4.0	26.0
Turboprop	0.5	2.5	4.5	26.0
Transport- piston	0.6	5.0	4.6	13.0
General Aviation:				
Business Jet	0.4	0.5	1.6	13.0
Turboprop	0.5	2.5	4.5	26.0
Piston	0.3	5.0	6.0	16.0
Helicopter	-	6.5	6.5	7.0

Emission Factors for non-regulated engines have been derived by engine manufacturers and released (e.g. FAA Aircraft Engine Emission Database, User Version 2.1, November 1995). A comprehensive list of turboprop engines is administered by the Swedish Institute FOI, relying on the provided data by engine manufacturers.

2.4 Conventional LTO Emission Calculation

Aircraft emission inventories are traditionally calculated by using the reference ICAO LTO-cycle (table 2-1) and the engine fuel flow and emission factors as provided by ICAO. The quite simple method is to use the proper aircraft/engine combination per LTO, and calculating the:

sum of the four LTO mode products of time-in-mode × fuel flow × emission-index

A more precise method is to substitute the time-in-mode for "taxi/ground idle" by an individual airport average. The most detailed version is to actually determine the taxi-/ground idle times by using other reference times like off-block/take-off or touch-down/on-block. However, the thrust settings in all modes and the time in the modes for take-off, climb and approach are taken from the reference cycle.

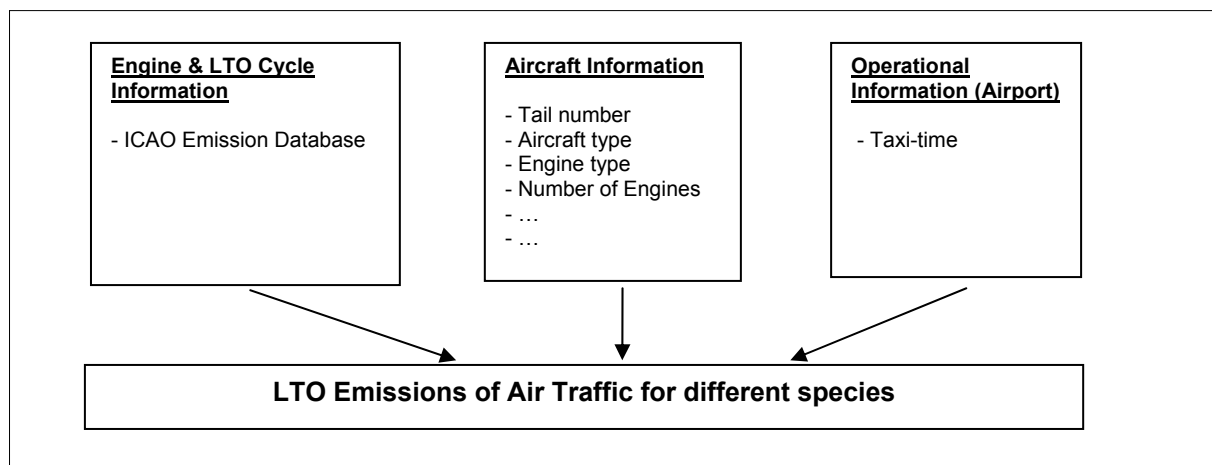


Figure 2-3: Conventional LTO Emission Calculation

The results of these emission inventories have often been used by airports or consultants for pollution concentration modelling or by environmental authorities for requesting mitigation plans.

¹ US EPA, September 1985: "Compilation of Air Pollutant Emission Factors Volume II, Mobile Sources", AP-42 (Aircraft Data from February 1980, Ann Arbor, Michigan)

3 Operational Considerations

3.1 Development of Aircraft Operations over Time

The ICAO reference LTO cycle as developed in the late seventies/early eighties was designed for certification processes for the specified engine types. Once the emission data had been derived and published, emission inventories have been calculated, assuming to some degree that this would adequately describe aircraft emissions in the vicinity of an airport. Over the past 25 years, operational procedures for aircraft have changed considerably. Two engine powered long-haul aircraft or small commuter jets have been brought into operation. While their performance varies from that of earlier times, the LTO cycle as a base for calculating their emissions remained unchanged. In addition, not all phases are clearly defined (e.g. at what point ends the approach phase?).

For certification purposes it is highly desirable to keep methodology and procedures of emission calculation over long time periods. This also enhances the continuous development and adaptation of standards and their comparability. However, for assessing the actual emissions from aircraft, the operational parameters are as important as the emission factors. They thus need to be continuously developed to represent current state of the art.

3.2 Study on Operational Landing- and Take-Off Cycle

Within this context, Unique (Flughafen Zürich AG) initiated this study in cooperation with Swiss Flight Data Monitoring.

The aims of the study are to:

- develop and propose a definition of a LTO cycle that reflects current aircraft operations;
- determine operational times in mode, thrust settings and fuel flows;
- calculate operational emission factors (NO_x);
- compare fuel and emissions with previous inventories;

By:

- evaluating Swiss/Edelweiss/Belair flights in the LTO cycle of Zurich Airport;
- using the Swiss ADAS-Data (Aircraft Data Acquisition System) and EMS (Event Measurement System).

4 Operational LTO Emission Assessment

4.1 Aircraft Data Evaluation

Aircraft Data Acquisition System (ADAS) and Event Measurement System (EMS)

In order to get absolutely reliable operational-technical data and perform the mathematical analysis, we used ADAS and EMS. The relevant (efficiency and statistical) advantage using EMS is the fact, that we have the capability of calculating reliable, intermediate results according to a given definition (instead of getting 'only' raw FOQA data), which saves significant programming effort and improving the significance of the statistical analysis;

These data include, but are not limited, to mean ground speed over a predefined sample interval (given by time-points, events, durations etc.), max. true airspeed at a given altitude, average mach number over a recurring period of 5 seconds, average fuel flow to all engines measured from lift-off to throttle back or for an interval of 60 seconds every 5 minutes etc. We also have the capability of combining these measurements with weather data, projection of the flight trajectory, including taxi, waypoints etc. and running a thrust model.

A further, relevant advantage using EMS is also the fact that the data remain available for further analysis (in the flight data warehouse) or that the application can be rerun with using exactly the same EMS profile or further enhance the specification to be used for an alternative definition of the ICAO-cycle modes or for a complete flight. Of course we also have engine parameters in order to calculate emissions using the P3/T3 method and compare with the results using the Boeing method.

For this study, sufficient FDR/EMS data were available (thousands of long- & short-haul flights) in order to perform statistical analysis for different aircraft types (cf. table 4-1): A321/A320/A319, A330-200, A340-300, B757-200 & B767-300 (A320, A330 & A340 with different engines or configuration; B777 & Embraer available in the next future).

Table 4-1: Aircraft/engine-combination for evaluation

Aircraft	Engines	Remarks	Average ATOW (t)
Swiss A319	CFM56-5B6/2P	DAC (double annular combustor)	57.5
Swiss A320	CFM56-5B4/2P	DAC	63.1
Swiss A320	CFM56-5B4/P	SAC (single annular combustor)	63.7
Swiss A321	CFM56-5B1/2P	DAC	70.8
Swiss A330-200	P&W 4168A	Flotwall, 68'000lbs rated thrust	207.0
Swiss A340-300	CFM56-5C4/P	34'000lbs	240.5
Edelweiss A320	CFM56-5B4/2P	DAC	63.1
Edelweiss A330-243	RR Trent 772B-60/16	71'000lbs rated thrust	206.0
Belair 757	RR RB211-535E4		93.4
Belair 767	P&W 4060		146.0

Since EMS (the owner of which is Swiss Flight Safety) is fully up-and-running, Flight Data Monitoring rendered services also to external institutions like the Swiss Federal Office of Civil Aviation, Eurocontrol Experimental Centre (e.g. calibrating and validating the Advanced Emissions Model), Airport Authorities, Swiss Federal Institute of Technology Zurich, TU Munich etc. beyond the classical Flight Safety / FOQA use, making full use of the expert system and the expertise associated with using FOQA data.

Further applications and opportunities are not only related to fuel flow, fuel on board, fuel savings etc. but: velocities, times, holdings, systems-performance, malfunctions and monitoring, communications / navigation, statistical air and ground distances, routes, winds, weights, center of gravity, temperatures, thrust settings, engine emissions, empirical values, key performance indicators, etc.

Airport Characteristics

All cycles evaluated are departures and arrivals from and to Zurich Airport (ZRH). Runways available for take-offs and landings are RWY 16/34 (3700m), RWY 14/32 (2300m) and RWY 10/28 (2500m) at an average elevation of 424 m.

Ambient Conditions

Zurich Airport experiences prevailing westwinds. Ambient temperature conditions of all evaluated flights ranged from -9°C to $+35^{\circ}\text{C}$ (minimum: -9.0° to -5.5° ; average: $+4.8^{\circ}$ to $+12.5^{\circ}$; maximum: $+12.0^{\circ}$ to $+35.0^{\circ}$ over the nine aircraft types).

4.2 Operational LTO Cycle

Emissions are determined by fuel flow and emission indices and the fuel flow itself is determined by the engine thrust setting. Thus it has to be determined at which points below the average mixing height the thrust settings of an aircraft change considerably. This might happen quite often, so in order to also maintain some consistency with the reference LTO cycle (e.g. define four major phases), some generalisation will be necessary.

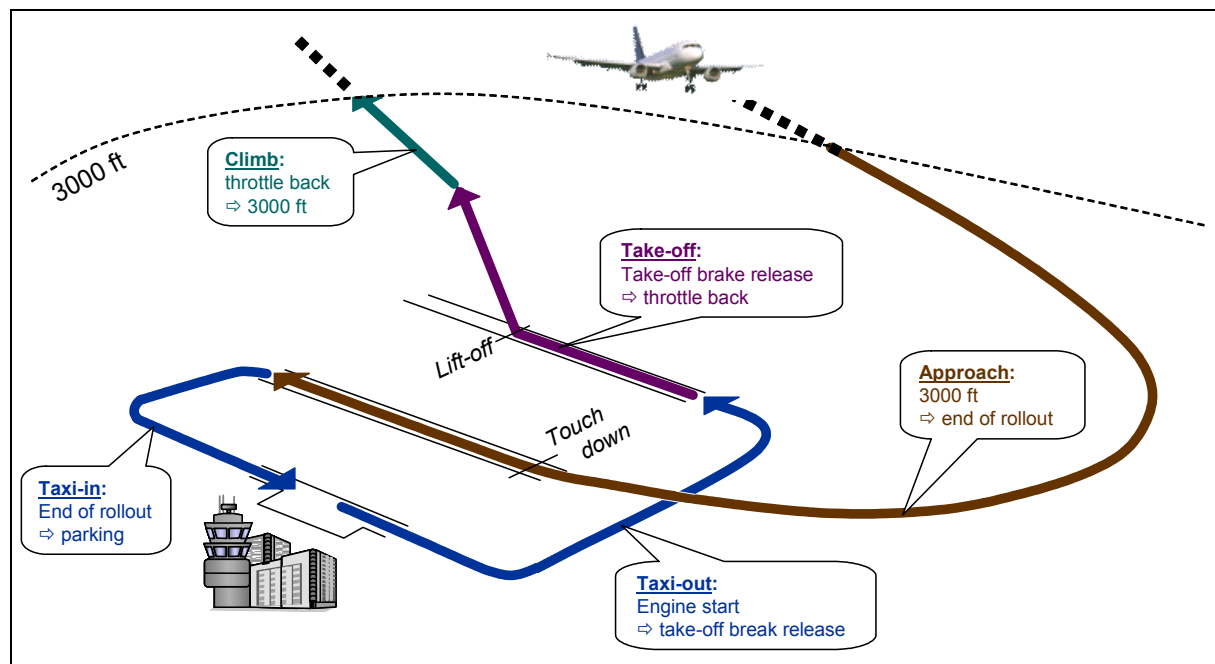


Figure 4-1: Proposal of a definition of an operational LTO cycle

Based on the evaluation of the existing data, it is suggested to define an operational LTO cycle with four phases (as in figure 4-1):

Take-off:	Average thrust setting from take-off brake release to the point of main engine throttle back. This point is variable and dependent on a number of parameters (take-off weight, meteorological conditions, flight procedures).
Climb:	Thrust setting from the point of throttle back to the mixing height altitude, or more generally 3000 feet.
Approach:	Average thrust setting from mixing height altitude (or 3000 ft) over the touch down point to the end of the rollout on the runway.
Taxi / Ground Idle:	Average thrust setting from engine start to the point of take-off brake release for taxi-out and from the end of rollout after landing to parking and main engine turn-off for taxi-in.

Alternatively, the take-off phase could be split into the phases from brake release to lift-off and from lift-off to throttle back and the approach phase could be split into 3000 ft to touch-down and from touch-down to end-of-rollout (cf. figure 4-1). However, for consistency reasons, it is suggested to define only four phases for describing the LTO-cycle.

4.3 ICAO Guidance Material

"CAEP/5 required WG3 to provide guidance on the use of emissions certification data for assessment of operational impacts and to make recommendations for incorporation into Annex 16, Volume II. The Alternate Emissions Methodology Task Group (AEMTG) of WG3 has examined the consequences of variations in key operational parameters and ambient conditions.

It concluded that a relatively simple mathematical approach based on the Emission Indices and the fuel flow [‘the Boeing curve fitting method’] is an acceptable method for estimation of all gaseous emissions across the whole engine power range, though engines with fuel staged combustors may need individual attention to HC emissions, due to the multiple fuel staging at low powers. Development into formal guidance material requires a decision on the appropriate place for publication.

Ambient humidity changes affect NO_x, but can be accounted for by a correction factor already used in Annex 16, Volume II. Detailed examination has shown that the factor should be amended from 0.00629 to 0.00634 kg of water per kg of dry air. The consequence of this difference is very small (~0.1%) and AEMTG concluded that it would be unnecessary to request changes to the NO_x emission certification values of existing engines.

WG3 has accepted these findings and incorporated them in its report to CAEP (CAEP/6-WP/4).² Within this study, the results have not been corrected for the reference humidity.

4.4 Operational Emission Calculation

The Boeing Fuel Flow Curve fit method (see Appendix A) has been applied to derive adapted emission factors for NO_x. The fuel and NO_x emission calculation for an aircraft in the operational LTO-cycle follows the same methodology as for the certification LTO-cycle:

$$\text{Value LTO} = \text{Sum of the four LTO mode products of time-in-mode} \times \text{fuel flow} \times \text{emission-index}$$

This methodology allows using the same database and calculation structures by simply replacing the original certification values by the derived operational values. At the same time, results can easily be compared.

² CAEP/6-IP/5, November 2003.

5 Results

5.1 Changes in Time in Mode

Following the suggested modes for an operational LTO cycle, there is a distinctive change in times in mode, particularly for the phases take-off and climb-out (table 5-1).

Table 5-1 Differences in time in mode (times in minutes).

Mode	ICAO LTO	Operational LTO	Difference
Take-off	0.7	1.6	+130%
Climb-out	2.2	0.5	-77%
Approach	4.0	4.4	+10%
Taxi / Ground Idle	26.0	14.8	-43%

The LTO times are averaged over all aircraft-engine-combination evaluated

5.2 Changes in Fuel Consumption

Accordingly there are considerable differences in fuel flow and NOx-emissions (tables 5-2 and 5-3).

Table 5-2: Differences in fuel consumption (operational LTO to ICAO LTO)

Aircraft	Take-off	Climb-out	Approach	Taxi/Idle	LTO Cycle
Airbus A319	107%	-94%	-29%	-58%	-45%
Airbus A320/DAC	73%	-84%	-31%	-60%	-47%
Airbus A320/SAC	73%	-84%	-34%	-54%	-45%
Airbus A321	73%	-81%	-33%	-54%	-43%
Airbus A330/RR	77%	-68%	-43%	-63%	-44%
Airbus A330/PW	117%	-69%	-46%	-35%	-29%
Airbus A340	229%	-75%	-34%	-32%	-14%
Boeing B757	66%	-84%	-31%	-65%	-49%
Boeing B767	93%	-90%	-28%	-58%	-43%
Average	101%	-81%	-34%	-53%	-38%

5.3 Changes in NOx-Emissions

Table 5-3: Differences in NOx-emissions (operational LTO to ICAO LTO)

Aircraft	Take-off	Climb-out	Approach	Taxi / Idle	LTO Cycle
Airbus A319	97%	-94%	-52%	-58%	-41%
Airbus A320/DAC	49%	-86%	-45%	-60%	-44%
Airbus A320/SAC	59%	-85%	-55%	-54%	-43%
Airbus A321	41%	-84%	-47%	-54%	-42%
Airbus A330/RR	46%	-75%	-65%	-63%	-41%
Airbus A330/PW	120%	-71%	-72%	-35%	-20%
Airbus A340	203%	-75%	-54%	-32%	4%
Boeing B757	32%	-86%	-48%	-65%	-50%
Boeing B767	37%	-90%	-47%	-58%	-47%
Average	76%	-83%	-54%	-53%	-31%

It can be seen that the A340 NOx emissions are slightly higher than with the ICAO cycle. This is due to the facts that the aircraft has often operated at a very high actual take-off mass

(240 t) and that the take-off phase with 2.5 minutes (ICAO: 0.7 minutes) is off-setting the lower fuel flow and NOx-emissions of the other phases.

The comparison is generally limited by the differences in the definitions of the LTO modes, in particular the phases take-off and climb-out. Nevertheless, the operational LTO cycle also describes the movements of an aircraft between ground and 3000 ft.

5.4 Comparison with Zurich Airport Emission Inventory

Zurich airport has calculated emission inventories already with a detailed methodology by using the actual aircraft-engine-combinations (tail number) and the actual taxi-times as recorded by the airport's aircraft operations data base system (figure 5-1, middle column). All other times in mode, as well as the fuel flow and emission indices were as specified by ICAO in the Engine Emission Data Bank .

By applying the obtained average correction factor for fuel and NOx, operational NOx emissions can be calculated for the LTO cycle and set in relation to the overall airport induced emissions.

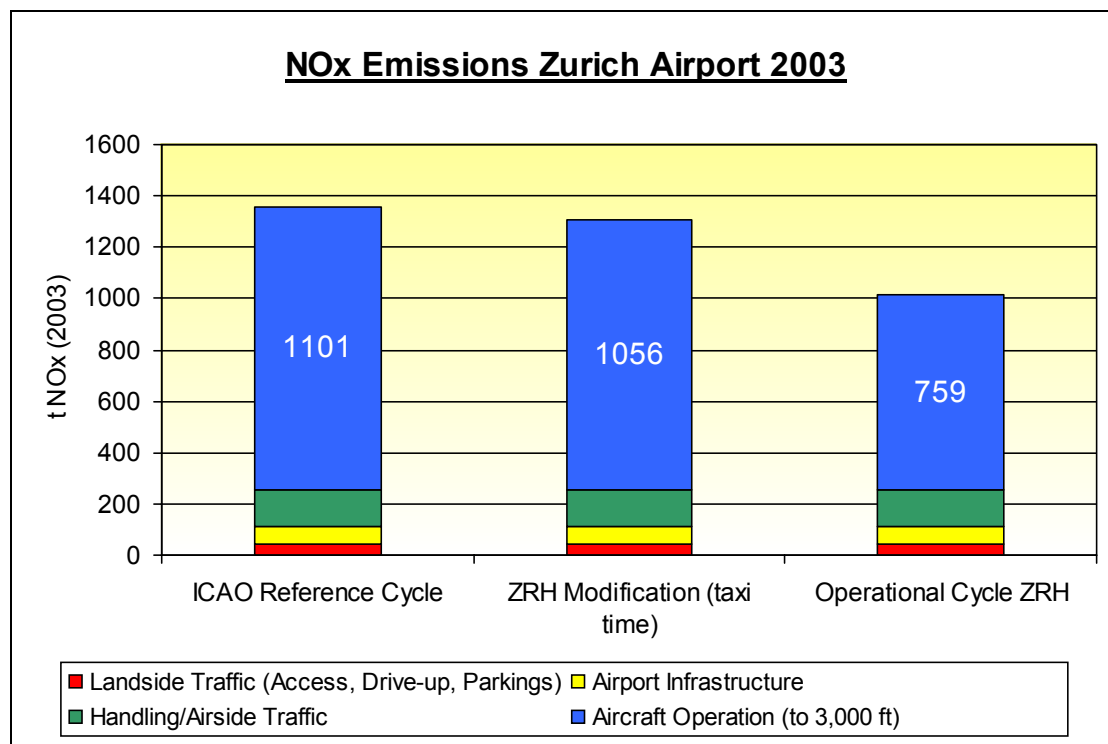


Fig. 5-1: NOx-Emissions Zurich Airport 2003 (134,650 aircraft cycles)

As can be seen from figure 5-1, operational NOx-emissions are significantly lower than the according reference cycle emissions. Further consequences will be seen when using the operational emission inventory as input into a dispersion model. In the case of Zurich airport, the LASPORT model has been successfully used in the past. It can easily be adapted to modified fuel flow and emission indices.

6 Outlook

The findings as described in chapter 5 provide a rough estimate on the effects on fuel consumption and NOx-emissions by using operational data instead of reference data. For more precise assessment, operational data would have to be obtained for all aircraft-engine-combinations, or at least for a representative sample. In this case, more aircraft have to be evaluated and a proper grouping has to be made.

A different option is to develop guidance on how to calculate emissions based on additional non-sensitive, static aircraft and airport data.

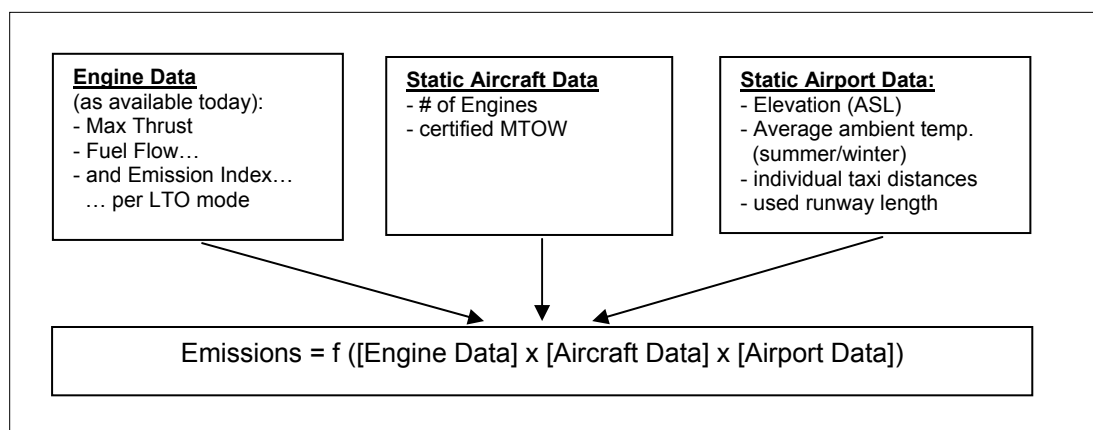


Fig. 6-1: Option for calculating operational LTO emissions.

The additional information is usually available (at least better than dynamic data like ATOW or actual ambient temperature).

Any guidance that can be described in a "mathematical formula" can also be implemented into a computer program to calculate the LTO emissions.

It will be necessary to enhance the today's methodology for a more precise assessment of local air quality. More and more, these emission inventories, in combination with dispersion modelling, will be the base line for local or national authorities to impose mitigation plans on airports to reduce the impacts by reducing the emissions from the airport system.

7 Appendix A

Boeing Fuel Flow Curve Fitting Method³

1. Background

- 1.1. Boeing had developed a method for estimating emissions at altitude flight conditions based on the Emission Indices and fuel flow for the four LTO certification modes as part of the NASA/AESA (Atmospheric Effects of Stratospheric Aviation) Program, in order to generate a global 3-D gridded emission inventory [Ref: NASA, 1996⁴]. This required estimation of the emissions at power levels other than the set mode points. The method adopted was to plot the Emissions Indices and fuel flow on a logarithmic basis and make a series of linear fits between pairs of mode points. This gave agreement with more rigorous and proprietary methods that was acceptable for the purposes of inventory generation. This curve fit method has been modified since originally developed and is widely used.

2 Detail

- 1.2 Figure B-1 shows an example fit
 1.3 for EINO_x three linear fits are made between each pair of points [7% to 30%; 30%-85% and 85% to 100%]
 1.4 for EIHC and EICO two linear fits are made by extrapolating the line that fits the 7% and 30% power points to where it intersects the horizontal line that represents the average EI of the 85% and 100% power points
 1.5 knowing the fuel flow for any other specific condition, the EIs can be estimated from the curve fit

- END -

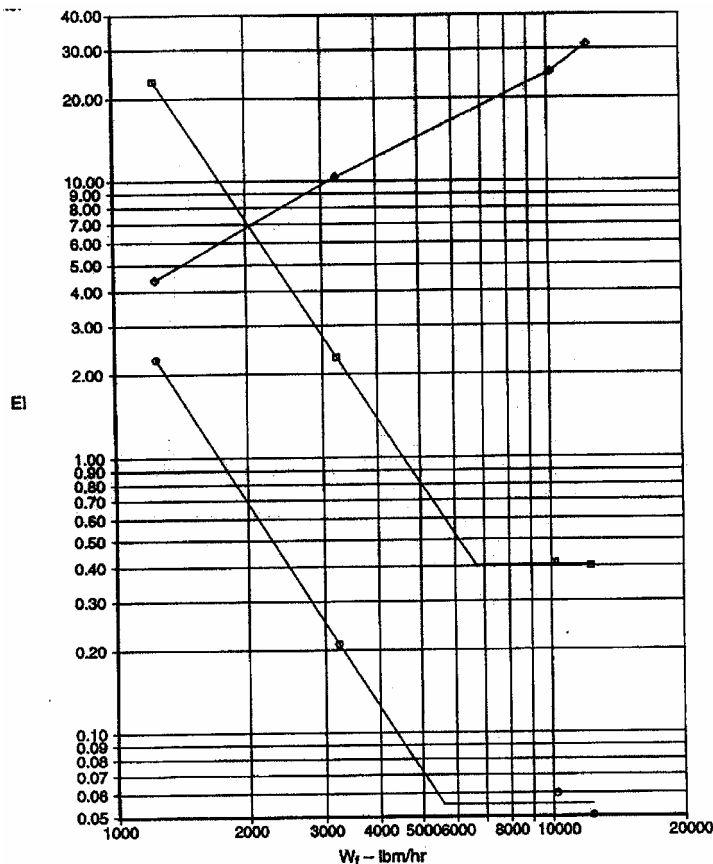


Figure B-1: Example curve fit

³ CAEP/6-IP/5, Appendix B, November 2003

⁴ Baughcum S L, Tritz G T, Henderson S C and Picket D C: "Scheduled civil aircraft emissions inventories for 1992: Database development and analysis" NASA Contract Report 4700.

8 Appendix B

Interpolation formula:

For

$$EINOx'_{TO} = \text{POTENZ}(10; (\log EINOx_{TO} - \log EINOx_{CL}) / (\log ff_{TO} - \log ff_{CL}) * (\log ff_{TO} - \log ff_{CL}) + \log EINOx_{CL})$$

Where:

EINOx = emission index NOx (ICAO)

EINOx' = interpolated emission index NOx

TO = take-off

CL = climb

ID = idle

ff = fuel flow (ICAO)

ff' = measured fuel flow (EMS)

- The EINOx for the other phases are calculated accordingly.
- Where the ff'_{ID} was lower than the ff_{ID} , then the $EINOx_{ID}$ has been used unchanged.