

Taxi-Emissions at Zurich Airport

Calculation Analysis and Opportunities



Contents

1.	Introduction	3
1.1.	Background	3
1.2.	Purpose of this Study	3
1.3.	Data and Models	3
2.	Relevance of Taxi-Emissions at Zurich Airport	4
2.1.	LTO Emission Calculations	4
3.	Modelling of Taxi-Emissions	7
3.1.	Taxi-Emission Parameters and Calculation	7
3.2.	Sensitivity Analyses	7
3.2.1.	Sensitivity of taxi-out time	7
3.2.2.	Sensitivity of fuel flow	9
3.2.3.	Sensitivity of emission indices	11
3.3.	Total Sensitivity and Conclusions	12
4.	Effects of Operational Opportunities in Taxiing	14
4.1.	Single engine taxi-in operations	14
4.2.	Other alternative taxi operations	14
4.3.	Departure Manager	17
4.4.	Conclusions	17
	Annexes	18
A.1.	Definition Operational Flight Cycle	18
A.2.	Zurich Airport Layout	19
A.3.	List of Abbreviations	20

1. Introduction

1.1. Background

Local air quality at and around airports is influenced by the airports operations, including the aircraft operations. The concentrations depend on the amount of emissions and the meteorological and atmospheric conditions. Such concentrations are usually determined by the use of numerical models that both calculate the emissions based on activities and their emissions and the concentration based on meteorological parameters and a dispersion algorithm.

As described in ICAO Doc 9889, Airport Air Quality Manual, there are various levels and approaches to assess the air quality situation. Models are available that describe the effects of airport related operations on the local air quality. Depending on the results and analysis, airports may opt to implement measures to reduce the concentration of pollutants by reducing the emissions.

One very important source of emissions is the aircraft. Their emissions, mostly assessed in the landing and take-off cycle (LTO) are usually the largest single emission source at an airport. However, there can be a significant variation in the results, depending on the available operational information and models.

1.2. Purpose of this Study

The purpose of this study is to analyze the taxi/idle-emissions of aircraft in more detail. While some phases of the landing and take-off cycle like take-off and climb out have been studied and modelled in detail, the taxi or idle phase is usually based on default information with little variation. However, it is this phase of the LTO-cycle that can be influenced to some degree, e.g. by operational or technical measures.

The study discusses the relevance of the taxi emissions in the context of aircraft performance based calculations and the impact relevance of emissions below the atmospheric mixing height. It further explores ways of improving the emission calculation and finally analyses the benefits of selected operational measures in taxi operations.

1.3. Data and Models

The study is based on actual air traffic at Zurich Airport, usually from the year and 2016. All engine fuel and emission factors are based on the ICAO Engine Emission Database.

The study further uses data and information kindly provided by Swiss International Air Lines that reflect real operations.

Emission calculations are performed using the airport air quality model LASPORT (version 2.2) or are based on calculation tables.

2. Relevance of Taxi-Emissions at Zurich Airport

2.1. LTO Emission Calculations

The LTO cycle comprises several phases of the aircraft movement as illustrated in figure 1. While in the past, a simple LTO-cycle of only 4 phases (taxi, take-off, climb-out and approach) has been considered, an operational flight cycle is used today for more advanced studies. Depending on the approach, performance based modelling is introduced for the take-off and climb-out phases (E, F). Studies¹ have demonstrated the significance of performance based calculations, as emissions and thus potentially also concentrations can vary significantly.

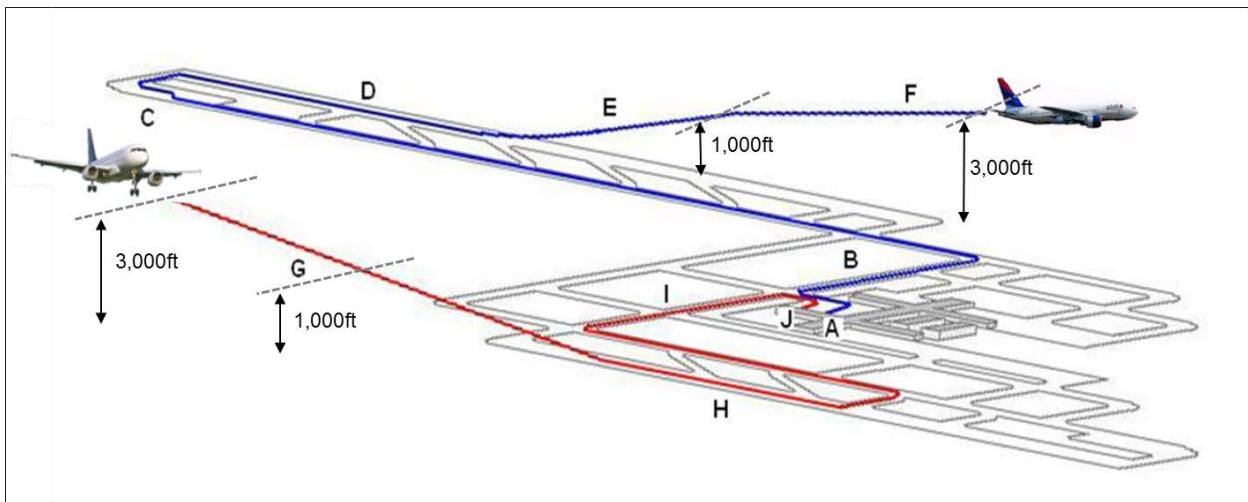


Figure 1 Operational LTO Cycle (ICAO Doc 9889, figure 3-A1-1).

Another important factor is the consideration of the impacts. Traditionally, emissions are calculated within the full certification LTO-cycle, which extends up to an elevation of 3,000 ft above ground (assumed average mixing height in the atmosphere). However, only emissions up to an elevation of approximately 1,000 ft (305 m) above ground actually contribute to the ground concentrations². This additionally introduces another significant variation in the total emission mass of the LTO cycle and to the break down into the phases.

As such, a first emission calculation has been done as described in table 1.

¹ E.g. Zurich Airport: ZRH Air Quality Assessment Sensitivities V2, May 2012.

² EUROCONTROL: ALAQS project: Sensitivity Analysis Zurich Airport 2004. Study EEC/SEE/2006/003

	Standard LTO	Improved LTO	Impact LTO
LTO-Cycle	Certification LTO + average taxi-time	Operational LTO cycle	Impact LTO cycle
Performance	None	Take-off (phases E, F)	Take-off (phases E, F)
Cut-off elevation	3,000 ft	3,000 ft	1,000 ft
Taxi-time	Average for Zurich Airport (17.45 min)	Individual for each movement	Individual for each movement

Table 1 LTO-emission calculation approaches

Figure 2 shows the emissions for selected substances in relation to the respective LTO cycle definition (as in table 1). The most significant change can be observed for NOx where actually only approximately 50% of the initially calculated NOx emissions are relevant for the ground based NO₂ concentrations. Similarly, the fuel burn for the LTO cycle decreases by 39%.

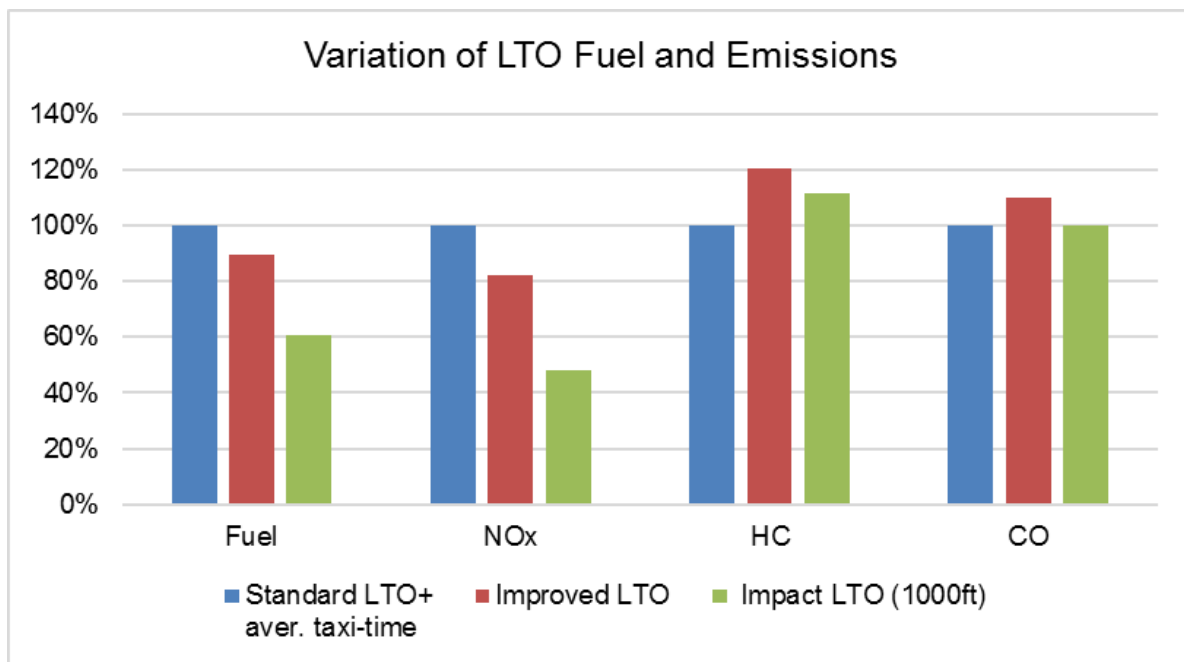


Figure 2 Fuel and Emissions depending on LTO definitions (Zurich Airport, 2016)

For the purpose of this study, the relevance of the taxi phase within the total LTO-cycle has been analyzed in detail. The results for the fuel burn and NOx (figure 3) demonstrate that the share of the taxi phase is indeed much larger when looking at the impact LTO-cycle rather than the traditional certification LTO-cycle.

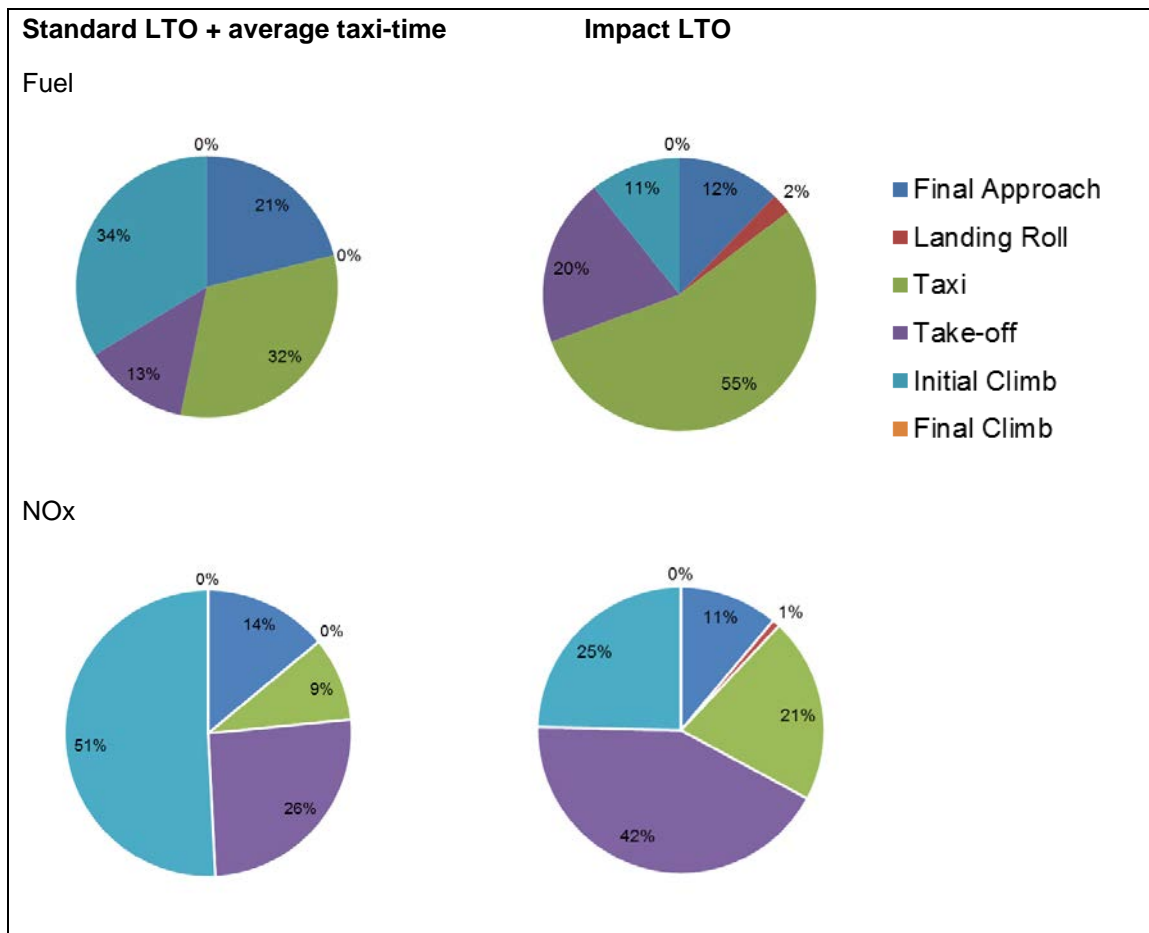


Figure 3 Relevance of fuel burn and NOx for taxi within the LTO cycle (Zurich, 2016)

The total taxi fuel burn raises from a share of 32% in the standard LTO cycle to 55% in the impact LTO cycle. The split of the taxi phase is approximately 73% for taxi-out and 27% for taxi-in in the scenario “impact LTO”. The NOx emissions raise from 9% (standard LTO) to 22% (impact LTO).

This demonstrates that the taxi-phase is indeed more important within the LTO cycle when viewed from the more advanced (and environmentally relevant) impact LTO cycle.

3. Modelling of Taxi-Emissions

3.1. Taxi-Emission Parameters and Calculation

The taxi-emissions are calculated using part of the LTO cycle as depicted in figure 1 (phases B, C, I). The information required and used for calculations is listed in table 2. Depending on the approach, more and detailed information is required to calculate fuel burn and emissions.

The resulting taxi-emissions are the product of the three factors time, fuel flow, and emission index.

Parameter	Description and Sensitivity
Taxi-out time	The taxi-out time expands from the moment the main engine is started-up and established until the engine power setting is set to acceleration for take-off. Sensitivities: <ul style="list-style-type: none"> • Push-back operation or self-powered operation (depending on the stand location); • Stop-and-go operations (e.g. for crossing taxiways, runways, de-icing, etc); • Queueing (on the way to or at the runway threshold).
Fuel flow	The fuel flow is measured and reported at the thrust level of generally 7%, irrespective of the actual required power setting to accelerate, move or idle the aircraft. It can vary between approx. 4% to maybe 25-30% (break away power) and is also speed dependent.
Emission index	The emission index for the regulated substances is measured and reported in correspondence with the thrust level of 7% for the fuel flow. It varies depending on the set thrust level.

Table 2 Taxi-emission parameters

3.2. Sensitivity Analyses

3.2.1. Sensitivity of taxi-out time

The first analysis is done for the taxi-out times of various aircraft from different aircraft stands to the various runways (cf Annex 2 for airport map). The actual measured time in minutes is based on detailed airline analysis, while the calculated and the modelled times are based on airport information and models:

- Actual times: Detailed airline information from aircraft data acquisition systems.
- Calculated times: Difference between the logged take-off time (from the runway) minus the off-block time; any queueing time is thus automatically accounted for.
- Modelled times: Analysis on average taxi-speed and queueing time based on radar tracks in combination with a default taxi routing from stand to runway to determine the taxi distance.

Taxi-routing	Actual measured taxi-time (min)	Calculated taxi-out time (off-block/ take-off; min)	Modelled taxi-out time with radar tracks (min)
Large Aircraft: Push-back to RWY	14.21	16.65	16.92
Medium Aircraft: Push-back to RWY	12.31	14.45	16.02
Small Aircraft: Push-back to RWY	11.59	13.85	13.13
Small Aircraft: Self-power to RWY	12.75	12.17	15.10
Regional Aircraft: Push-back to RWY	10.64	12.21	11.33
Regional Aircraft: Self-power to RWY	12.70	9.92	11.42
Average: Push-back to RWY	11.97	14.12	13.75
Average: Self-power to RWY	12.72	10.81	11.83

Table 3 Comparison of various taxi-out times per operation (cf. Annex 2 for map)

The detailed analysis revealed a remarkable difference between taxi-times from push-back stands to runways and from self-power stands to runways. Indeed, the reflection of the actual operations as displayed in figure 4 shows the difference between those two operations. In the case of push-back stands, the calculated taxi-time is overestimating the actual taxi-time (+2.15 min) while the self-power stand taxi-time is underestimated (-1.9 min).

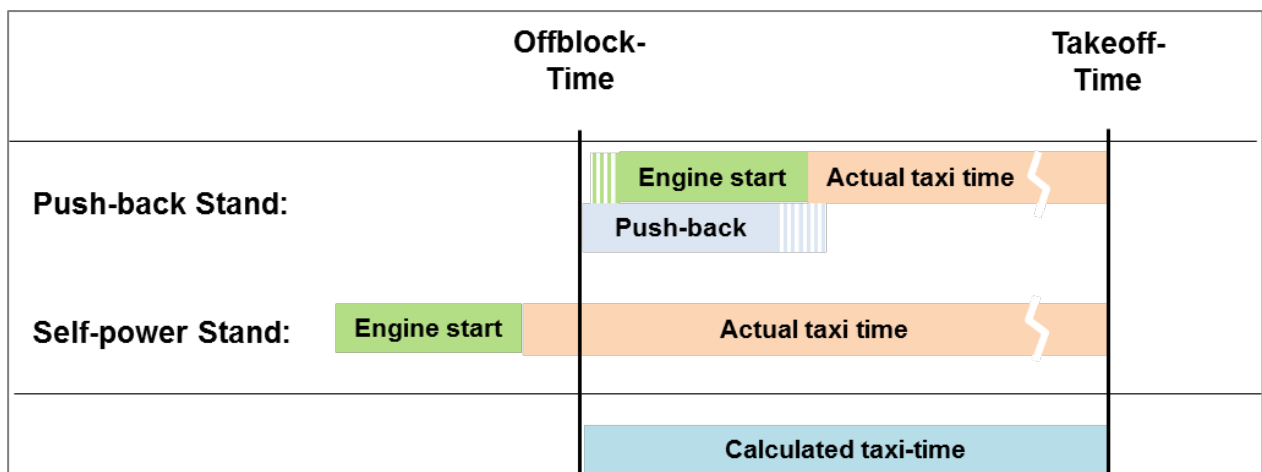


Figure 4 Actual taxi-time difference between stand properties (bars are not to scale)

The following table shows the distribution between contact stands (all push-back) and open stands (mostly self-power) for Zurich airport, considering the aircraft size on the basis of 122,288 departures of those aircraft groups.

Aircraft Group	Group share	Contact stand operations	Open stand operations
Large (A340, A380, B777)	5.8%	95.5%	4.5%
Medium (A330, B767, B787)	7.0%	96.6%	3.4%
Small (A320, B737, CS10)	55.0%	87.1%	12.9%
Regional (E170, F100, RJ85)	32.1%	33.0%	67.0%
Total	100%	70.8%	29.2%

Table 4 Contact/open stand distribution of aircraft groups (Zurich Airport, 2016)

Given that overall, more aircraft are parked on contact stands than open stands and that large aircraft with higher fuel consumption are mostly parked on contact stands and regional aircraft with low fuel consumption on open stands, the overall result will be an overestimation of the total taxi-out time (table 5).

Scenario	Total airport taxi-out times (min/a)
Uncorrected calculation (using off-block/take-off time stamps)	1'611'724
Corrected with rounded average correction (+/-2 min) for push-back and self-power stand taxi phase operations	1'486'118
Difference	125'606 -7.8%

Table 5 Taxi-out time sensitivity results (Zurich Airport, 2016)

This means that on a weighted average, every taxi-out operation is overestimated by almost one minute each when using the standard offblock/take-off time stamps. In this study, the details and sensitivities of taxi-in operations have not further been analyzed.

3.2.2. Sensitivity of fuel flow

The second factor in calculating taxi emissions is the fuel flow. According to the ICAO certification LTO definition, the phase of taxi or idle is assumed to be at a uniform 7% thrust of the engine. The fuel flow – and the resulting emissions – have been measured and certified at this thrust level.

In an operational environment, however, taxi operations are more complex: turns, acceleration and deceleration as well as queueing result in changing thrust settings with resulting variable fuel flows. Technology developments also have yielded more efficient power and thrust usage. This resulted in actual taxi operations being performed at an average of less than 7% thrust.

Figure 5 illustrates the split between actual taxi time and queueing time for the different runways. The figure also shows the taxi speed during the actual taxiing (not queueing). The data – derived from ground radar tracks – show differences that are due to the overall taxi distance (e.g. higher share of taxiing vs. queueing for

Runway 16) and the general taxiway layout (e.g. longer, not-interfered taxiway to Runway 16 vs. shorter taxiways and –lanes to Runway 28). This analysis shows the potential variability in speed and thus fuel flow.

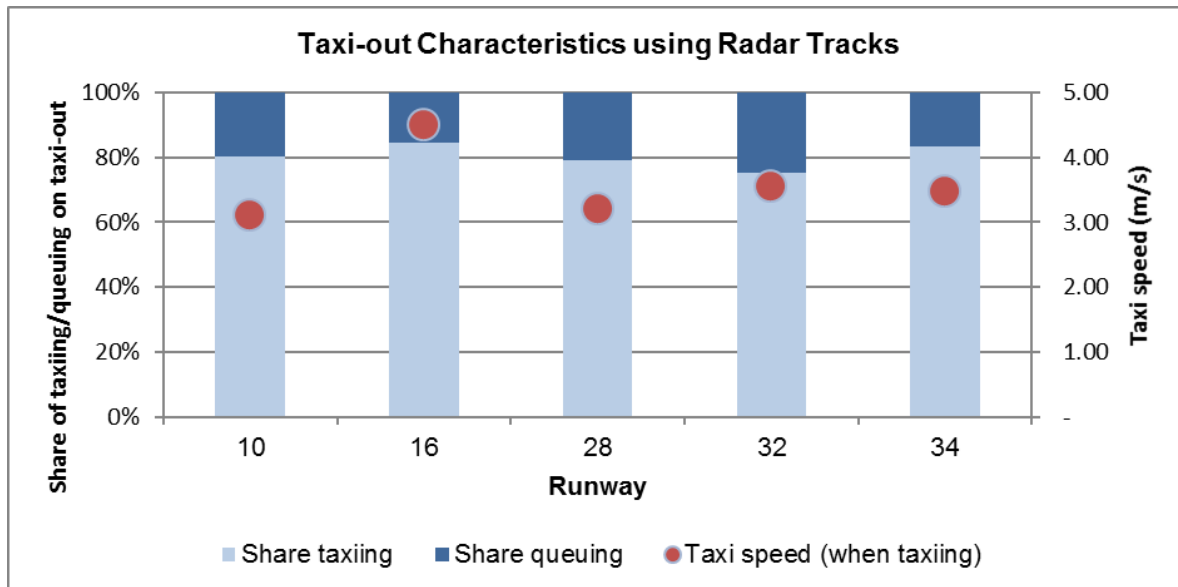


Figure 5 Average taxi-roll and idle/queuing ratios and taxi speed (Zurich Airport, 2016)

Table 6 shows the difference for some specific aircraft types between actual measured fuel flow during taxi operations and the respective certification fuel flow at 7% thrust (identical engines).

Aircraft	Measured fuel flow (kg/s)	Certification value 7% (kg/s)	Difference (certification higher)
A319	0.218	0.22	0.8%
A320	0.193	0.24	24.3%
A321	0.201	0.24	19.3%
A330-300	0.431	0.54	25.4%
A340-300	0.447	0.46	2.9%
RJ100	0.168	0.18	6.9%
B777-300ER	0.555	0.76	36.9%
CS100	0.146	0.16	9.2%

Table 6 Taxi fuel flow sensitivity

The variation in the difference was further analyzed in an attempt to find correlations with either the total installed thrust or the maximum take-off mass of the aircraft or a combination thereof. However, there seem to be not sufficient information or data to support any conclusions. To this end, it is suggested to use an average

-10% reduced fuel flow for aircraft of the categories «Regional/Small» and -15% fuel flow for aircraft categories «Medium/Large» for further sensitivity analysis.

3.2.3. Sensitivity of emission indices

The emission indices for the various regulated substances are dependent on the fuel flow of the engine including changes in fuel/air ratio and are neither static nor linear. As such, any change in fuel flow also triggers a change in emission index; this can be a positive or negative change. While there are agreed methods to interpolate emission indices for fuel flows between the certification thrust setting points of e.g. 30% and 85% (approach and climb out respectively), there is currently no method to account for emission indices below the 7% thrust fuel flow. One particular difficulty is the different combustion condition at ground idle of an engine running on wing and in an engine test cell. On wing, the engine provides electric power and bleed air, which have an influence on the combustion conditions at these low powers. The on board fuel flow recording provides real world fuel flow, which takes the additional engine loadings into account.

We therefore developed a method to use real world fuel flow and emission factors available from certification data for lower power settings to estimate changes in emission factors. We however point out that derived emission factors for below 7% thrust will be worst case for uncomplete combustion products (HC and CO) and best case for NOx. In order to derive emission factors for fuel flows below 7% thrust we analyzed the fuel flow at 7% thrust and the respective emission factors over a set of engines of the same model, but different installed maximum thrust. This would imply that a higher rated engine has a higher absolute fuel flow at 7% than a lower rated engine at the same thrust level. Given the known emission indices for either engine at 7%, a simple correlation can be established. Figures 6 and 7 demonstrate this approach using a smaller and a larger engine family with fuel flows and emission factors always at 7% thrust but different engine thrust ratings.

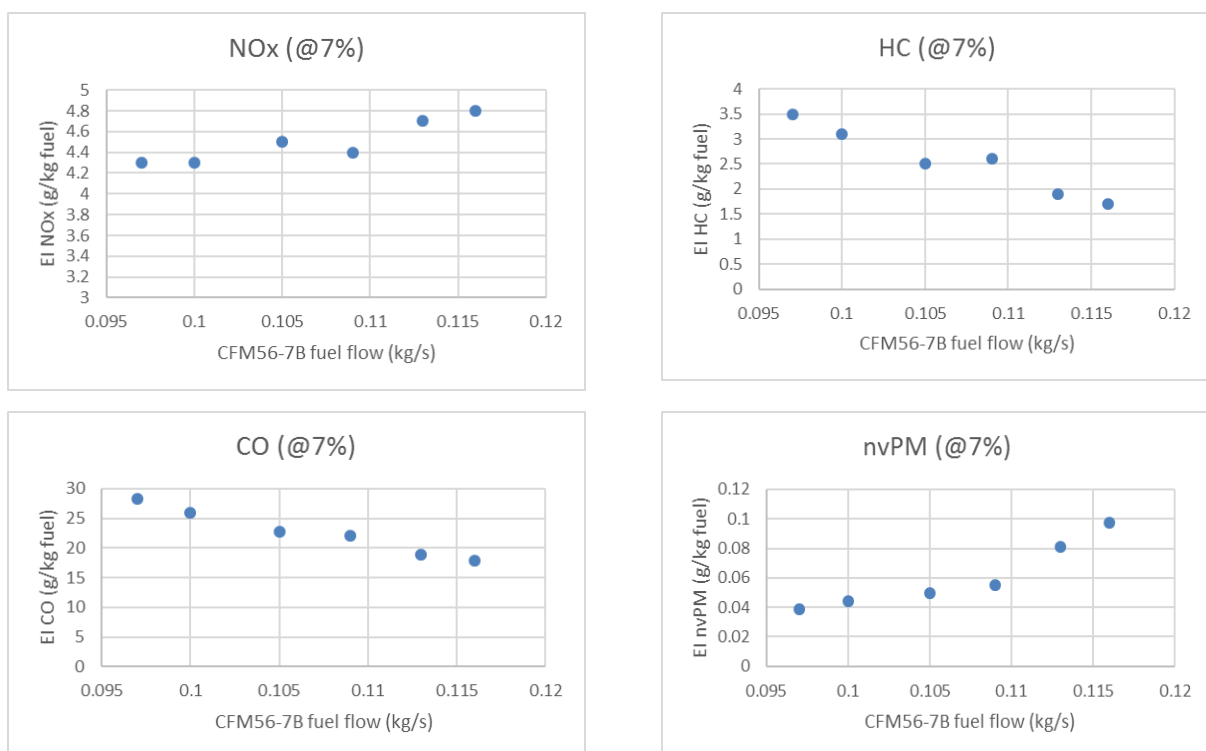


Figure 6 Fuel flow and emission factors CFM56-B7 engine family at idle thrust

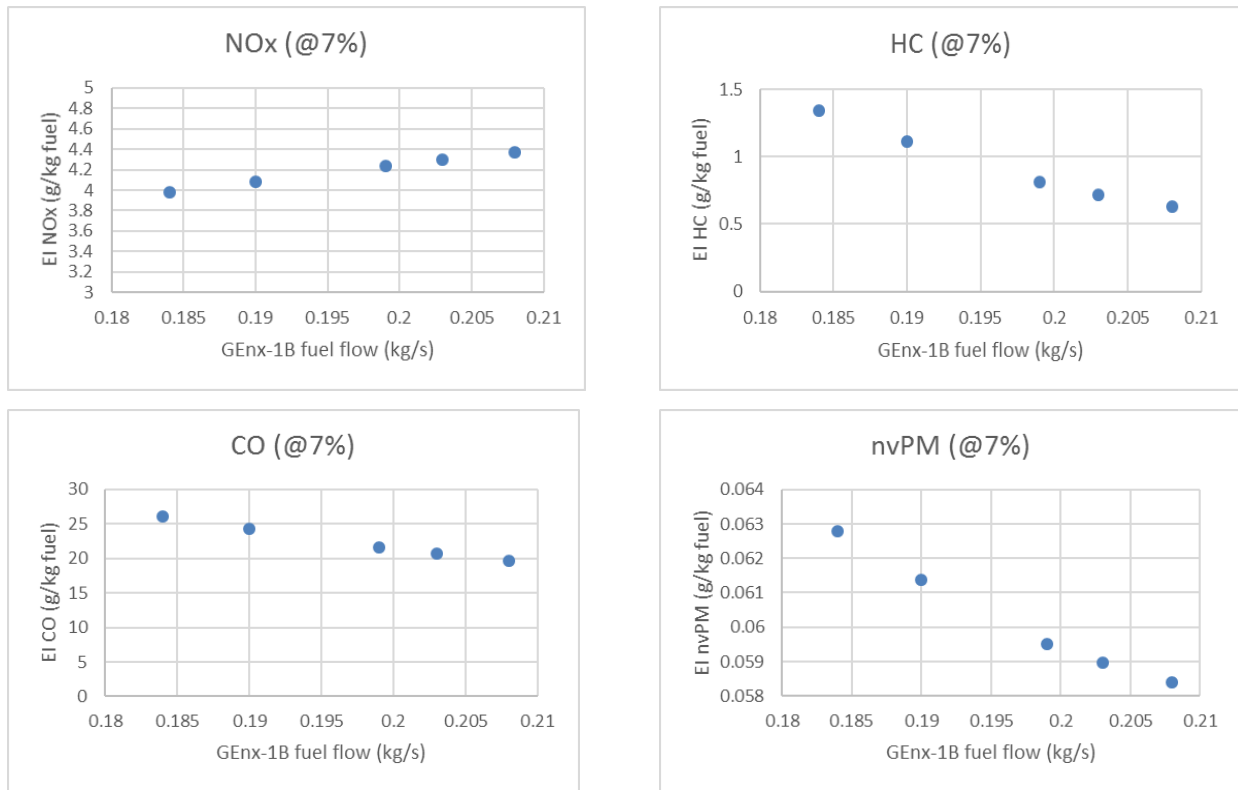


Figure 7 Fuel flow and emission factors GEnx-1B engine family at idle thrust

It is recognized that this is a simple extrapolation approach and more research is needed to derive robust adjustment factors, However, a simple table has been derived for the purpose of some further sensitivity analysis in this study.

Aircraft Group	FF	NOx	HC	CO	nvPM
Regional / Small	-10%	-5%	+25%	+15%	+150%
Medium / Large	-15%	-10%	+50%	+25%	+5%

Table 7 Generic adjustment of emission indices below 7% thrust

3.3. Total Sensitivity and Conclusions

As demonstrated in the previous sections, the actual taxi-times can vary significantly, together with the fuel flow and thus, as a consequence, the emission factors. For this study purpose, the effects have then combined and a refined approach applied versus the standard approach for calculating the taxi-emissions. Table 8 lists the differences for the fuel burn and the various substances emitted for the taxi-out phase and for the total impact relevant LTO.

Parameter	Standard Approach	Refined Approach	Difference
Taxi time	Using off-block/take-off times	Using corrections of +/-2 min for push-back/self-power stands	
Fuel flow	Fixed at 7%	modified (table 7)	
Emission indices	Fixed at 7%	modified (table 7)	
Results			
Taxi-time	1'611'724 min/a	1'486'118 min/a	-7.8%
Fuel Burn			
• Taxi-out	24,517.7 t/a	19,947.2 t/a	-18.6%
• Total impact-LTO	60,245.3 t/a	55,679.2 t/a	-7.6 %
NOx emissions			
• Taxi-out	106.0 t/a	88.5 t/a	-16.5%
• Total impact-LTO	679.1 t/a	661.6 t/a	-2.6%
HC emissions			
• Taxi-out	109.4 t/a	135.0 t/a	23.3%
• Total impact-LTO	160.3 t/a	185.0 t/a	15.9%
CO emissions			
• Taxi-out	826.8 t/a	886.6 t/a	7.3%
• Total impact-LTO	1,231.0 t/a	1,291.0 t/a	4.9%
nvPM emissions			
• Taxi-out	2.4 t/a	4.2 t/a	76.6%
• Total impact-LTO	6.8 t/a	8.6 t/a	26.6%

Table 8 Total sensitivities for refined taxi-out modelling (Zurich Airport 2016)

Conclusions

The use of refined information on current taxi operations has an impact on the fuel burn and the emissions during the total taxi phase. While results are quite lower for fuel burn and NOx emissions, they are higher for HC, CO and PM emissions, although PM emissions are still subject to quite a large uncertainty. The effect on the overall impact-relevant LTO-cycle is less pronounced and has only a minimal impact on the actual ground-based concentrations.

One of the benefits certainly lies in the better correlation between modelled and measured concentrations of pollutants at the airport. Another benefit lies in better information on potential benefits of measures taken to reduce emissions during taxing.

A potential next step could be to better model the taxi-in phase as well. The sensitivities are expected to be much smaller due to the usually shorter taxi-times in general and more even traffic flow.

For the practitioner in air quality modelling, it is important to realize the step-wise changes in results when refining the input data and modelling approaches. It further demonstrates that many airport air quality studies – based on standard approaches and certification data – leave room for improvements.

4. Effects of Operational Opportunities in Taxiing

4.1. Single engine taxi-in operations

The taxi procedure with less than all engines operating is often referred to as “single engine taxiing” (SET). However, for aircraft equipped with four engines, the two inner ones would be turned on/off later/sooner, for aircraft equipped with three engines, the centre one would be turned on/off later/sooner and only aircraft equipped with two engines (although this today is the majority) would have one engine turned on/off later/sooner and would perform single engine taxiing. The use of less than all engines for taxi usually results in a slightly higher fuel consumption of the remaining engine(s) and – depending in the requirements or recommendations of the aircraft manufacturers – the additional use of the APU.

Single engine taxi operation is already widely applied by many airlines at many airports, mainly for taxi-in operations. Further analysis from an airline serving Zurich Airport has given the following results:

- Single engine taxi is performed on the inbound operations only, not on outbound.
- There is 10-20% higher fuel consumption on the one single engine because of higher load to move the aircraft.
- The net fuel reduction lies between 30-40%, both for two and four engine aircraft.
- The APU is usually not used, unless prescribed so by the manufacturer; it also depends on the engine cool down time of between 1-3 minutes.

The following table shows the analysis and sensitivity for the application of single engine taxi-in procedures at Zurich Airport. For the calculations, the standard fuel flow and emission indices have been used (no corrections).

Scenario	Current	All airlines	Maximum
Description (baseline: no SET)	Average of 20% of taxi-in operations of this one airline	Average of 20% of taxi-in operations, but all airlines serving ZRH	100% taxi-in operations by all airlines serving ZRH
Fuel Burn reduction	35 t/a	466 t/a	2,339 t/a
NOx-emission reduction	0 t/a	2 t/a	11 t/a
CO ₂ -emission reduction	110 t/a	1,471 t/a	7,353 t/a

Table 9 Single engine taxi-in fuel and emission benefits

4.2. Other alternative taxi operations

Several alternatives to the conventional standard aircraft taxi procedures are currently being developed or tested [1]. The standard taxi procedure comprises leaving the aircraft parking positions either by means of a tug (when push back is required) or own main engines (when the parking position can be left self-powered)

and moving the aircraft to the runway by means of all engines operating. The alternatives for taxiing in addition to the “single engine taxi operations” described above currently include:

- Operational towing is the procedure where the aircraft is not only being pushed back from an aircraft stand, but towed to the runway threshold afterwards. The aircraft remains connected to the tug (usually towbarless systems) with its APU running for provision of electrical and pneumatic energy. The tractor driver moves the plane as close to the runway as possible where the aircraft is disconnected from the tractor which then returns to the apron.
- Taxi roboter: This system is essentially the same as the operational towing, with the difference that the aircraft pilot controls the tractor remotely until disconnection.
- Electric taxiing: This system allows aircraft to taxi without requiring the use of aircraft engines by using the Auxiliary Power Unit (APU) generator to power motors in the main gear or nose gear wheels.

All discussed systems have their advantages and some disadvantages. Their weighting depends on local circumstances (legal, operational, company policies). The decision if and what system should be used remains primarily with the airlines. Airports, as well as other parties may have a significant supporting role: Providing infrastructure (e.g. service roads, GSE staging area), specially equipped GSE (tow tractors) or adapted taxi procedures.

The described procedures (including – for comparison – the “single engine taxi”) have been analysed in terms of fuel consumption and gaseous emissions (NOx, HC, CO and CO₂). Assumptions as well as results for fuel burn and emissions are listed in the following tables.

Element	Assumptions
Aircraft	Airbus A320
Engines	2x CM56-5B4/2P (ICAO UID 3CM021)
APU	Type “Smaller (100 ≤ seats < 200, newer types) of ICAO Doc 9889
Tractor	Towbarless tow tractor, 163 kW, operated at 25% load

Table 10 General assumptions for alternative taxi analysis

The schematic procedures for an operation contact gate – runway are displayed in the following figure. It shows the use of the tow tractor, the APU and the main engines.

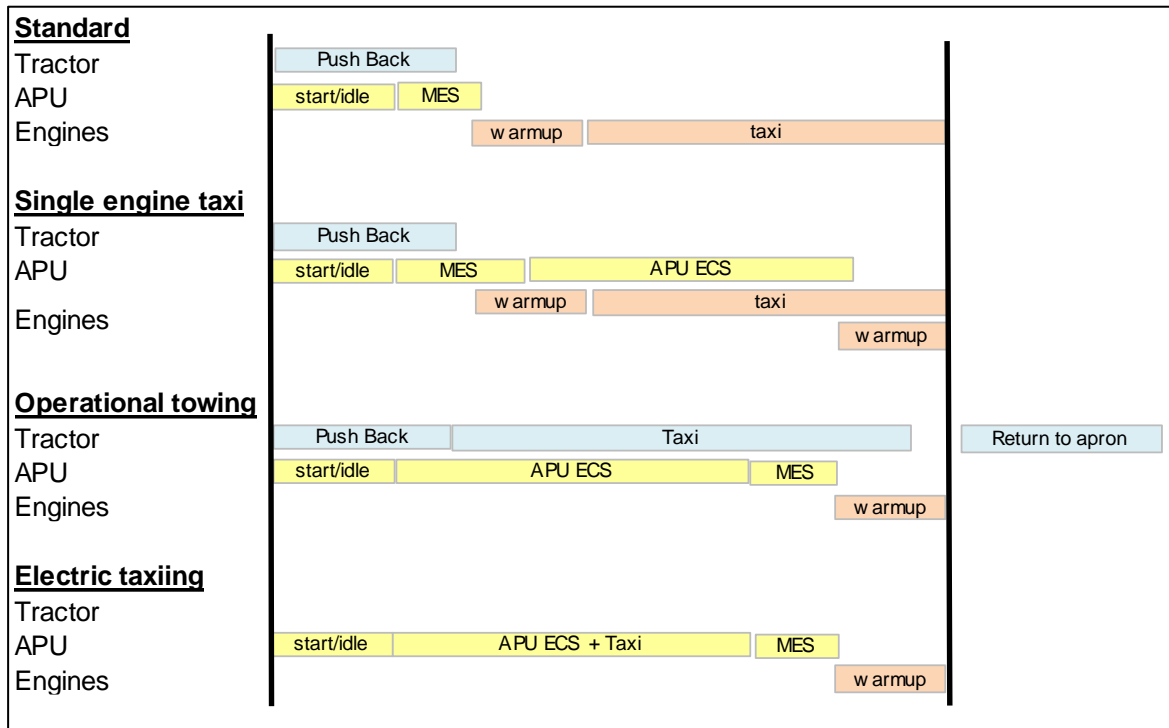


Figure 8 Aircraft taxi procedures overview (bars not to scale)

Scenario	Current taxi procedure	Single engine taxi	Operational towing	Electric taxiing
Operations				
Engines for taxi	Both used	One used	None used	None used
Engine warm up	4 min each	4 min each	4 min each	4 min each
Taxi thrust setting	7%	8.4%	0%	0%
APU used	ECS during pushback and MES only	ECS during taxi and MES	ECS during taxi and MES	ECS during taxi and MES (no higher load assumed)
Tractor	Push back only	Push back only	Push back, towing to RWY and return	None
Pushback time	2 min	2 min	2 min	0 min
Taxi time (without pushback)	15 min	15 min	20 min	20 min
Emission Results (for one single narrow-body aircraft taxi-out operation, using certification data)				
CO ₂ -emissions (kg)	707.2	536.5	328.6	312.6
NO _x -emissions (kg)	0.91	0.80	0.73	0.55
HC-emissions (kg)	0.92	0.65	0.39	0.38
CO-emissions (kg)	8.87	5.80	2.72	2.65

Table 11 Modelling results for alternative taxi-out procedures

The results demonstrate that systems that do not require the aircraft’s main engines or a tow tractor show the lowest emissions, even if the overall taxi time might be longer (calculation assumption). Scaled to all “Small”-size aircraft departures in 2016 (A320 types), the benefits against the standard procedure would be -7 t NOx (single engine taxi), -12 t NOx (operational towing) and -24 t NOx (for electric taxiing).

4.3. Departure Manager

The Airport Collaborative Decision Making concept (A-CDM) developed by EUROCONTROL and supported by ACI and IATA has been partly implemented at Zurich Airport in May 2012. With the implementation of Collaborative Management of Flight Updates (Departure Planning Information (DPI) exchange with NMOC in August 2013 Zurich Airport became a full A-CDM Airport.

The big advantage is the direct exchange of local information to the Network Manager Operations Center (NMOC) at EUROCONTROL. Therefore, the network impact of flights departing from A-CDM airports can be assessed more accurate and in return essential ATFM regulations can be allocated to the specific needs. In terms of potential environmental benefits, the most important is an average reduction of the taxi-out times of 40 seconds per flight in 2014 compared to 2012 [1]. This reduction cumulates to be approx. 1,450 hours of taxi-time (or 60.4 days).

The environmental benefits have been quantified based on the operational benefits assessment and the airports aircraft, emission and operations database [2]. All aircraft are considered individually in terms of aircraft and engine combination (aircraft registration/engine UID). The quantified operational improvement for the A-CDM 2014 of 40 seconds lower taxi time per flight has then been applied uniformly to all scheduled and charter operations. The resulting emission reductions are listed in the following table.

Emission Reductions	A-CDM 2014	
		% of all taxi-emissions
Reduction of CO ₂	3,680 t	1.4%
Reduction of NOx	4.8 t	0.5%
Reduction of HC	4.4 t	3.0%
Reduction of CO	34.9 t	3.0%
Reduction of PM	0.1 t	1.1%

Table 12 Environmental Benefits of A-CDM (Zurich Airport 2014)

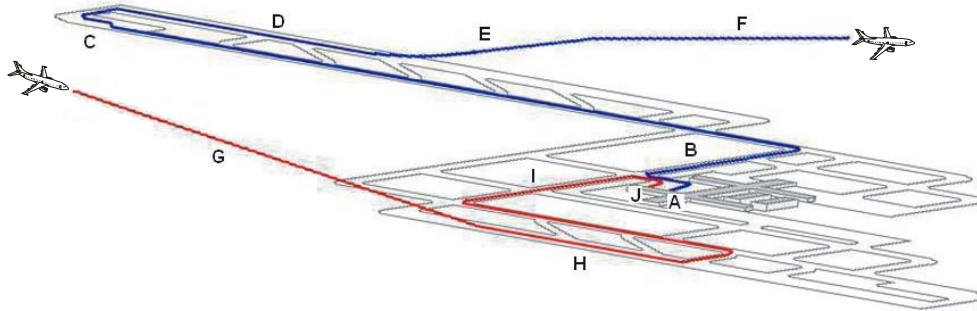
4.4. Conclusions

The implemented measures show positive effects on fuel burn and emissions. These effects can be increased usually by a more widely implementation among the airlines and operations. One of the prerequisites is the availability of the required technology (e.g. for electric taxiing); however, the development and certification of such technologies may be very time-consuming and costly.

Best results in emission reductions are achieved when combining all opportunities and deploy them to all users at an airport.

Annexes

A.1. Definition Operational Flight Cycle



DEPARTURE

- A. *Engine start.* It is normal to start the main engines prior to, or during, pushback from the aircraft gate/stand. Where aircraft do not require pushback, the main engines are started immediately prior to taxi.
- B. *Taxi to runway.* Aircraft typically taxi out on all engines to the runway or holding area prior to entering the runway, though aircraft may taxi on fewer than all engines under some circumstances. Taxi-out is normally carried out at the idle/taxi power setting, apart from brief bursts of power to overcome the initial inertia at the start of taxiing or, if necessary, to negotiate sharp turns.
- C. *Holding on ground.* Where necessary, aircraft may be required to hold in a queue while awaiting clearance to enter the runway and taxi to the take-off position. Main engines are normally set to idle thrust with brief bursts of power to move into position.
- D. *Take-off roll to lift-off.* The aircraft is accelerated along the runway to the predetermined rotation speed at the end of the take-off run with the main engines set to take-off power. Operators rarely use full power for take-off; rather, a predetermined thrust setting is set at the beginning of the take-off roll. Operators use either derated take-off thrusts or, more often, reduced (e.g. flexible) thrust settings, which are determined by the aircraft's actual take-off weight, runway length and prevailing meteorological factors. Throttle handling during the take-off run is sometimes staged in the early part, whereby the throttles are initially set to an intermediate position, then a few seconds later are advanced to the predetermined take-off power setting.
- E. *Initial climb to power cutback.* After leaving the ground, the undercarriage (i.e. wheels) of the aircraft is raised and the aircraft climbs at constant speed with the initial take-off power setting until the aircraft reaches the power cutback height (i.e. between 800 and 1 500 ft AGL) where the throttles are retarded.
- F. *Acceleration, clean-up and en-route climb.* After the throttle cutback, the aircraft climbs at a thrust setting less than that used for take-off with flap/slat retraction following as the aircraft accelerates and reaches cruising altitude.

ARRIVAL

- G. *Final approach and flap extension.* The stabilized final approach from the final approach fix (FAF) follows a relatively predictable glide slope at low engine thrusts. Thrust settings are increased to counteract the additional drag as flaps and the undercarriage are lowered, while speed decreases towards the flare.
- H. *Flare, touchdown and landing roll.* Throttles are normally retarded to idle during the flare and landing roll. This is followed by application of wheel brakes and, where appropriate, reverse thrust to slow down the aircraft on the runway.
- I. *Taxi from runway to parking stand/gate.* Taxi-in from the runway is similar to taxi-out described above; however, operators may shut down one or more engines, as appropriate, during the taxi-in if the opportunity arises.
- J. *Engine shutdown.* Remaining engines are shut down after the aircraft has stopped taxiing and power is available for onboard aircraft services.

Source: ICAO, Doc 9889: Airport Air Quality Manual, 1st Edition, 2011, Figure 3-A1-1

A.2. Zurich Airport Layout



Zurich Airport map with Runways (numbers) and main aircraft stands (blue: push-back; red: self-power)

A.3. List of Abbreviations

A-CDM	Airport Collaborative Decision Making
APU	Auxiliary Power Unit
ATFM	Air Traffic Flow Management
CDM	Collaborative Decision Making
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
ECS	Environmental Control System (air conditioning of the aircraft through the APU)
FB	Fuel Burn
FF	Fuel Flow
FOCA	Federal Office for Civil Aviation, Bern
GSE	Ground Support Equipment
HC	Hydrocarbon
ICAO	International Civil Aviation Organization, Montreal
kN	Kilonewton (thrust)
kW	Kilowatt (power)
LASPORT	LASAT for Airports
LTO	Landing and Take-Off Cycle
MES	Main Engine Start (through the APU)
NO _x	Nitrogen Oxides
nvPM	non-volatile particulate matter
PM	Particulate Matter
RWY	Runway
SET	Single engine taxi
SETI	Single engine taxi-in
TWY	Taxiway

Figures

Figure 1	Operational LTO Cycle (ICAO Doc 9889, figure 3-A1-1).	4
Figure 2	Fuel and Emissions depending on LTO definitions (Zurich Airport, 2016)	5
Figure 3	Relevance of fuel burn and NOx for taxi within the LTO cycle (Zurich, 2016)	6
Figure 4	Actual taxi-time difference between stand properties (bars are not to scale)	8
Figure 5	Average taxi-roll and idle/queuing ratios and taxi speed (Zurich Airport, 2016)	10
Figure 6	Fuel flow and emission factors CFM56-B7 engine family at idle thrust	11
Figure 7	Fuel flow and emission factors GEnx-1B engine family at idle thrust	12
Figure 8	Aircraft taxi procedures overview (bars not to scale)	16

Tables

Table 1	LTO-emission calculation approaches	5
Table 2	Taxi-emission parameters	7
Table 3	Comparison of various taxi-out times per operation (cf. Annex 2 for map)	8
Table 4	Contact/open stand distribution of aircraft groups (Zurich Airport, 2016)	9
Table 5	Taxi-out time sensitivity results (Zurich Airport, 2016)	9
Table 6	Taxi fuel flow sensitivity	10
Table 7	Generic adjustment of emission indices below 7% thrust	12
Table 8	Total sensitivities for refined taxi-out modelling (Zurich Airport 2016)	13
Table 9	Single engine taxi-in fuel and emission benefits	14
Table 10	General assumptions for alternative taxi analysis	15
Table 11	Modelling results for alternative taxi-out procedures	16
Table 12	Environmental Benefits of A-CDM (Zurich Airport 2014)	17

Sources

No.	Document Name
[1]	Flughafen Zürich AG: Alternative Aircraft Taxi Systems: Effects on local air quality. December 2013 (not published).
[2]	Flughafen Zürich AG: Environmental Benefits of A-CDM at Zurich Airport. October 2015.

Acknowledgment

Swiss International Air Lines, Operational Efficiency & Analytics, Zurich

Version	Date	Name	Modifications
01	04.12.2017	Fleuti	Incl. review by FOCA and Swiss

Authors: Emanuel Fleuti, Silvio Maraini
Division/Unit: Legal & Environment

emanuel.fleuti@zurich-airport.com
Phone +41 (0)43 816 21 81, Fax +41 (0)43 816 47 60

Flughafen Zürich AG
P.O. Box, CH-8058 Zurich-Airport
www.zurich-airport.com