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CHARACTERISTICS AND MITIGATION MEASURES OF AIRCRAFT POLLUTANT EMISSIONS AT NANJING LUKOU INTERNATIONAL AIRPORT (NKG), CHINA

ABSTRACT

The assessment of local air pollution due to aircraft emissions at/near the airport is an important issue from the standpoint of environment and human health, but has not received due attention in China. In this paper, the pollutant emissions (i.e. HC, CO, NO_x, SO_x and PM) from aircraft during landing and take-off (LTO) cycles at Nanjing Lukou Airport (NKG) in 2016 were investigated using an improved method, which considered the taxi-in and –out time calculated based on the real data from the Civil Aviation Administration of China (CAAC), instead of using the referenced time recommended by ICAO. First, the pollutant emissions and their characteristics were studied from different perspectives. Second, two various mitigation measures of emissions were proposed, and the performance of emission reduction was analysed. Our analysis shows that: (1) A320 and B738 emitted the largest emissions at NKG; (2) pollutants were mainly emitted during the taxi mode, followed by climb mode; (3) B738 had the lowest emissions per (seat•LTO) among all aircraft, while CRJ had the lowest emissions per unit LTO; (4) shortening the taxiing time and upgrading aircraft engines are both effective measures to mitigate pollutant emissions.

KEY WORDS

air pollution; aircraft emissions; LTO method; pollutants; emission intensity;

1. INTRODUCTION

In recent years, air pollution has attracted an increasing concern within public opinion and scientific community in developing countries, just like what happened in the developed countries several decades ago. This is because of the known relationship between being surrounded by the polluted air and the increased adverse impact on human health [1, 2].

With the rapid growth in the aviation industry, pollutant emissions from the aviation sector increased by 98% from 1990 to 2006 [3]. They became an air pollution source that cannot be ignored. Some studies indicate that aircraft emissions can seriously affect the air quality [4-8], human health [2, 9], at airports and in communities around airports. It has been reported that for a modern twin-engine aircraft operating over an 800 km flight, about 25% of the total emissions are emitted during the landing and take-off (LTO) cycle [10]. Consequently, airports are suffering from enormous pressure to pay close attention to and reduce pollutant emissions.

Given this background, extensive research has been performed to discover types, amounts, and characteristics of pollutant emissions at/near airports [11-16]. There are several different approaches to measure and estimate pollutant emissions around airports [11, 17, 18]. An estimation approach was based on the total fuel consumption by aircraft, which uses fewer data [19]. Another approach, recommended in the China National Guide [20], was based on the total LTO number and the emission indices per LTO [16, 17, 21]. Considering the emission difference between engine thrust settings and aircraft types, the International Civil Aviation Organization (ICAO) promulgated the LTO

cycle method [17]. As it provides a constant analytical frame of reference that allows the comparison of emissions calculation for different airports, the LTO cycle method is widely used to assess the pollutant emissions released by aircraft movements. A standard LTO cycle contains all aircraft operations at and near the airport below the altitude of 3,000 ft (914 m) above field elevation. It includes four operation phases (approach, taxi, take-off, and climb), in terms of both aircraft engine thrust settings (expressed as a percentage of maximum rated thrust) and standard operating time in each specific operating mode (time-in-mode, TIM). *Table 1* provides TIM and thrust setting for a standard LTO cycle.

Table 1 – TIM and thrust setting for a standard LTO cycle (ICAO, 2011)

Operating mode	TIM [min]	Thrust setting [%]
Approach	4.0	30
Taxi	26.0	7
Take-off	0.7	100
Climb	2.2	85

Though there are still some limitations in the usage of standard LTO cycles, e.g. classification of operating modes, emission indices, default thrust settings, and TIM [6, 22-25], the LTO cycle method has been used widely by different researchers and organizations around the world. In these studies, airports investigated were located in Europe [15, 26-29], Asia [13, 30-33], America [14, 34, 35], and Australia [8, 36, 37]. The pollutant emissions from aircraft operations at airport have been studied at a specific airport level [27, 35, 38-40], on a regional multi-airport scale [13, 15, 30], nationwide [16, 37, 41, 42], and also globally [9, 43-45]. These fruitful papers developed inventories of pollutant emissions at airports, helped people understand emissions better, and laid a solid foundation for the following studies.

Also, some studies have focused on emission reduction approaches and their benefits analysis, from an LTO cycle point of view. Taxi, one of LTO cycle operating modes, has the longest operation time. Consequently, taxiing aircraft are an essential source of pollutant emissions. A decrease of two minutes of taxiing time may result in a reduction of approximately 4-6% in the amount of LTO emissions or a decrease of approximately 7-8% in the amount of emissions in the taxiing mode [15, 27]. At the same time, the aircraft taxiing speeds and taxiing routes have also impact on emissions [28]. Moreover, ambient meteorological conditions are also key factors of emission reduction. For example, the humidity has an obvious effect on pollutant emissions. For a fixed air-fuel ratio and ambient temperature, humidity affects NO_x formation with a negative correlation [46-48]. And, as an aircraft operating at low engine thrust, e.g. taxiing and queuing, it has a significant portion of total pollutant emissions, APU and other handling equipment usage may serve as a valuable new approach to emission reduction [28, 39]. Also, flight procedure optimization is another effective measure to reduce fuel consumption and emissions, such as the Continuous Descent Approach (CDA) [49].

Furthermore, some recent studies have sought to do further research on different topics, using pollutant emissions data, which were calculated by the LTO cycle method. These issues include the relationships between pollutant emissions, local air quality, and human health and the factors that drive aircraft pollutant emissions, etc. [14, 29, 31, 50, 51].

In China, as one of the biggest aviation markets around the world, the pollutant emissions at airports are increasing rapidly and account for a larger portion in global amounts in the recent years [45]. Meanwhile, China seeks to build "greener" airports and aviation sector in the near future [52, 53]. However, the existing papers on pollutant emissions for China aviation are insufficient [33, 42, 54], especially for a specific airport with detailed analysis. The significance of this kind of research is uncontested from the viewpoint of air pollution, human health, emission reduction, and administration policies. In order to understand the extent to which the measure of emission reduction is required, it is necessary to investigate the inventory, level, and characteristics of pollutant emissions at/near the airport. Furthermore, as the taxi phase takes the largest share of operational time during the LTO cycle, accounting for 79.03%, the uncertainty of the taxiing time could bring great deviation to the final assessment results of pollutant emissions. An estimation of aircraft pollutant emissions using an adjusted TIM for taxiing in China is lacking, to the best of our knowledge. In particular, previous studies usually focused on the adjustment of TIM for climb and approach [31, 33].

In light of this, the objectives of this paper are reported to: (i) develop a relatively accurate inventory of pollutant emissions (HC, CO, NO_x, SO_x and PM) from aircraft LTO operations based on the actual taxi-in and -out information of each flight and adjusted TIM, as well as fuel flows and emission

indices revised by real meteorological parameters; (ii) grasp the distribution characteristics of pollutant emissions from four different views; (iii) investigate the emission reduction results of two different mitigation measures (shortening taxiing time and upgrading aircraft engines), at the Nanjing Lukou International Airport (NKG), China.

The remainder of this paper is organized as follows. Section 2 introduces the calculation methodology of aircraft pollutant emissions. Section 3 gives the research region and data sources. Section 4 presents the research results, including characteristics of aircraft pollutant emissions and performances of emission mitigation measures, and Section 5 draws the research conclusions.

2. METHODOLOGY

2.1 Emission of pollutants

In this paper, the LTO method is selected, which was recommended by ICAO to assess the pollutant emissions at NKG. This typical method is widely accepted and used. ICAO provides three different approaches: simple, advanced, and sophisticated techniques [17]. Each method has a degree of accuracy and an inverse degree of uncertainty, that is, the higher degree of accuracy and the lower degree of uncertainty. In this study, the advanced approach was accepted, according to the availability of data and information required.

In the advanced method, total emissions of pollutant i (HC, CO, NO_x, SO_x) produced by aircraft j for one LTO cycle (in grams), E_{ij}, are calculated by the following formula [17]:

$$E_{ij} = \sum (TIM_{jk} \cdot 60) \cdot FF_{jk} \cdot EI_{ijk} \cdot NE_j \qquad (1)$$

where:

TIM_{jk} – time-in-mode k (approach, taxi, take-off, and climb) for aircraft j [min];

FF_{jk} – fuel flow for mode k for each engine used on the aircraft j [kg/s];

EI_{ijk} – emission index for pollutant i (HC, CO, NO_x, SO_x) in mode k for each engine used on aircraft j [g/kg fuel]; as ICAO does not provide standard approach for the calculation of SO_x emissions, an average SO_x emission index of 1 g/kg fuel from the EPA's (Environmental Protection Agency) research was used.

NE_j – number of engines used on aircraft j.

Under the advanced approach, aircraft/engine combinations and the number of LTO cycle must be known first. The procedure for total pollutant emissions at a specific airport contains three steps as follows:

1) the pollutant emissions of a certain aircraft/engine combination per LTO cycle were calculated by previously stated formulas;
2) repeat step one, the emissions of each aircraft/engine combination per LTO cycle can be calculated;
3) the total pollutant emissions could be obtained multiplying the individual emissions of each aircraft/engine combination per LTO cycle by the number of LTO cycle for the entire investigation period.

2.2 Emission of particulate matter

In this paper, the new First-order Approximation (FOA3.0) methodology was used to estimate the particulate matter (PM) emissions at the NKG [55]. The PM emissions produced by aircraft j for one LTO cycle, $E(PM)_j$, can be calculated by the following formula:

$$E(PM)_j = \sum (TIM_{jk} \cdot 60) \cdot FF_{jk} \cdot EI(PM)_{jk} \cdot NE_j \qquad (2)$$

where $EI(PM)_{jk}$ is the emission index for PM in mode k for each engine used on aircraft j [g/kg fuel].

PM emissions include volatile and non-volatile emissions. Non-volatile PM exists at the engine exit plane while volatile PM nucleates as new particles or condenses on existing particles in the cooling exhaust plume [29, 55]. Currently, each component of PM must be calculated separately, with the total emission index being the sum of the parts [17]. Therefore, the emission index of PM can be calculated by the following formulas:

$$EI(PM) = EI_{vols} + EI_{nvols} \qquad (3)$$

$$EI_{vols} = EI_{vol-FSC} + EI_{vol-FuelOrganics} \qquad (4)$$

$$EI_{vol-FSC} = \left(\frac{FSC \cdot \varepsilon \cdot MW_{out}}{MW_s} \right) \cdot 10^3 \qquad (5)$$

$$EI_{vol-FuelOrganics} = Non\_S\_component \cdot \frac{EI_{HC(Engine)}}{EI_{HC(CFM56)}} \cdot 10^{-3} \qquad (6)$$

$$EI_{vols} = Q \cdot CI \cdot 10^{-3} \qquad (7)$$

If the smoke number $SN \leq 30$, best estimate:

$$CI = 0.0694 \cdot SN^{1.24} \qquad (8)$$

and upper bound:

$$CI = 0.0012 \cdot SN^2 + 0.1312 \cdot SN + 0.2255 \qquad (9)$$

If $SN > 30$, best estimate:

$$CI = 0.0297 \cdot SN^2 - 1.802 \cdot SN + 31.94 \qquad (10)$$

and upper bound:

$$CI = 0.0297 \cdot SN^2 - 1.6238 \cdot SN + 26.801 \qquad (11)$$

$$Q = Q_{core} \ or \ Q_{mixed} \qquad (12)$$

If the engine type is turbofan:

$$Q = Q_{core} = 0.776 \cdot AFR + 0.877 \qquad (13)$$

If the engine type is internally mixed turbofan:

$$Q = Q_{mixed} = 0.776 \cdot AFR \cdot (1 + \beta) + 0.877 \qquad (14)$$

where:

$EI(PM)$ – emission index of PM (including volatile and non-volatile PM) [g/kg fuel];

EI_{vols} – emission index of the total of volatile PM [g/kg fuel];

EI_{nvols} – emission index of non-volatile PM [g/kg fuel];

FSC – fuel sulphur content (mass ratio with default 0.00068);

$EI_{vol\text{-}FSC}$ – volatile emission index attributable to FSC [g/kg fuel];

$EI_{vol\text{-}FuelOrganics}$ – volatile PM emission index of fuel organics [g/kg fuel];

ε – S^{IV} to S^{VI} fractional conversion (default 0.033);

$MWout$ – 96 (sulphate in the exhaust);

MW_s – 32 (S^{IV} in fuel);

$Non\_S\_component$ – a value derived from CFM56-2-C1 trends [mg/kg fuel];

$EI_{HC(CFM56)}$ – mode-specific HC emission index for CFM56-2-C5 engine [g/kg fuel];

$EI_{HC(Engine)}$ – mode-specific HC emission index for the engine of concern [g/kg fuel];

CI – concentration index [mg/m³];

SN – smoke number;

Q – core or mixed flow depending on engine test parameters during SN measurements [m³/kg fuel];

Q_{core} – core exhaust volumetric flow rate [m³/kg fuel];

Q_{mixed} – exhaust volumetric flow rate including core and bypass flow [m³/kg fuel];

AFR – modal mass air-to-fuel ratio;

β – bypass ratio.

2.3 Revision of fuel flow

The LTO fuel flow of a specific engine has been given in the ICAO Aircraft Engine Emissions Databank [56]. However, the data are suitable for the International Standard Atmosphere (ISA) condition at sea level. If the airport meteorological conditions are not idealized, the fuel flow needs revision to fit the real conditions better.

The fuel flow in reference conditions (i.e. ISA condition at sea level with temperature 288.15 K and pressure 101.325 kPa) should be converted to the fuel flow in real conditions. The conversion formulas are as follows [37, 42]:

$$FF = \frac{FF_{ref} \delta_{amb}}{\theta_{amb}^{3.8} e^{0.2M^2}} \qquad (15)$$

$$\theta_{amb} = \frac{T_{amb} + 273.15}{288.15} \qquad (16)$$

$$\delta_{amb} = \frac{P_{amb}}{101.325} \qquad (17)$$

where:

FF – fuel flow in real conditions [kg/s];

FF_{ref} – fuel flow in reference conditions [kg/s];

θ_{amb} – temperature ratio of real conditions to reference conditions;

δ_{amb} – pressure ratio of real conditions to reference conditions;

M – flight Mach number;

T_{amb} – ambient temperature in real conditions [°C];

P_{amb} – ambient pressure in real conditions [kPa].

2.4 Revision of emission indices of HC, CO, NOₓ

Similarly, the emission indices of HC, CO, and NO_x, given in the ICAO Aircraft Engine Emissions Databank, also just fit the ISA condition at sea level. The emission indices are required to revise under real conditions.

For a clear distinction, emission indices for the ISA condition at sea level are called REIs (Reference Emission Indices), which are recommended by ICAO. In order to obtain the emission indices corresponding to different fuel flows under reference conditions, develop a log-log relationship between REIs and FF_{ref}. The three species emission indices (i.e. HC, CO, and NO_x) and the corresponding fuel flow of each mode of LTO obtained from ICAO Aircraft Engine Emissions Databank are plotted on log-log scales, respectively. Take B738 equipped with CFM56-7B26 as an example: the regression fit of three species emission indices and fuel flow
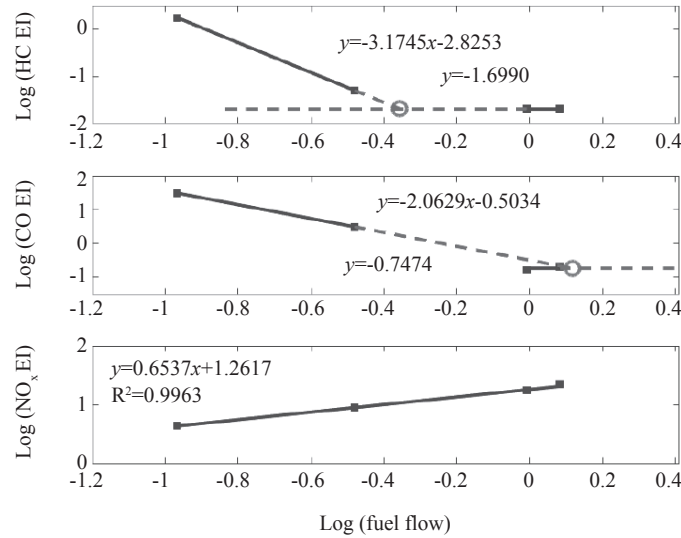
Figure 1 – Log-log relationships between fuel flow and emission indices of HC, CO, and NO_x (CFM56-7B26)

are shown in *Figure 1*. It shows that the HC and CO are bi-linear regression fitted curves, and the NO_x is curved by a point-to-point linear fit. Therefore, REIs of each pollutant could be obtained from a log-log coordinate system corresponding to the *FF* figured out in Section 2.3.

The REIs obtained by the above method fit the ISA condition at sea level. The REIs need converting to the real terms as follows [42, 57, 58]:

$$EI(HC) = \frac{REI(HC)\theta_{amb}^{3.3}}{\delta_{amb}^{1.02}} \qquad (18)$$

$$EI(CO) = \frac{REI(CO)\theta_{amb}^{3.3}}{\delta_{amb}^{1.02}} \qquad (19)$$

$$EI(NO_x) = REI(NO_x)\exp(H)\left(\frac{\delta_{amb}^{1.02}}{\theta_{amb}^{3.3}}\right)^{\frac{1}{2}} \qquad (20)$$

$$H = -19.0 \cdot (\omega - 0.0063) \qquad (21)$$

where:
$EI(HC)$, $EI(CO)$, $EI(NO_x)$ – emission indices of HC, CO, and NO_x in real conditions [g/kg fuel], respectively;
H – humidity coefficient;
ω – specific humidity.

2.5 Total pollutant emission

Emissions of total pollutant (HC, CO, NO_x, SO_x and PM) for a particular aircraft *j* in one LTO cycle can be calculated by the following formula:

$$\begin{aligned} E_j(HC,CO,NO_x,SO_x,PM) = \\ = \sum (TIM_{jk} \cdot 60) \cdot FF_{jk} \cdot EI_{jk}(HC,CO,NO_x,SO_x,PM) \cdot NE_j \cdot 10^{-3} \end{aligned} \qquad (22)$$

where:
FF_{jk} – fuel flow in real conditions, for mode *k* for each engine used on aircraft *j* [kg/s];

EI_{jk}(HC, CO, NO_x, SO_x, PM) – emission indices of HC, CO, NO_x, SO_x, and PM, respectively in real conditions, in mode *k* for each engine used on aircraft *j* [g/kg fuel].

Monthly pollutant emissions can be calculated by adding up the above emissions of all flights in one month. By adding up the emissions of each month, the annual pollutant emissions could be estimated.

3. DATA SOURCES

Nanjing Lukou International Airport was founded in 1997. The airport is located approximately 20 km south from the centre of the Nanjing city, Jiangsu province, China. With the rapid development in the past ten years (*Figure 2*), NKG has become one of the most important airports in the Yangtze River Delta, or even in China. The number of passengers and
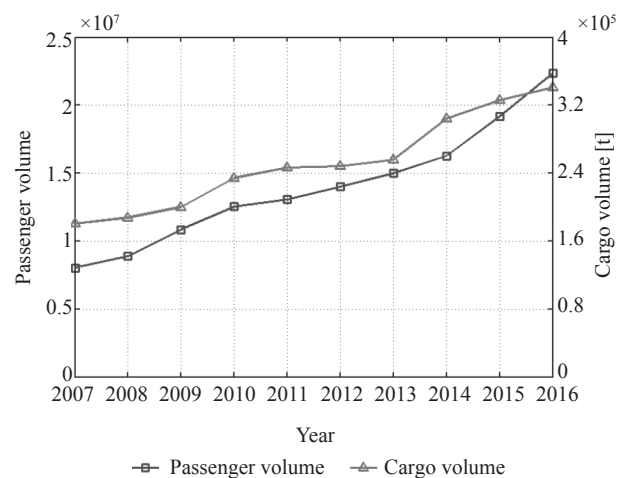

Figure 2 – The passenger and cargo volume at NKG from 2007-2016

freight carried were 22.4 million and 341.3 thousand tons in 2016, with an increase of 16.7% and 4.7%, respectively, over the previous year. Facing a strong demand for air travel, NKG is expected to have a rapid growth in aircraft LTO cycles and pollutant emissions in the future. Meanwhile, excessive pollutant emissions and aircraft movements will inevitably cause a series of environmental problems around NKG [59, 60]. Therefore, NKG has been taken as the research area for empirical analysis.

One focus of this paper is to produce an inventory of annual pollutant emissions during aircraft LTO cycles at NKG from January to December 2016. The flight schedules are taken from the airline schedules database (www.OAG.com) and an Operation Monitoring Center of Civil Aviation Administration of China (CAAC) airline on-time database. The operating carrier, flight number, aircraft type, origin airport, destination airport, and distance are given for each passenger and cargo flight. The flights have been sorted by time and flight number in order to avoid some miscalculations, such as flight double counting.

Schedule database

ICAO gives the standard value of TIM, which is shown in *Table 1*. However, considering the differences in airport layout, traffic congestion on the airfield, or operational rules of runways at a specific airport, the TIM varies from airport to airport, or even from flight to flight; and the default value of taxiing time has the most significant diversity [61].

To have a more precise estimation, the real taxi-in and -out information was used from the CAAC airline on-time database to modify the default value of taxiing time. The real average taxiing time of each type of aircraft operated at NKG in 2016 is shown in *Figure 3*.

Aircraft/engine combinations

The engine type is a crucial factor in calculating the pollutant emissions. Aircraft/engine combinations are selected from the official websites of airlines and aircraft manufacturers. The detailed aircraft/engine
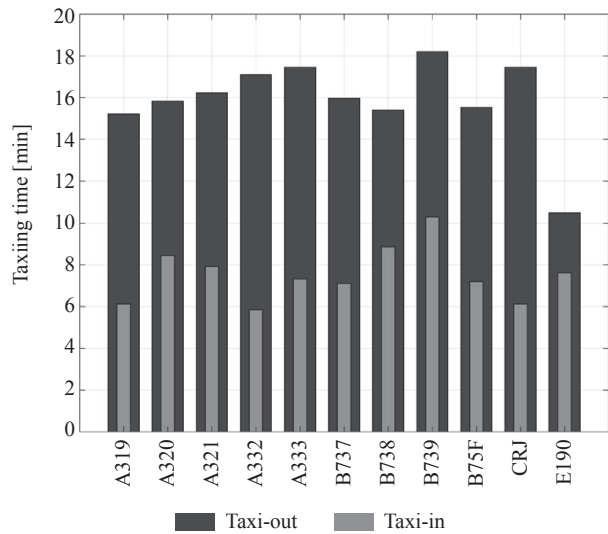

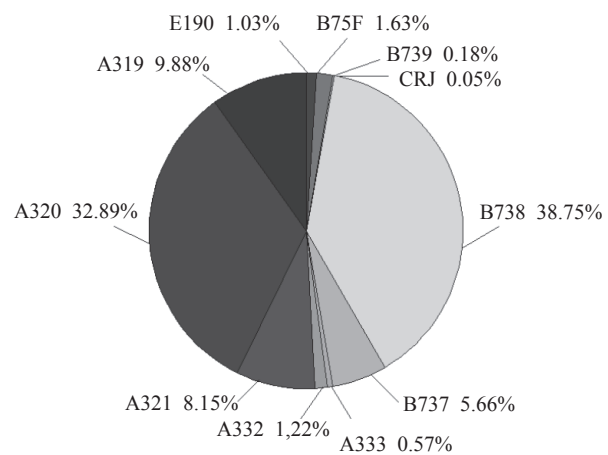*Figure 3 – The modified real average taxi-in and taxi-out time of each aircraft type*

Figure 4 – Percentage of LTO cycles by aircraft category at NKG in 2016

combination information is too complicated and difficult to reckon. To simplify the analysis, the most typical combinations from the aircraft manufacturers and ICAO Aircraft Engine Emissions Databank were selected [56]. The distribution of aircraft operated at NKG in 2016 is shown in *Figure 4*. The combinations used for calculation in this paper are listed in *Table 2*.

Table 2 – Typical aircraft/engine combinations used for calculation

Aircraft type	Engine type	Aircraft type	Engine type
A319	CFM56-5B7-P	B737	CFM56-7B22
A320	CFM56-5B6	B738	CFM56-7B26
A321	CFM56-5B3/3	B739	CFM56-7B26
A332	Trent 772	B75F	PW2037
A333	Trent 772	E190	CF34-10E5
CRJ	CF34-8C5		

Engine emission indices

The ICAO Aircraft Engine Emissions Databank has HC, CO, and NO_x emission indices and smoke number of different aircraft engine types. The engine emission indices are measured under the ISA condition at sea level. However, ICAO does not give referenced values of SO_x emission indices. The amount of SO_x emission is directly related to the amount of sulphur in the fuel burned. In this study, the SO_x emission index was set at 1 g/kg- fuel, recommended by the EPA.

4. RESULTS AND DISCUSSIONS

The total pollutant emissions at Nanjing Lukou International Airport in 2016 were about 1,943.62 tons. The CO, NO_x were released in the highest quantities (totals were 1,019.34 and 766.70 tons, respectively), followed by HC (80.46 tons), SO_x (71.27 tons), and PM (5.85 tons). The simple descriptive statistics in *Table 3* gives an overview of all the used variables. The mean monthly number of LTO cycles was 7,180 during the 12-month observational period in 2016. The mean monthly fuel consumption was 5,939.19 tons. The mean monthly values of CO and NO_x were the highest of all pollutants (84.95 tons and 63.89 tons, respectively). The mean monthly value of HC was 6.71 tons, SO_x 5.94 tons, and PM 0.49 tons.

4.1 Characteristics of aircraft pollutant emissions

Temporal distribution

Figure 5 presents the estimated emissions of HC, CO, NO_x, SO_x, and PM, monthly.

In July and August, the emissions of HC (7.32 and 7.84 tons), CO (95.02 and 100.34 tons), and PM (0.51 and 0.53 tons) were larger than in the other months in 2016. By contrast, in these months, the emissions of NO_x and SO_x were the lowest in 2016. In addition to factors like fuel consumption and the number of LTO cycles, the effect of meteorological parameters on emission indices may be another main reason for this trend. Aircraft engines could consume less fuel, and emit more HC, CO and less NO_x with the rise of ambient temperature and the descent of ambient pressure with the same other operation conditions (engine type, number of LTO cycles, etc.), which could be implied from the formulas in Section 2.4. The average temperature in July and August were 28.8, 29.1°C, which were higher than in January and December (3.2 and 7.5°C, respectively). Meanwhile, the average pressure in July and August was 1,001.1, 1,001.8 hPa, which were the lowest two months in 2016. The monthly variation trend of emission of SO_x was the same as the variation of monthly fuel consumption due to the invariability of SO_x emission index.
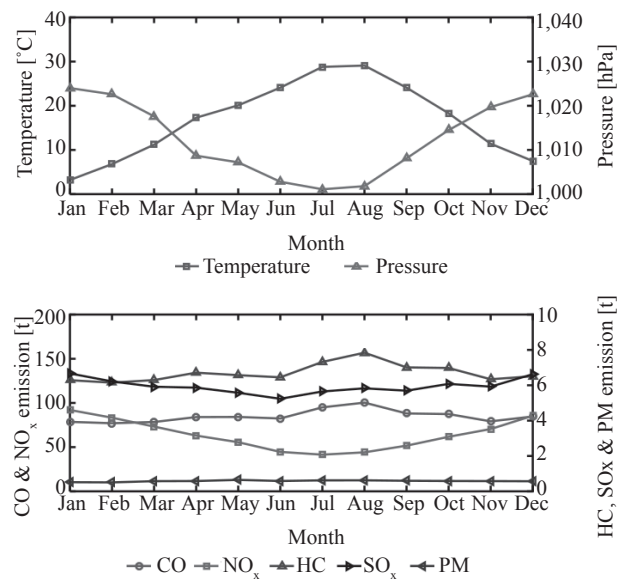

Figure 5 – Monthly variations in pollutant emissions and meteorological conditions

Table 3 – Descriptive statistics of all used variables in 2016

	Minimum	Maximum	Mean	Std. deviation	Variance
LTO	6,608	8,184	7,180	555.01	308,031.33
Fuel [t]	5,234.61	6,667.94	5,939.19	414.76	172,023.06
HC [t]	6.15	7.84	6.71	0.50	0.25
CO [t]	77.03	100.34	84.95	7.02	49.22
NO_x [t]	41.46	92.01	63.89	17.21	296.12
SO_x [t]	5.23	6.67	5.94	0.41	0.17
PM [t]	0.45	0.53	0.49	0.02	0.00

Flight phase distribution

The distribution of pollutant emissions for LTO operating modes is shown in *Figure 6*, including approach, taxi, take-off, and climb. On the whole, the taxi mode accounts for the most significant portion of total pollutant emissions at 53.48%, followed by climb mode at 24.06%, approach mode at 12.03%, and take-off mode at 10.43%, respectively.
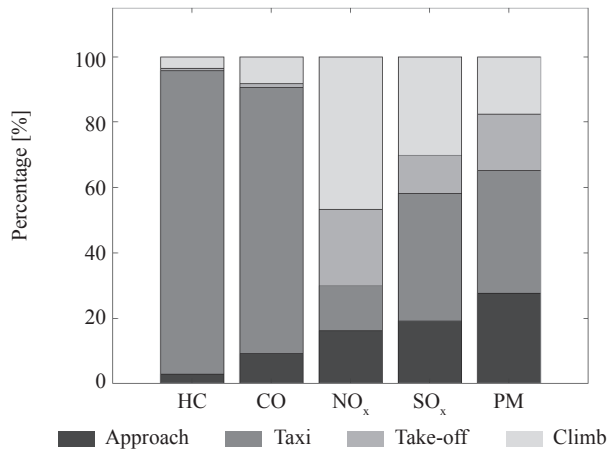

Figure 6 – Distribution of pollutant emissions for each operating mode at NKG in 2016

On the other hand, *Figure 6* shows that there are significant differences between different pollutant emissions in each flight phase. HC, CO, and PM are mainly emitted during the taxiing mode, accounting for 92.82%, 81.33%, and 37.42%, respectively, in the whole LTO cycle. As we know, the emission indices of HC and CO decrease with an increasing thrust, and taxiing mode has the longest operating time in the LTO cycle. Thus, in a working condition of lower thrust and longer time, the temperature and pressure of the engine combustion chamber are relatively low, which could lead to incomplete combustion of fuel and to an increase of HC and CO emissions. On the contrary, CO and HC emissions during take-off and climb modes account for 1.04%, 1.26%, respectively, in the whole LTO cycle.

NO_x is mainly emitted during the climb mode, accounting for 46.74% in the LTO cycle, and the modes of approach, taxi, and take-off account for 16.04%, 13.78%, and 23.44% in the LTO cycle, respectively. It has been discovered that the emission index of NO_x is positively correlated to thrust setting [29, 56]. As a sequence, the operating modes with high thrust setting, as take-off and climb, account for more NO_x emission. This can also explain why TIM for take-off is only 0.7 min (2.13% of

TIM for a standard LTO cycle), while NO_x emission accounts for as much as 23.44% in the whole LTO cycle.

The flight phase distribution of PM emission was more complex. The emission index of PM is relevant to smoke number and HC emission index. The value of the smoke number is positively related to thrust setting, while the HC emission index has a negative correlation with thrust setting. This makes PM emissions depend more on the operating time. Therefore, PM emissions account for 37.42% during the taxi mode.

The emission index of SO_x is a constant, as SO_x emission is proportional to fuel burn and depends on the fuel sulphur content. Thus, SO_x emission during the approach, taxi, take-off, and climb modes account for 19.09%, 39.06%, 11.71%, and 30.14%, respectively.

Aircraft type distribution

Using the above emission calculation methods combined with flight schedules and aircraft/engine combination information, enables estimation of the annual total emissions of each pollutant released by various types of aircraft. The results sorted by quantity are illustrated in *Figure 7*. As seen in *Figure 7*, A320 produced about 40.47% of total LTO pollutant emissions (785.95 tons), which was larger than produced by any other type of aircraft, followed by B738 (615.52 tons).

The largest NO_x, SO_x emissions were released by B738 (total 345.54 and 27.87 tons, respectively), followed by A320. This is because B738 operated
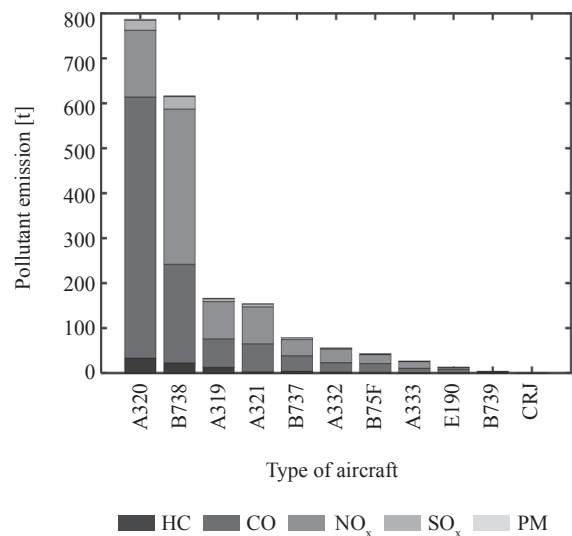

Figure 7 – Distribution of pollutant emissions from various types of aircraft at NKG in 2016

the majority of LTO cycles at NKG (about 38.75% in the total LTO cycles). Moreover, the CO, HC and PM emissions of A320 were higher than B738, due to the difference of combustion efficiency between two engines of A320 and B738, even if the LTO cycles that operated by A320 were lower (about 32.89% in the total LTO cycles) than by B738.

Emission intensity distribution

The pollutant emission intensity (kg/LTO or kg/ (seat•LTO)) is an index of pollutant emissions released per unit LTO or unit seat during one LTO cycle, which could be used to assess the pollutant emission efficiency of various types of aircraft. The results sorted by pollutant emission intensities are illustrated in *Figure 8*.

From an LTO-emission intensity point of view, CRJ is the most efficient type of aircraft, as CRJ is a small aircraft, about 90 seats, consuming less fuel during one LTO cycle. But from a seat-emission intensity point of view, B738 is the most efficient type of aircraft, followed by B737 and A321. From an environmental point of view, it would be a feasible approach of emission reduction to operating more aircraft with lower seat-emission intensity.

From the emission intensity point of view, inferences can be made about which type of aircraft has better performance at lower emissions. Aircraft emissions per unit LTO cycle, unit carrying capacity, and capacity utilization are likely to be more relevant considerations when choosing aircraft [36].
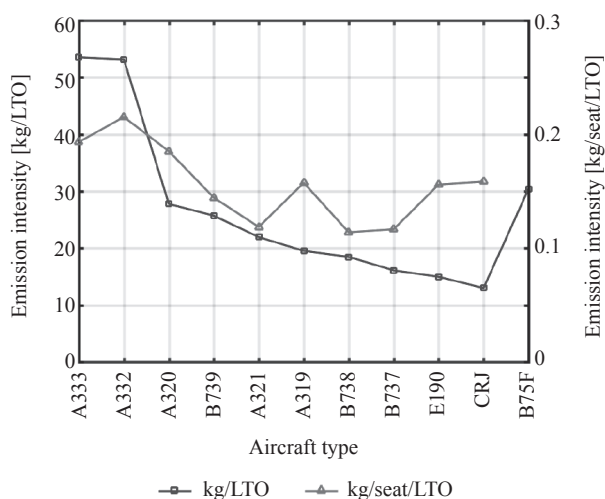

Figure 8 – Distribution of pollutant emissions intensity from various types of aircraft at NKG in 2016
Note: The data of typical seating are selected from official websites of aircraft manufacturers. B75F was only used for cargo transportation.

Uncertainty analysis

However, these pollutant emissions are subject to some uncertainties as they are dependent on many factors. In this paper, there are two primary sources of uncertainties in the aircraft pollutant emission estimation. First, as the actual mixing height would change at different times [33], the difference of mixing layer height between the LTO cycle method and actual value will lead to uncertainty. Ambient temperatures have a dominant position in mixing layer height estimation [33, 62]. The annual average temperature around NKG in 2016 was 16.8°C (http://data.cma.cn/) and very close to the default value of ISA. Therefore, we accepted the recommended values of mixing layer height in the LTO cycle method in this study. Secondly, the simplification of aircraft/engine combinations may be another source of uncertainty. The same type of aircraft may be equipped with different types of engines and vice versa. Taking B738 in Air China fleet operated at NKG as an example, most aircraft are equipped with the CFM56-7B26 engines, and only a few aircraft are equipped with CFM56-7B24 type. We made a calculation and found that there was less than a 5% difference in total pollutant emissions between these two different engines during the same LTO operation. So, in this paper, we used the most typical combinations of aircraft/engine (listed in *Table 2*) for pollutant emission calculation.

4.2 Mitigation measures of aircraft pollutant emissions

A number of actions can be employed by airports, airlines, and other aviation operators to reduce aircraft pollutant emissions [28, 63-65]. These include shortening the taxiing time by optimizing ground taxi routes and operating the latest types of aircraft. The effects of these two measures on mitigating the aircraft pollutant emissions at NKG will be evaluated.

Shortened taxiing time

The taxi mode accounts for more than half of total pollutant emissions, at 53.48%. However, taxiing is essential for an aircraft to access the terminals, the runways, and their home hangar or fixed based operators. Taxiing time varies from airport to airport, or even from day to day, from flight to flight at the same airport, due to the size and layout of the airfield area, traffic congestion on the ground, local meteorological conditions, etc. From an

environmental point of view, the pollutant emissions during the taxi mode could be reduced by shortening the taxiing time.

To investigate the effect of taxiing time on pollutant emissions, a sensitivity analysis was conducted to evaluate the change of emissions for various durations of taxiing time. We set four different scenarios of taxiing time based on the current average taxiing time at NKG (as shown in *Figure 3*), (1) shortening by four minutes, (2) shortening by two minutes, (3) increasing by two minutes, and (4) increasing by four minutes.

The estimations show that the total pollutant emissions during taxi mode have an 8.85% reduction of total LTO emissions when taxiing time is shortened by 4 minutes at NKG. Even if there is only a decrease of 2 minutes in taxiing time, it could result in a decrease of about 4.43% total LTO emissions and a decrease of about 8.28% of pollutant emissions in the taxi mode. This is an exciting result of pollutant emission reduction. However, flight delay is a very serious, but a ubiquitous challenge at NKG; there were 43.32% of flights delayed at NKG in 2016. The congestion on the ground was a significant effect factor of the flight delay. When taxiing time increases by four minutes at NKG, there will be an 8.85% increase of total LTO emissions, especially HC emission will increase more than 15.44%. Therefore, shortening the taxiing time is an effective measure to mitigate airport pollutant emissions at NKG (*Figure 9*).

The new terminal of NKG will be put into operation soon, and NKG will face more complex operating conditions with two runways and two terminals. Hence, the authority of NKG is expected to enhance cooperative scheduling of runways, terminals, and gates, to improve operating efficiency, shortening taxiing time, and reducing aircraft emissions.

Upgraded aircraft engines

The performance of aircraft engines also has an obvious effect on pollutant emissions. While the performance of engines was degraded due to long working hours and poor working conditions, fuel consumption and pollutant emissions increased. While aircraft are equipped with the latest types of engines using advanced design and manufacture technologies, the fuel consumption and pollutant emissions would be decreased, such as the A320neo equipped with LEAP-1A or PW1100G-JM offers efficiency with a 20% fuel burn reduction per seat
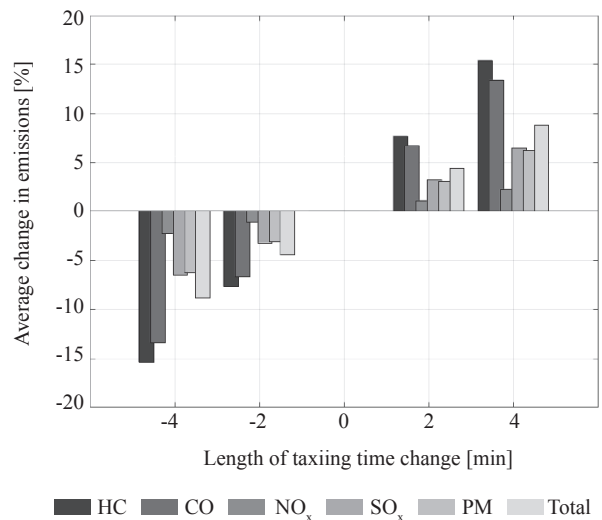

Figure 9 – Effect of shortening taxiing time on pollutant emissions at NKG in 2016

by 2020, and the A320neo's fuel savings translate into some 5,000 tons fewer CO_2 emitted per aircraft annually [66].

There were 1,185 aircraft of the A320 family in operation in China, which was more than 40% of the whole Chinese fleet. If these aircraft were all replaced by the A320neo family, it would have considerable environmental benefits, at least. So, to investigate the effect of upgrading aircraft engines on pollutant emissions, a sensitivity analysis was conducted to evaluate the change of emissions for various replacement ratios, which were the percentages of the A320 family (equipped traditional CFM56-5B engines) operated at NKG in 2016, replaced by A320neo family (powered LEAP-1A engines). The replacement ratio varied from 0 percent to 100 percent. *Figure 10* shows that an increase of 10% replacement ratio of A320neo family in A320 family results in a decrease of about 3.4% total LTO
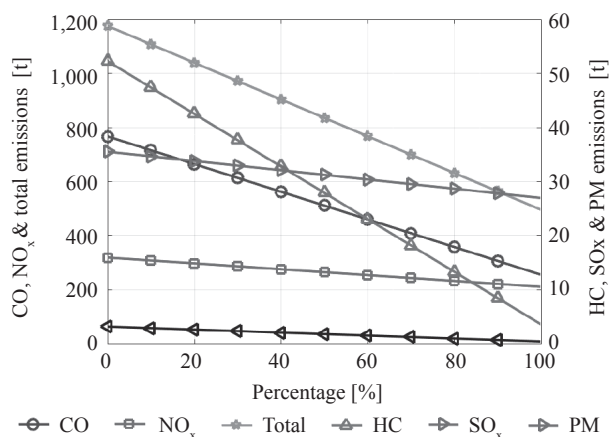

Figure 10 – Effect of upgrading aircraft engines on pollutant emissions of A320 family fleet at NKG

Table 4 – Emission indices of A320 and A320neo

Index	Aircraft/Engine type	Approach	Taxi	Take-off	Climb
Fuel flow [kg/sec]	A320 family/CFM56-5B6	0.315	0.111	0.998	0.827
	A320neo family/LEAP-1A	0.242	0.088	0.855	0.705
EI of HC [g/kg]	A320 family/CFM56-5B6	0.2	3.4	0.1	0.2
	A320neo family/LEAP-1A	0.04	0.28	0.02	0.02
EI of CO [g/kg]	A320 family/CFM56-5B6	17.75	46.1	4.48	12.18
	A320neo family/LEAP-1A	2.74	21.4	0.22	0.27
EI of NOx [g/kg]	A320 family/CFM56-5B6	10.32	3.9	13.51	10.41
	A320neo family/LEAP-1A	8.67	4.63	18.77	11.16
EI of PM [g/kg]	A320 family/CFM56-5B6	0.23	0.23	0.11	0.03
	A320neo family/LEAP-1A	0.03	0.03	0.07	0.005

pollutant emissions and a decrease of about 5.8% pollutant emissions released by A320(neo) family. While all A320 family are replaced by the A320neo family, it will reduce about 680 tons of pollutant emissions in total, which is approximately 34.98% of total LTO pollutant emission at NKG in 2016. The decrease amount of CO emission is most significant in all pollutant emissions, about 511.69 tons when replacement ratio varied from 0% to 100%; while the decrease proportion of HC emission is the highest in all pollutant emissions, the amount of HC emission at replacement ratio of 100%, is only 6.77%, of that the ratio is 0%. The reason for this phenomenon is that the engines for the A320neo family have more efficient performance and release less emissions than engines for the A320 family (*Table 4* shows the differences of engine performances between these two different types of engines). Therefore, using more aircraft equipped with the upgraded engines is also an effective, fast benefit measure to reduce pollutant emissions at airports.

5. CONCLUSION

In this study, the estimation of pollutant emissions (HC, CO, NO_x SO_x, and PM) of aircraft LTO cycles at Nanjing Lukou International Airport in 2016 is presented in great detail. The actual taxi-in and -out information of each flight and real meteorological data were used to have a more accurate adjusted TIM for taxiing and revised fuel flow and pollutant emission indices. The amount of pollutant emissions and its characteristics were analysed from four different viewpoints, and the emission reduction effects of two various mitigation measures,

i.e., shortening the taxiing time and upgrading the aircraft engines, were also discussed in detail. The main conclusions are as follows:

1) The total aircraft pollutant emissions from LTO cycles at NKG in 2016 were 1,019.34 tons CO, 766.70 tons NO_x, 80.46 tons HC, 71.27 tons SO_x, and 5.85 tons PM. The monthly variation of emissions is evident due to the airline schedule (i.e. the total number to LTO cycles) and meteorological conditions. In July and August, HC, CO, and PM were the highest, while NO_x was the lowest.

2) The taxi mode accounted for the most significant portion of total pollutant emissions at 53.48%, due to the longest operating time. For HC, CO, and PM emissions, taxi mode was the major contributor. And, NO_x was mainly emitted during the climb mode.

3) A320 was the maximum contributor among all aircraft types, followed by B738, due to their largest numbers of LTO cycles operated at NKG. From the seat-emission intensity distribution point of view, B738 is the most efficient type of aircraft, followed by B737 and A321. CRJ has the lowest emissions per unit LTO due to its smaller size.

4) Shortening the taxiing time is a feasible measure to mitigate the aircraft pollutant emissions. The results show that a decrease of 2 minutes in taxiing time caused a reduction of about 4.43% of total LTO pollutant emissions and a decrease of about 8.28% pollutant emissions in the taxi mode.

5) Upgrading aircraft engines also has a remarkable effect on emission reduction. If the aircraft fleet of A320 family operated at NKG in 2016 were

all replaced by the A320neo family, it would reduce almost 680 tons of pollutant emissions, about 35% of total LTO pollutant emissions.

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南京禄口国际机场飞机污染物排放特征及减排措施

摘要

从环境和人类健康的角度来看，评价机场附近因飞机污染物排放造成的空气污染是一个重要的议题，但在中国尚未得到应有的重视。本文对南京禄口机场（NKG）2016年着陆和起飞（LTO）循环过程中飞机的污染物排放（HC、CO、NO_x、SO_x和PM）进行了研究，根据中国民航局（$CAAC$）的实际数据计算滑入和滑出时间，而不是使用国际民航组织建议的参考时间，提出了一种改进的方法。首先，从不同角度研究了污染物排放及其特征。其次，提出了两种不同的减排措施，并对减排效果进行了分析。分析结果表明：（1）南京禄口国际机场$A320$和$B738$污染物排放量最大；（2）污染物排放主要产生在滑行阶段，其次是爬升阶段；（3）在所有飞机型号中，$B738$的每座位LTO排放量最低，CRJ的每单位LTO排放量最低；（4）缩短滑行时间和升级飞机发动机都能有效减少污染物的排放。

关键词：

空气污染；飞机排放；LTO方法；污染物；排放强度

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