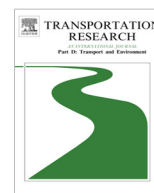


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Airport emissions reductions from reduced thrust takeoff operations

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ABSTRACT

Given forecast aviation growth, many airports are predicted to reach capacity and require expansion. However, pressure to meet air quality regulations emphasises the importance of efficient ground-level aircraft activities to facilitate growth. Operational strategies such as reducing engine thrust setting at takeoff can reduce fuel consumption and pollutant emissions; however, quantification of the benefits and consistency of its use have been limited by data restrictions. Using 3336 high-resolution flight data records, this paper analyses the impact of reduced thrust takeoff at London Heathrow. Results indicate that using reduced thrust takeoff reduces fuel consumption, nitrogen oxides (NO_x) and black carbon (BC) emissions by 1.0–23.2%, 10.7–47.7%, and 49.0–71.7% respectively, depending on aircraft-engine combinations relative to 100% thrust takeoff. Variability in thrust settings for the same aircraft-engine combination and dependence on takeoff weight (TOW) is quantified. Consequently, aircraft-engine specific optimum takeoff thrust settings that minimise fuel consumption and pollutant emissions for different aircraft TOWs are presented. Further reductions of 1.9%, 5.8% and 6.5% for fuel consumption, NO_x and BC emissions could be achieved, equating to reductions of approximately 0.4%, 3.5% and 3.3% in total ground level fuel consumption, NO_x and BC emissions. These results quantify the contribution that reduced thrust operations offer towards achieving industry environmental targets and air quality compliance, and imply that the current implementation of reduced thrust takeoff at Heathrow is near optimal, considering operational and safety constraints. © 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

1.1. Context

The rapid growth of global aviation in recent years is widely forecast to continue at an average annual rate of 5% (Boeing, 2014; Masiol and Harrison, 2014). This has led to concerns regarding the capacity of many components of the air traffic system, including the airport (Gelhausen et al., 2013). Several international hub airports, including London's Heathrow, are currently described as being effectively 'full' (DfT, 2013) and many more are expected to reach maximum capacity by 2030 (Weiszer et al., 2015). However, proposals for UK airport expansion, to meet both current and future demand, are increasingly constrained on the grounds of adverse environmental impacts (Mahashabde et al., 2011); consequently airport

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operations are subject to increasing scrutiny (Airports Commission, 2015; Simonetti et al., 2015). Airport operations emit pollutants deemed harmful to human health including nitrogen oxides (NO_x), black carbon (BC), hydrocarbons (HC) and carbon monoxide (CO) (Lee et al., 2009) and these contribute considerably to the degradation of local air quality (LAQ) (Yim et al., 2013). For example, air quality around London Heathrow currently exceeds EU limit values for NO_x (Masiol and Harrison, 2015), and it has estimated that airport operations contribute to 27% and up to 15% of annual mean NO_x concentrations at the airport boundary and 2–3 km downwind, respectively (Carslaw et al., 2012). Of all the airport pollutant emission sources, expected additional local air pollution from increased landing and takeoff (LTO) operations is of primary concern for many airports (Levy et al., 2012; Masiol and Harrison, 2014). Other sources are either outside the direct influence of airport operators, such as road traffic, or contribute relatively small amounts of pollutant emissions, such as ground support equipment (GSE). Consequently, aircraft operators face increasing pressure to adopt lower-emitting LTO operations to enable continued traffic growth within environmental limits (Heathrow Airport Ltd., 2010). Furthermore, at the European regulatory level, the Single European Sky Air Traffic Management Research (SESAR) has emphasised the importance of reducing aviation-related local emissions. As a high-level target, SESAR seeks to achieve an improvement in LTO cycle fuel efficiency of 2.8% per flight through the optimisation 3D aircraft trajectories (latitude, longitude and altitude) by 2020 (SESAR, 2012). Furthermore, SESAR states that solutions towards improving aviation efficiency must have no negative impact on air quality (SESAR, 2015).

Recent studies have sought to model aircraft LTO emissions and quantify the benefits of adopting reduced pollutant-emitting operations, primarily during taxiing activities. Weiszer et al. (2015) applied a holistic optimisation framework to several airside ground movement elements to minimise fuel consumption and identified reductions of between 19 and 31%, however they did not consider variability in takeoff thrust setting. Ravizza et al. (2013) identified a fuel consumption difference of 1.2% when optimising aircraft taxi activities for taxi time or fuel consumption efficiency. Simonetti et al. (2015) quantified an increase in pollutant emissions from additional takeoff activity (90% for NO_x) due to a theoretical runway redevelopment and a 40% increase in air traffic at Amerigo Vespucci airport, however the planned expansion caused a relative reduction in aircraft taxi emissions. Without empirical data, assumptions regarding aircraft operations including engine thrust setting and the duration of different LTO phases, referred to as time-in-mode (TIM), are often required. These assumptions tend to be simplified versions of reality, such as the International Civil Aviation Organisation (ICAO) LTO reference cycle (ICAO, 2011), and consequently inaccurately represent operations and fail to acknowledge airport operating constraints (Kurniawan and Khardi, 2011), which in turn reduces the applicability of such research to aircraft operators. Weiszer et al. (2015) explicitly referred to their model's inability to deal with airport operational uncertainty (for example due to weather conditions and external delays) and real-time scheduling as research limitations, which compromised their results with regards to optimisation planning. These factors are mitigated through the use of recorded data. For example, Khadilkar and Balakrishnan (2012) used flight data records (FDRs) to show that taxi fuel consumption was significantly dependent on the number of acceleration events and that using recorded operational data improved fuel consumption; fuel flow estimates using the ICAO method over predicted fuel burn by up to 35% compared to the FDRs.

At London Heathrow, the takeoff roll is responsible for approximately 22% of total ground level fuel consumption and CO₂ emissions, 60% of NO_x emissions and 50% of BC emissions (Stettler et al., 2011). Furthermore, Carslaw et al. (2012) states that airport-related emissions account for 23% of NO_x measured at receptor locations near London Heathrow (13.5 µg/m³). Reduced thrust takeoff is an operation intended to reduce this through the adoption of less-than-maximum thrust settings during the takeoff roll. The rates of engine fuel consumption are reduced at lower engine thrust settings. Since the mass of CO₂ emitted per kg of fuel burned, referred to as the emissions index (EI), is constant dependent on the hydrogen to carbon ratio (approximately 3160 g/kg for aviation fuel) (Stettler et al., 2011), CO₂ emissions are reduced in line with fuel consumption. NO_x and BC emissions may be reduced to a greater degree as the EIs for these pollutants generally increase non-linearly with increasing engine thrust setting (King and Waitz, 2005; Timko et al., 2010a,b). Reduced thrust takeoff also reduces engine wear (Chenghong, 2002). The thrust setting chosen by the pilot is dependent on several factors, of which aircraft takeoff weight (TOW) is the most critical (FAA, 2014; Suchkov et al., 2003). The relationship between thrust and TOW will alter the aircraft takeoff roll trajectory (e.g. TIM, rate of acceleration, required speed at lift off) in addition to the fuel flow rate and EI of the aircraft engines. Quantification of the benefit of reduced thrust takeoff has been limited by the aforementioned data restrictions and inadequate modelling methodologies (Romano et al., 1999). Furthermore, the extent and consistency to which reduced thrust takeoff is used in practice, has not been well characterised.

1.2. Research objectives

In the light of the above discussion, this paper aims to quantify the potential benefits for fuel consumption, NO_x and BC emissions enabled by the consistent adoption of reduced thrust takeoff for six commonly used aircraft-engine combinations at London Heathrow, which could improve ambient air quality around the airport. Aircraft TOW, fuel consumption, NO_x and BC emissions are modelled using high-resolution (1 Hz) FDRs for 3336 aircraft takeoff rolls. The objectives of this paper are to (i) quantify the observed reduction in fuel consumption and NO_x emissions due to the adoption of reduced thrust takeoff, relative to 100% thrust at takeoff, (ii) analyse the relationship between thrust setting and aircraft TOW in order to quantify the distribution of engine thrust settings adopted for different aircraft-engine combinations; (iii) identify the engine thrust setting corresponding to the minimum fuel consumption and emissions for different TOWs and different aircraft-engine

combinations; and (iv) quantify the total benefit of the consistent application of reduced thrust takeoff to fuel consumption and emissions at London Heathrow.

Subsequent sections will be structured as follows. Section 2 will describe the data and the methods used to model aircraft thrust, emissions and TOW. Section 3 will describe current takeoff roll procedure using references from literature and supported by discussion with practicing pilots to identify operational limitations and potential sources of inefficiency. Section 4 presents the results and discussion aligned to the objectives of this paper. Finally, Section 5 will summarise the benefits of the analyses and introduce future research avenues. Details omitted from the main text of this paper are included in the [Supporting Information \(SI\)](#) where referenced.

2. Data and methodology

2.1. Flight data records

This study uses high-resolution (1 Hz) aircraft departure activity FDRs, recorded by a single airline at London Heathrow airport between the 5th and 18th of November 2012. A thorough quality assurance process was conducted to ensure that aircraft operations classed as irregular were omitted from the dataset. Data from the 4th November was removed due to high wind speed periods (+6.4 to −11.4 m/s resolved in the takeoff roll directions). The range of temperatures recorded during the study period (2.5–14.5 °C) is not expected to have a significant impact on operations and no significant rainfall events occurred. Major aircraft technical issues were also removed from the dataset (e.g. takeoff events with one engine shutdown). Furthermore, no operating incidents were reported over the period. Ultimately, 3336 takeoff roll events covering six distinct aircraft-engine combinations, shown in [Table 1](#), were analysed, corresponding to 35.6% of all takeoff roll activities at London Heathrow during the analysis period.

2.2. Uncertainty analysis

Several of the input parameters used in the modelling of engine thrust, pollutant emissions and aircraft TOW have associated uncertainties. These uncertainties have been identified through an extensive review of the existing literature and empirical analyses and are represented with triangular distributions, with minimum, modal and maximum values, where appropriate and unless otherwise stated. Following the method adopted by [Stettler et al. \(2011\)](#), a Monte Carlo 1000-member ensembles was used to give the modelling outputs associated distributions. From this, summary statistics have been calculated (5th and 95th percentiles) and are reported to support the results shown in [Section 4](#).

2.3. Thrust setting and emission modelling

Each FDR contains 1 Hz resolution data detailing the 4D trajectory (latitude, longitude, altitude and time), ground speed, and fuel flow for each engine of a single aircraft. Thrust setting, NO_x and BC emissions time series' are modelled for each engine using the Boeing Fuel Flow Method II (BFFM2) ([ICAO, 2011](#); [Kim and Rachami, 2008](#)). This method has been widely used (e.g. ([Simone et al., 2013](#); [Stettler et al., 2011](#); [Wasiuk et al., 2015](#))) to calculate the engine thrust setting, as a percentage of rated thrust (maximum force generated by an aircraft engine at International Standard Atmosphere (ISA) sea level static conditions), based on the engine-specific data contained in the ICAO Engine Emissions Databank (EEDB) ([ICAO, 2015](#)). The thrust setting is calculated for each second of corresponding aircraft activity using recorded fuel flow rates for each engine, given by,

$$F/F_{00} = A \cdot \dot{m}_f^2 + B \cdot \dot{m}_f + C, \quad (1)$$

where F/F_{00} is the thrust setting as a ratio relative to rated thrust (F_{00}) at ISA, \dot{m}_f is the fuel flow rate, and A , B , C are engine specific constants derived by fitting a quadratic to data in the ICAO EEDB, as shown in [Table S1](#). This thrust setting is subsequently used to calculate engine-specific EIs. $EI(\text{NO}_x)$ is derived by fitting a log-log curve to the $EI(\text{NO}_x)$ data at F/F_{00} values of 7, 30, 85 and 100%, contained in the ICAO EEDB. $EI(\text{BC})$ is estimated using the Formation Oxidation (FOX) method ([Stettler et al., 2013](#)). Under complete combustion, $EI(\text{CO}_2)$ is dependent on the hydrogen to carbon ratio of aviation fuel and is

Table 1
Aircraft-engine combinations and number of associated FDR observations.

Identifier	Aircraft type	Engine type	Observation count
A319	Airbus A319	V2522-A5	1302
A320	Airbus A320	V2527-A5	1049
A321	Airbus A321	V2533-A5	388
B747a	Boeing 747-400	RB211-524G	191
B747b	Boeing 747-400	RB211-524G-T	211
B777	Boeing 777-A	GE90-85B	195

approximately 3160 g/kg (Stettler et al., 2011). The 1 Hz emissions rates ($\dot{m}_f \times EI$) are summed for the duration of the takeoff roll phase, resulting in total masses of fuel consumption and emissions.

Changes in ambient temperature are known to impact the absolute thrust (kN) generated for a given fuel flow rate. Two different methods were used to identify the percentage change in absolute thrust per °C difference with ISA (15 °C). Using an off-design gas turbine simulation (GasTurb GmbH, Germany) and the temperature correction given by BFFM2 (Baughcum et al., 1996), we estimated that the generated absolute thrust increases by between 0.26% and 0.97% for each degree below ISA. This uncertainty, has been accounted for in the Monte Carlo analysis by implementing a correction sampled from a uniform distribution over the same range. Analysis of EI(NO_x) measurements reported by Timko et al. (2010a) with corresponding ambient temperatures in the range of 8–19 °C suggest that EI(NO_x) can differ significantly from that stated in the EEDB as a result of ambient temperature and engine variability. Thus, a multiplicative factor sampled from a triangular distribution with minimum, mode and maximum values of 0.6, 0.9, and 1.3, respectively, is used to quantify uncertainty in EI(NO_x) (Stettler et al., 2011). EI(BC) uncertainties due to engine variation, FOX model accuracy and the effect of ambient temperature have been quantified using a ±55% factor (Stettler et al., 2013).

2.4. Calculation of relative aircraft TOW

Aircraft TOWs were not included in the original dataset; therefore, aircraft TOW has been estimated using a force balance equation applied to the initial phase of each takeoff roll. Both the thrust setting and acceleration were found to be approximately constant during an initial phase of the takeoff roll corresponding to the ground speed range of 20–50 m/s (as shown in the SI, Section S.2). TOW was calculated as,

$$TOW = \frac{\left(F_{00} \cdot \frac{F}{F_{00}} \cdot \alpha_{age} \cdot \alpha_{bleed}\right) - (F_D + F_{RR})}{a}, \quad (2)$$

where F_{00} is the maximum rated thrust at ISA stated in the ICAO EEDB, F/F_{00} is the thrust setting relative to rated thrust (calculated using recorded fuel flow). Engine aging can lead to a 10% decrease in rated thrust due to a decrease in fuel consumption efficiency (Lukachko and Waitz, 1997). All takeoff roll events relate to a single airline, consequently, a factor of 0.95 has been used to represent α_{age} , with an associated uncertainty range of 0.90–1.00. An average engine bleed factor α_{bleed} of 0.9895 is taken from Baughcum et al. (1996) with an associated range of 0.9870–0.9920. F_D is the aerodynamic drag force on the aircraft, F_{RR} is the rolling resistant force and a is the aircraft acceleration for the initial phase of each takeoff roll. Acceleration has been assigned an uncertainty of ±5% to account for the 1 m/s resolution of recorded ground speed values.

2.4.1. Force due to rolling resistance

The drag due to rolling resistance F_{RR} is given by (Austyn Mair and Birdsall, 1996),

$$F_{RR} = C_{RR}(TOW \cdot g - F_L), \quad (3)$$

where g is acceleration due to gravity, F_L is the lift force and C_{RR} is the rolling resistance coefficient. C_{RR} is dependent on several factors including the type and number of tyres on the aircraft, as well as runway surface material. An average value of 0.02 with a range of 0.015–0.025 has been adopted based on a number of sources (Austyn Mair and Birdsall, 1996; Currey, 1988; Gerthoffert et al., 2014).

2.4.2. Aircraft lift coefficient and lift

The calculation of aircraft rolling resistance requires quantification of aircraft lift, F_L , which is given by,

$$F_L = \frac{1}{2} \cdot C_L \cdot \rho \cdot V^2 \cdot S, \quad (4)$$

where C_L is the aircraft lift coefficient, ρ is air density in kg/m³, V is aircraft true airspeed (TAS) in m/s and S is the aircraft wing surface area in m². Air density, ρ , is given by,

$$\rho = \frac{P_{amb}}{R \cdot T_{amb}}, \quad (5)$$

where P_{amb} is ambient air pressure in Pa, R is the specific gas constant for dry air (287.058 J/kg K) and T_{amb} is the recorded ambient temperature in K (Cavcar, 2014).

TAS is defined as the speed at which the aircraft is moving relative to the air surrounding it and was calculated using FDR ground speed corrected using recorded, minute-averaged resolved wind speeds. TAS is assigned an uncertainty of ±5% to account for the 1 m/s resolution of recorded ground speed values. The values for aircraft specific lift coefficient C_L are approximated through an analysis of flight records with the lowest recorded aircraft rotation speeds (<5th percentile) and highest TOWs (>95th percentile). For these records, C_L is calculated by assuming lift is equal to weight at the rotation speed (the speed at which the aircraft begins to rotate for lift-off). For cases where recorded rotation speeds are higher, or TOW is lower, the calculated lift coefficient would be lower. The approximated values of C_L are therefore upper bounds and are given by (EUROCONTROL, 2004),

$$C_L = \frac{2 \cdot M \cdot g}{\rho \cdot V_{R,\min}^2 \cdot S}, \quad (6)$$

where $V_{R,\min}$ is minimum TAS required to achieve aircraft rotation at maximum TOW. Table S2, containing the calculated values of $V_{R,\min}$ and C_L for each aircraft type, is shown in the SI. Errors in the assumptions used to calculate C_L are captured using an uncertainty of $\pm 20\%$.

2.4.3. Force due to aircraft drag

The aerodynamic drag, F_D , is modelled using the methods specified by the Base of Aircraft Data (BADA) (EUROCONTROL, 2004) and is given by,

$$F_D = \frac{C_D \cdot \rho \cdot V^2 \cdot S}{2}, \quad (7)$$

where C_D is the drag coefficient calculated by (EUROCONTROL, 2004),

$$C_D = C_{D0} + \Delta_{lg} + (C_{D2} \cdot C_L^2) \quad (8)$$

C_{D0} is the parasitic drag coefficient, Δ_{lg} is drag due to landing gear and C_{D2} is the induced drag coefficient, given as constants in BADA (EUROCONTROL, 2004). C_L is the aircraft lift coefficient calculated in Eq. (6).

3. Takeoff roll operating procedure and constraints

In order to place the analysis of reduced thrust settings presented in this study into the applied operational context, the general procedure for successful completion of a takeoff roll is described below to identify influencing decision factors and limitations (ATSB, 2009). Two pilots with experience of the airline and all the aircraft types in the dataset were consulted to verify this (see Section S.4 in the SI). The procedure involves the computation of takeoff parameters including the 'V' speeds (V_1 , V_R , V_2) and the takeoff roll thrust setting (Airbus, 2004) using flight performance data based on the operating conditions. The required data includes:

- Estimated aircraft TOW;
- Runway characteristics (condition (wet/snow/contaminated), takeoff distance available, temporary obstacles, slope);
- Engine anti-ice on/off;
- Air conditioning pack on/off;
- Barometric pressure;
- Temperature;
- Wind speed and direction;
- Runway entry points;
- Pilot preferences (i.e. flap setting and aircraft defects).

This data is entered into the Flight Management System (FMS), which computes the aforementioned V speeds and takeoff roll thrust setting. In both Airbus and Boeing aircraft, the pilot selects a reduced thrust setting indirectly from a selection of assumed temperatures, calculated by the FMS. These temperatures correspond to the thrust settings required to achieve safe takeoff for different TOWs. In response to the assumed temperature increase, the FMS decreases the fuel flow to the engine and consequently the thrust generated by the engine decreases. For example, an ambient temperature of 15 °C, will correlate to rated (100%) thrust, and may be used for the maximum aircraft TOW. If the TOW is less than maximum TOW, less thrust is needed to perform the takeoff roll. The pilot will reduce the fuel flow by selecting the assumed temperature closest to, but not less than, the estimated TOW, resulting in a reduced takeoff roll thrust. The indirect application of reduced thrust operations may lead to the use of suboptimal thrust settings.

The pilots indicated that the amount by which the thrust setting can be reduced is limited by safety constraints and is aircraft/engine specific. For example, a minimum of 75% of maximum rated thrust is a constraint imposed on Airbus A319, A320 and A321s. Under certain circumstances, the pilots will elect to takeoff with maximum thrust setting regardless of TOW. Such circumstances may be due to runway contamination, heavy rain, snow, or runway obstacles. Additional conditions where reduced thrust should not be used include: when brakes are defective; takeoff is made with a tailwind or if headwind adjustment has been used to increase allowable TOW (Zagoren, 2009).

Thus, the selection of aircraft takeoff roll thrust setting is dependent on a number of flight performance data, primarily aircraft TOW, and variation in the thrust setting for a given aircraft TOW may be caused by pilot subjectivity or the use of indirect input data (assumed temperature) to select the appropriate thrust setting. Despite efforts taken to ensure that the takeoff operations are reflective of standard operating procedures, unaccounted for operational constraints may also lead to variation in the selected thrust setting. This study seeks to quantify the impact of these operational inefficiencies and make recommendations for the thrust settings that lead to the lowest fuel consumption and emissions of NO_x and BC.

4. Results and discussion

4.1. Comparison of observed thrust setting fuel and emissions to ICAO approaches

The first objective of this research is to quantify the fuel consumption and NO_x emissions associated with the observed data and make comparisons to estimated values based on aircraft takeoff trajectory assumptions. As previously stated, it is widely reported in literature that regular takeoff operations occur at 100% thrust (Kurniawan and Khardi, 2011; Mazaheri et al., 2011). Therefore, the baseline scenario assumes 100% thrust for takeoff. As the takeoff roll TIM is a function of both the TOW and engine thrust setting (see Section S.8 of the SI), in this scenario we have set the takeoff TIM to the minimum observed for the same aircraft type and similar TOW (within ±1%). The estimated fuel consumption and pollutant emissions from these scenarios are shown in Table 2, where the final row ('Total') refers to the sum from the total number of takeoff events across all aircraft-engine combinations.

Table 2 shows that the fuel consumption and NO_x emissions associated with the observed takeoff roll events can be significantly lower than the equivalent values for takeoff roll events using 100% thrust. Depending on the aircraft-engine combination, reductions in fuel consumption, NO_x and BC emissions fall in the range of 1.0–23.2%, 10.7–48.7% and 49.0–71.7%, respectively. The reductions identified for Airbus A319 and A320 aircraft are relatively small compared to other aircraft, which is attributable to the high thrust setting (and consequently high fuel flow rate and emission rates) used during the takeoff roll for these activities, which is discussed further in the following sections. Across all recorded activities, the total reduction in fuel consumption, NO_x and BC emissions due to the use of reduced thrust takeoff is 13.2%, 34.7% and 58.8% respectively. Under the assumption that takeoff operations contribute approximately 22% of the total fuel consumed, 60% of NO_x and 50% of BC emitted by ground level phases of the LTO (Stettler et al., 2011), total ground level fuel consumption, NO_x and BC emissions would be increased by 3.3%, 31.9% and 71.3% respectively if all flights were to use 100% thrust setting during the takeoff roll relative to observed values. The benefits of reduced thrust takeoff are therefore significant, however it is acknowledged that the utilisation of reduced thrust operations is dependent on several underlying explanatory variables. The following sections of this paper analyse the impact of these variables on the consistency of use of reduced thrust takeoff operations.

4.2. Thrust setting to mass relationship

The relationship between thrust setting and aircraft TOW is evaluated in order to quantify the distribution of engine thrust settings adopted for different aircraft-engine combinations at London Heathrow. Fig. 1 shows the thrust setting adopted for each individual takeoff roll and the corresponding relative TOW (relative to the maximum estimated TOW for each aircraft). To assist the analysis, the continuous distribution of aircraft TOWs are assigned to discretised levels (TOW categories) of equal width (±1%) from the minimum (0.639) to the maximum (1.000) relative TOW.

Fig. 1 shows a general trend of lower takeoff thrust settings as aircraft TOW decreases. However, for the same aircraft-engine combination, there is a considerable amount of variability in the thrust settings for a given aircraft TOW, as shown by the error bars which represent the 5th and 95th percentiles. This variability is highest for Boeing 747-400 aircraft, for which thrust settings are observed to range from 5% below to 18% above the median. The variability is less for the other aircraft types and is generally characterised by a range of ±5% from the median thrust setting. Quantified values for each aircraft-engine combination are given in Section S.5 of the SI. This observed variability may be caused by either operational constraints or due to the use of an indirect thrust setting selection procedure and pilot subjectivity, as described in Section 3. Thrust settings greater than 100% rated thrust at ISA (F_{00}) for 7.3% of records demonstrate the effect of the ambient temperature corrections.

Observed thrust settings do not go below an apparent low-thrust limit that is specific to each aircraft type. This limit is most prominent for smaller aircraft; and, for example, is found at a thrust setting of approximately 84% for A319 activity, 94% for A320s and 89% for A321s (5th percentile thrust setting limits of 83%, 92% and 86% for A319, A320 and A321 aircraft

Table 2

Takeoff roll fuel consumption, NO_x and BC emissions for a 100% thrust setting assumption and observed thrust settings by aircraft-engine combination during the study period.

Aircraft-engine	100% thrust fuel (t)	Observed fuel (t)	Red. (%)	100% thrust NO _x (kg)	Observed NO _x (kg)	Red. (%)	100% thrust BC (kg)	Observed BC (kg)	Red. (%)
Airbus A319 V2522-A5	92.0	86.2	6.3	2254.4	1771.4	21.4	57.7	20.8	64.0
Airbus A320 V2527-A5	76.6	75.9	1.0	2030.1	1812.5	10.7	48.1	20.4	57.5
Airbus A321 V2533-A5	38.8	34.3	11.5	1415.9	992.0	29.9	22.4	6.7	70.2
Boeing 744 RB211-524G	98.1	75.4	23.2	5762.1	2953.8	48.7	57.3	28.0	51.2
Boeing 744 RB211-524G-T	102.1	83.1	18.6	2902.9	1762.3	39.3	59.6	30.4	49.0
Boeing 777A GE90-85B	48.5	41.1	15.2	2524.5	1740.5	31.1	40.4	11.4	71.7
Total	456.2	396.1	13.2	16889.8	11032.5	34.7	285.5	117.7	58.8

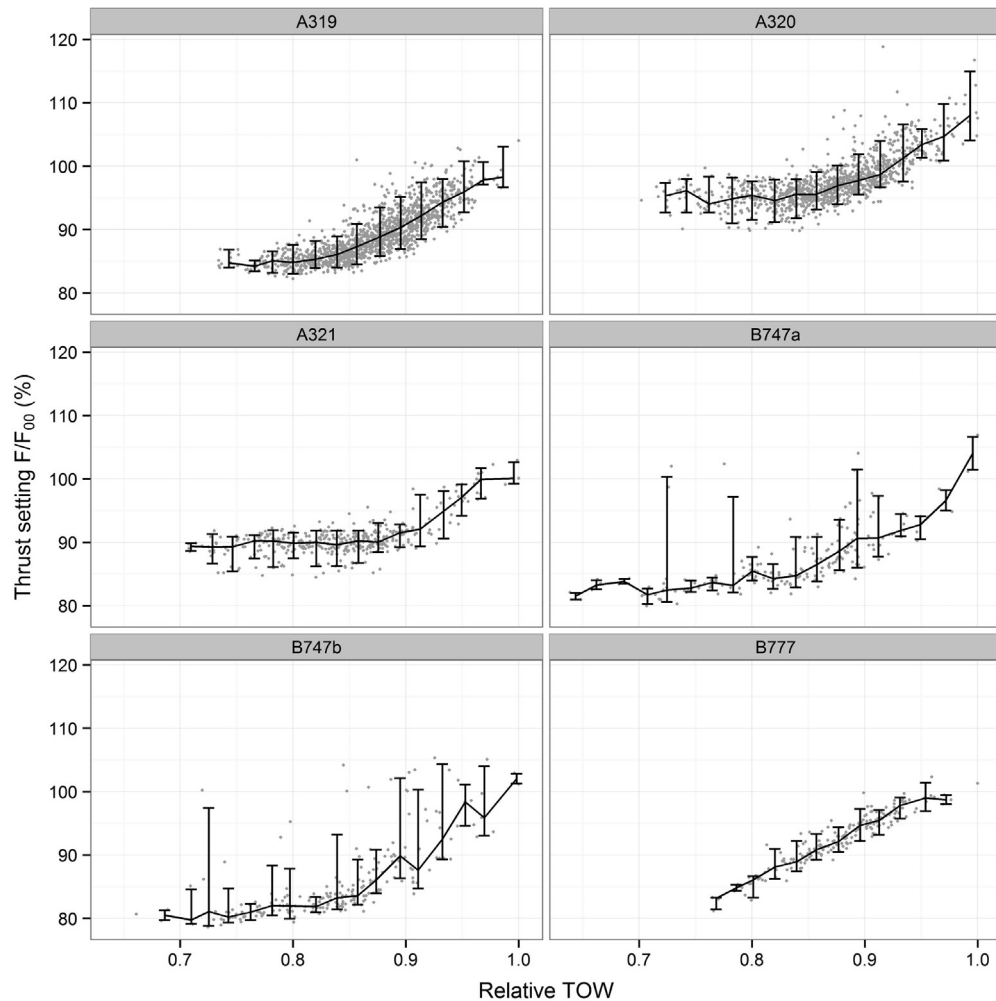


Fig. 1. Takeoff roll thrust setting against relative takeoff weight for 6 aircraft/engine combinations. Linear interpolation between median thrust setting values for each TOW category is shown with error bars corresponding to the 5th and 95th percentile of thrust settings.

respectively). The minimum observed thrust settings can be cross-referenced with the 75% limit highlighted in Section 3, which suggests that pilots operating these aircraft apply a further safety factor. The variation in the lower thrust setting limit value is a function of the rated thrust of the engine installed on the aircraft, relative to maximum TOW. For example, for a Boeing 747-400 aircraft with the same maximum TOW, the thrust setting limit is 82% and 80% for activities using the RB211-524G and RB211-524G-T engines respectively. These results indicate that pilots adhere to the limit values imposed by the airlines to ensure safe activity. Thus, while reduced thrust takeoff operations are used at London Heathrow airport, the safety constraints outlined in Section 3, limit the degree to which it is implemented.

4.3. Impact of thrust setting and aircraft TOW on fuel consumption, NO_x and BC emissions

The relationship between thrust setting and TOW will affect the characteristics of the aircraft takeoff roll trajectory (see Sections S.6 and S.8 in the SI) and determine the takeoff roll fuel consumption, NO_x and BC emissions. Therefore, the correct and consistent use of this relationship is of considerable importance to aircraft operators. However, the findings in Section 4.1 show that there is variability in the thrust setting used for a given aircraft TOW. This provides scope to identify the takeoff thrust settings that lead to the activities associated minimum fuel consumption and emissions. In this section, the thrust settings that minimise fuel consumption, NO_x and BC emissions will be identified for different aircraft-engine combinations and TOWs.

Aircraft TOW discretisation is maintained from the analysis in Section 4.1. Further discretisation is used to categorise the takeoff roll thrust settings into discrete levels using the same method. Equal width discretisation is applied to the continuous distribution of thrust settings between the minimum (78.6%) and maximum (118.8%) observed thrust settings at increments

of ~2%, within each TOW level. The same levels are used for each aircraft-engine combination. The average fuel consumed, NO_x and BC emitted for all thrust setting categories is calculated at all TOW levels for London Heathrow operations. For each aircraft TOW level, the thrust setting is plotted against: total fuel consumed in Fig. 2; average total NO_x emitted in Fig. 3; and average total BC emitted in Fig. 4. This shows the variation in fuel consumption and pollutant emissions against the average adopted thrust setting for any given TOW.

For any specific aircraft-engine combination, there is a large spread of values for fuel consumption over the takeoff roll (see Fig. 2); using Boeing 747-400 activities as an example, fuel consumption ranges from 260 kg to 488 kg, corresponding to a difference of 87.7%. For the six aircraft-engine combinations the average difference between the minimum and maximum fuel consumed for a takeoff roll is 63.7%. This is dependent on aircraft TOW, which governs the takeoff roll thrust setting and consequently takeoff roll TIM. However, there is also variation in the mass of fuel consumed for any given TOW (for the same aircraft-engine combination); for example, a Boeing 747-400 takeoff roll activity with a relative mass of 0.886–0.905, consumes between 413 kg and 462 kg of fuel, corresponding to a difference of 12%. This variation may be attributed to the variability in the thrust setting resulting from the assumed temperature selection procedure or unidentified operational constraints. When considering activities with the same TOW, there is no consistent trend between fuel consumption and either increasing or decreasing thrust setting for the aircraft-engine combinations analysed. This suggests that the thrust setting that leads to minimum fuel consumption does not consistently occur at either minimum or maximum possible thrust setting. For example, it is observed in Fig. 2 that the lowest average fuel consumption often does not correspond to the lowest observed thrust setting level; this is particularly evident for smaller aircraft types (A319, A320, A321) operating with low relative TOW (<0.8). For a given TOW, reduced thrust will lead to a lower acceleration and subsequently to a higher takeoff roll TIM, which may outweigh the reduction in fuel flow rate and lead to increased fuel consumption. However, this is not true for all aircraft-engine combinations and Fig. 2 shows that Boeing 777-A aircraft often achieve lowest takeoff roll fuel consumption with the lowest thrust setting recorded within each TOW level. In Section S.8 of the SI, we show that the range of takeoff TIMs is smaller for the B777 than the other aircraft. Furthermore, in S.10 we show that the GE90-85B produces ~20% more thrust per unit of fuel burned than the other engines suggesting that the fuel penalty associated with a marginal increase in the takeoff roll TIM is less significant than for the other aircraft.

A large range of total NO_x and BC emitted for takeoff rolls of the same aircraft type is shown in Figs. 3 and 4 respectively. The ranges between minimum and maximum NO_x emissions are 110% on average and are higher than identified for fuel con-

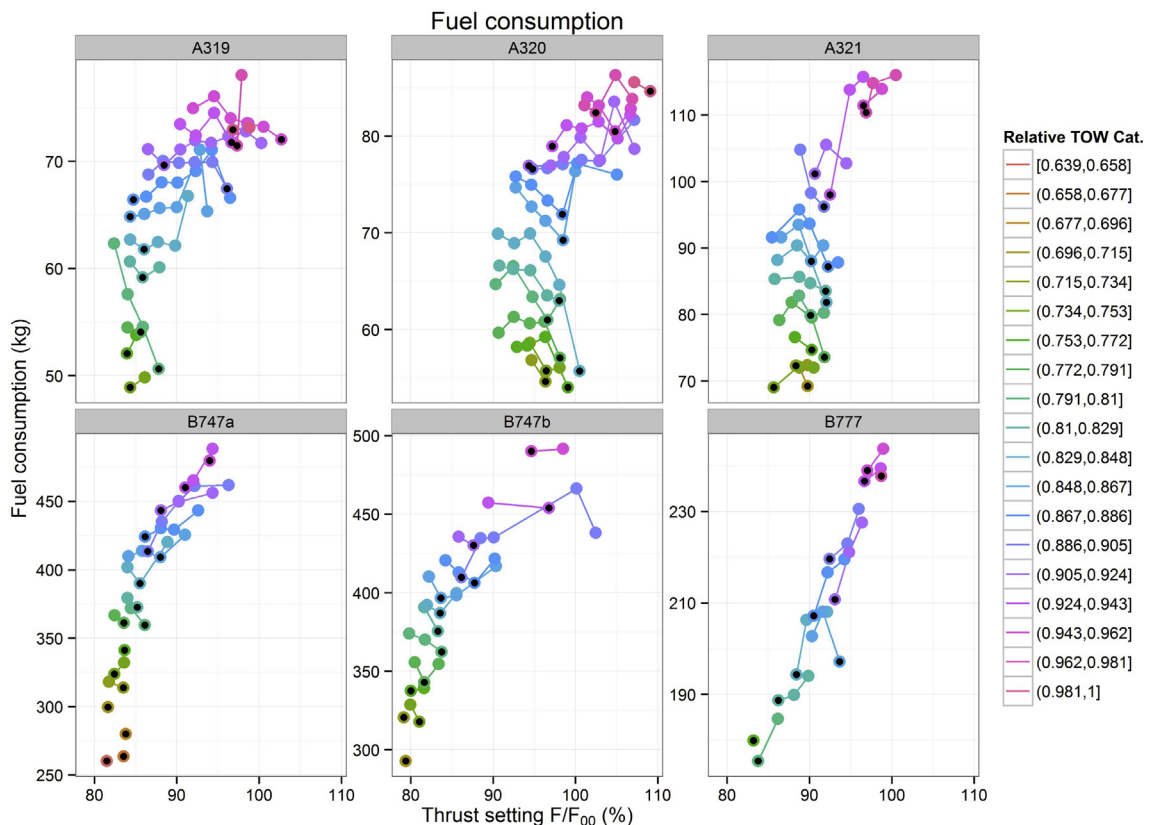


Fig. 2. Fuel consumption plotted against thrust setting for constant aircraft TOW categories, shown for each aircraft-engine combination. Filled black points represent the thrust setting associated with minimum fuel consumption for each aircraft TOW.

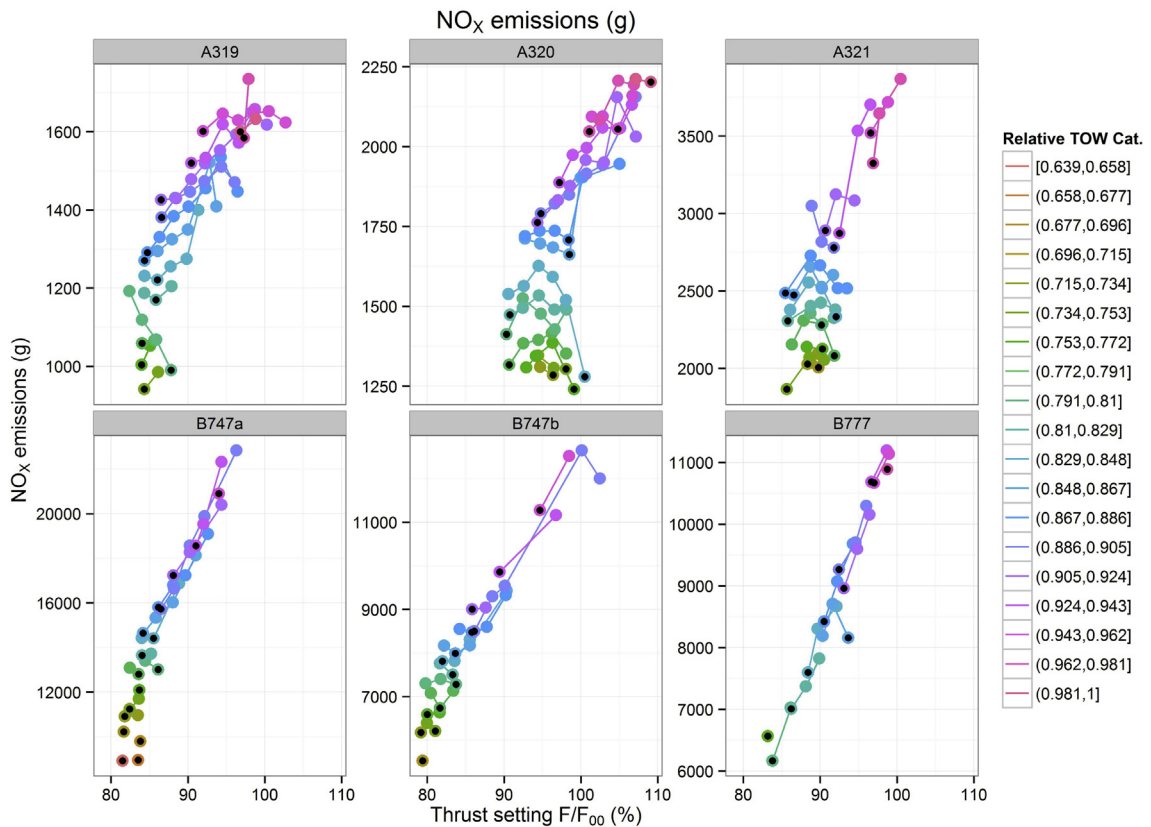


Fig. 3. NO_x emissions plotted against thrust setting for constant aircraft TOW categories, shown for each aircraft-engine combination. Filled black points represent the thrust setting associated with minimum NO_x emission for each aircraft TOW.

sumption (cf. 64%). This is attributed to the third explanatory variable for NO_x emissions, the emission index (EI), which, like fuel flow rate, is also dependent on thrust setting. For example, Boeing B747-400s equipped with the RB211-524G engine emit between 10,000 and 24,000 g of NO_x, whereas B747-400s equipped with the RB211-524G-T engine emit between 6,000 and 12,000 g of NO_x. B747-400s with the RB211-524G engine ($EI(NO_x) = 40.5 \text{ g/kg @ } 85\% F/F_{00}$) emit an average of 80% more NO_x than the same aircraft equipped with the RB211-524G-T ($EI(NO_x) = 21.8 \text{ g/kg @ } 85\% F/F_{00}$) when operating with the same TOW, for which the main reason is the 86% difference in $EI(NO_x)$ between the two engines (fuel flow rate are approximately equal). In contrast to fuel consumption, NO_x emissions generally increase with increasing thrust setting for a given aircraft TOW. The patterns identified for BC emissions are similar to those identified for NO_x. Maximum BC emissions generally occur at higher thrust settings and decrease as the thrust setting is reduced – this is particularly evident for large aircraft types (i.e. Boeing 747-400 and Boeing 777-A). The average range between minimum and maximum takeoff BC emissions across all aircraft-engine combinations is 159%, which is higher than the average range of NO_x emissions and fuel consumption. From this it is acknowledged that BC is the most sensitive of the three outputs to aircraft thrust setting, and therefore has the greatest potential to be lowered through reduced thrust takeoff operations. Figs. 2–4 are reproduced with error bars in S.9 of the SI.

4.4. Thrust setting optimisation for minimum fuel consumption, NO_x and BC emissions

The analysis in Section 4.2 led to the identification of the thrust setting corresponding to trajectories associated with minimum fuel consumption, NO_x and BC emissions for each aircraft-engine combination at any given TOW. This relationship between the optimum thrust setting and aircraft TOW is visualised in Fig. 5. Second-order polynomials are fitted to the data points using least-squares regression and provide a good fit for the majority of aircraft types, as shown by the R^2 values. The polynomial regression represents the thrust settings that should be adopted for a specific aircraft-engine combination operating with a known TOW as a result of the analysis presented in this study. The coefficients are shown in the S.7 of the SI. The reported thrust settings have been corrected for ambient temperature and presented as a ratio of absolute thrust to maximum rated thrust at ISA (F_{00}).

The thrust setting corresponding to minimum fuel consumption, NO_x and BC emission varies with relative aircraft TOW. For high aircraft TOW, thrust settings that are relatively high for the given aircraft-engine are found to provide the optimum

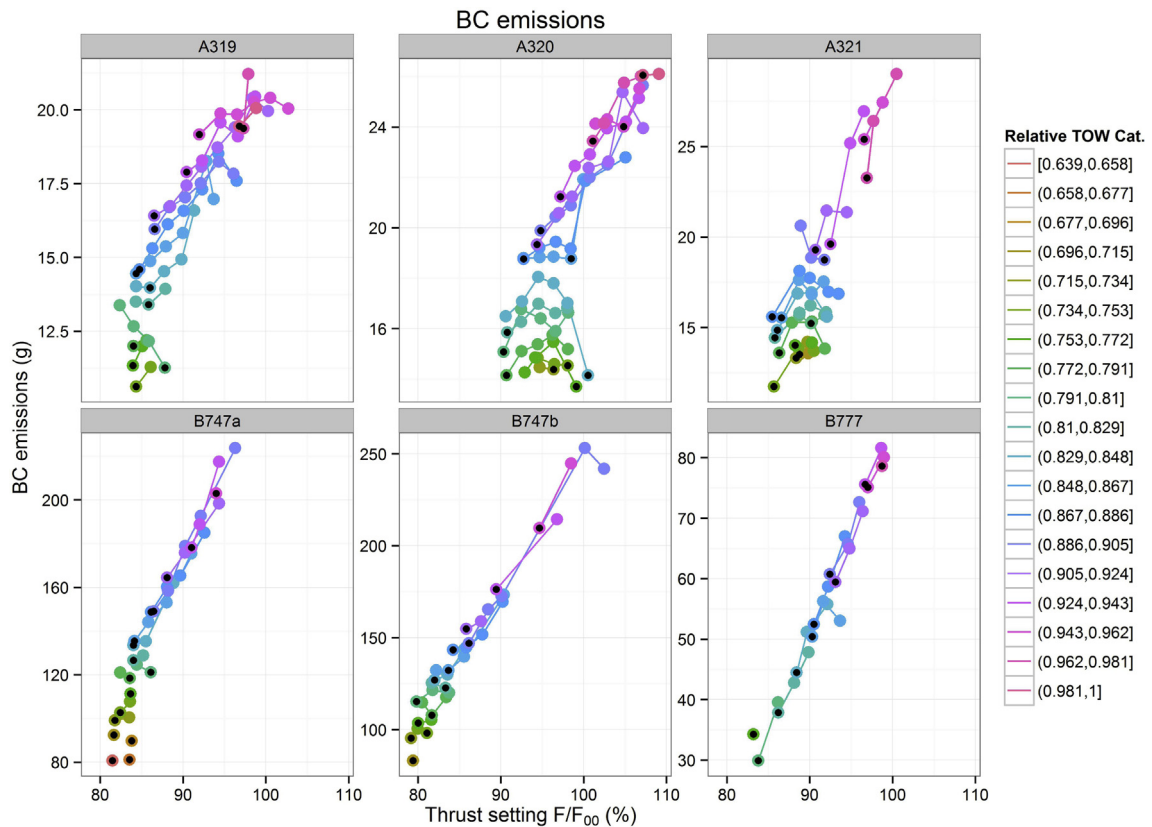


Fig. 4. BC emissions plotted against thrust setting for constant aircraft TOW categories, shown for each aircraft-engine combination. Filled black points represent the thrust setting associated with minimum BC emission for each aircraft TOW.

takeoff roll trajectories for reduced fuel consumption and pollutant emissions due to the reduced TIM, despite the increased fuel flow rate and EI associated with high-thrust operating modes. This also reflects that most activities at relatively high TOW were observed to adopt higher takeoff thrust settings. As aircraft TOW decreases, the recommended thrust setting also decreases. However, for many aircraft-engine combinations, a point is reached where further reduction of takeoff roll thrust setting increases fuel consumption and pollutant emissions, such as for B747 aircraft. This finding is aircraft-engine type dependent and, for example, is not observed for B777 aircraft, for which it is always favourable to use the lowest thrust setting. However, for other aircraft, such as Airbus A319, A320 and A321, it often becomes beneficial to increase thrust setting at low relative aircraft TOWs (<0.8) to minimise fuel consumption and pollutant emissions. This is due to the reduction in TIM, which outweighs the increased fuel flow rate and EI associated with high-thrust operating modes. From Fig. 5, it can be seen that different ranges of thrust settings are required to minimise either fuel consumption or pollutant emissions for different aircraft-engine combinations. In most cases, a lower thrust setting is required to minimise pollutant emissions than is necessary to achieve minimum fuel consumption for the same aircraft-engine combination with the same known TOW. This poses a trade-off, which should be addressed in future research and incorporated into the environmental priorities of aircraft operators (e.g. air quality versus CO_2). For the A320, the data implies lower ambient temperature and a subsequent thrust setting above $100\% F_{00}$ minimises fuel consumption, NO_x and BC for very high TOW operations (~ 1 relative TOW).

The modelled regression curves are recommended for an aircraft operator to use when calculating the thrust setting required to achieve the takeoff roll trajectory resulting in minimum fuel consumption or pollutant emissions, dependent on aircraft type, engine type and TOW, during regular operating conditions. As the results are derived from operational data, these recommendations adhere to the current operating constraints identified in Section 3. The necessary information to calculate thrust setting, for a given TOW, is presented in the form of quadratic coefficients shown in Section S.7. Given the operating procedure described in Section 3, it is suggested that the recommendations be used to inform the thrust setting computation when the pilot is using the FMS. The adoption of the regression equations would facilitate improved consistency and minimised ambiguity in the thrust setting selection process. The recommendations could be integrated with the current assumed temperature method or as a standalone alternative method. The potential reduction in fuel consumption, NO_x and BC emissions at London Heathrow are quantified in Section 4.4.

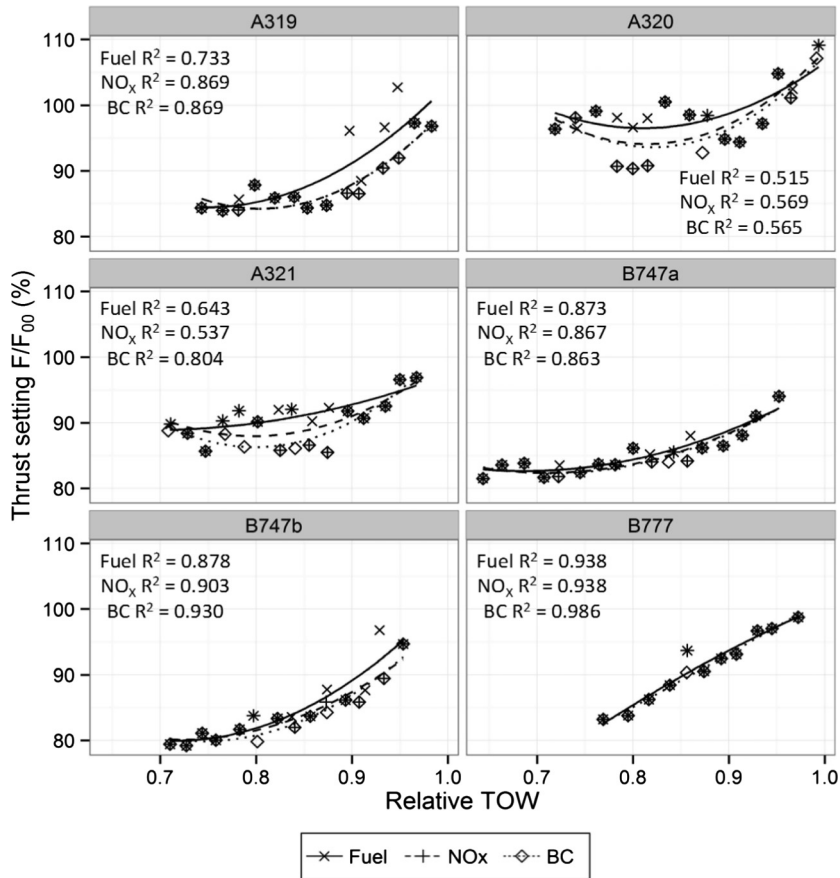


Fig. 5. Thrust setting (F/F_{00}) plotted against relative aircraft TOW for minimum fuel consumption, NO_x and BC emissions respectively. Polynomial regression curves are displayed and R^2 values shown.

4.5. Quantification of fuel consumption, NO_x and BC emission reductions

This section quantifies the reductions in fuel consumption, NO_x and BC emissions when operating with the reduced thrust settings recommended in Section 4.3. Tables 2–4 present this in absolute and percentage terms for each aircraft–engine combination where all of the observations in the dataset are assumed to have adopted the takeoff trajectory (thrust setting and TIM) that minimises fuel consumption or pollutant emissions for a given TOW. ‘Observed’ values are those that are based on recorded activities, while ‘minimum’ values correspond to the expected fuel consumption and pollutant emissions if the recommended reduced thrust settings had been adopted. The optimum absolute thrust and fuel flow is corrected for the ambient temperature at the time of each individual activity to demonstrate that the proposed thrust settings are suitable across a range of conditions. The 5th and 95th percentile uncertainty ranges for different aircraft types in Tables 3–5 account for parametric uncertainties and reflect the variability in the flight data records. For instance, the B777 has a smaller relative

Table 3

Average reduction in fuel consumption using the fuel optimised thrust settings for all observations during the study period.

Aircraft type	Engine type	Observed fuel (t)	Minimum fuel (t)	Absolute reduction (t)	Median percentage reduction (%) [5th, 95th]
Airbus A319	V2522-A5	86.3	84.3	2.0	2.4 [1.3, 3.1]
Airbus A320	V2527-A5	75.9	74.4	1.5	2.0 [1.0, 2.9]
Airbus A321	V2533-A5	34.4	33.8	0.6	1.7 [1.1, 2.6]
Boeing 747-400	RB211-524G	75.5	73.9	1.5	2.1 [1.0, 2.8]
Boeing 747-400	RB211-524G-T	83.2	82.2	1.0	1.2 [0.6, 1.9]
Boeing 777-A	GE90-85B	41.2	40.3	0.9	2.2 [1.6, 3.3]
Total		396.4	388.8	7.6	1.9

Table 4Average reduction in NO_x emissions using the NO_x optimised thrust settings for all observations during the study period.

Aircraft type	Engine type	Observed NO _x (kg)	Minimum NO _x (kg)	Absolute reduction (kg)	Median percentage reduction (%) [5th, 95th]
Airbus A319	V2522-A5	1638.6	1569.1	69.5	4.2 [3.6, 5.1]
Airbus A320	V2527-A5	1676.6	1584.0	92.6	5.5 [3.7, 8.1]
Airbus A321	V2533-A5	917.7	871.0	46.7	5.1 [2.9, 7.3]
Boeing 747-400	RB211-524G	2732.3	2506.0	226.4	8.3 [7.1, 9.7]
Boeing 747-400	RB211-524G-T	1630.2	1552.8	77.4	4.7 [3.6, 6.4]
Boeing 777-A	GE90-85B	1610.0	1530.9	79.1	4.9 [3.8, 6.9]
Total		10205.4	9613.8	591.6	5.8

Table 5

Average reduction in BC emissions using the BC optimised thrust settings for all observations during the study period.

Aircraft type	Engine type	Observed BC (kg)	Minimum BC (kg)	Absolute reduction (kg)	Median percentage reduction (%) [5th, 95th]
Airbus A319	V2522-A5	20.6	19.8	0.9	4.2 [3.5, 4.9]
Airbus A320	V2527-A5	20.3	19.7	0.6	3.1 [2.3, 4.3]
Airbus A321	V2533-A5	6.6	6.3	0.3	5.1 [4.1, 6.6]
Boeing 747-400	RB211-524G	27.8	25.2	2.6	9.3 [8.2, 10.4]
Boeing 747-400	RB211-524G-T	30.3	28.0	2.3	7.5 [6.2, 9.2]
Boeing 777-A	GE90-85B	11.3	10.4	0.9	8.1 [6.4, 10.0]
Total		117.0	109.3	7.6	6.5

uncertainty range than the A319 for both fuel consumption and NO_x emissions reduction due to less operational variability (e.g. thrust setting, and TIM) in the flight data records.

For fuel consumption, takeoff roll activity operating with the recommended thrust setting leads to a reduction of between 1.2 and 2.4% depending on aircraft–engine combination relative to takeoff operations as recorded. This corresponds to a total saving of 7.6 tonnes of fuel (equating to 1.9%) from the 3336 takeoff roll events. Reductions in NO_x emissions range from 4.3 to 8.4% depending on aircraft/engine combination. This corresponds to an absolute saving of 592 kg of NO_x (5.8%) for the combined takeoff roll events. Using the recommended thrust settings for BC emissions results in savings between 3.0 and 9.3% depending on aircraft–engine combination. This corresponds to a total saving of 7.6 kg (6.5%) for the combined takeoff roll events, relative to recorded takeoff roll operations.

The further reductions identified in this research are relatively small, and may be explained by the operational constraints identified in Section 3. While every effort was taken to ensure that takeoff events were reflective of standard operating procedures, other operational and safety constraints may not have been apparent in the data available. Therefore, we conclude that reduce thrust takeoff is already implemented near-optimally by this airline at London Heathrow Airport. However, these results may be of relevance to other airports and aircraft operators.

Departure events comprised half of the aircraft activities at London Heathrow during the two-week period. FDRs were available for 35.6% of takeoff rolls, however, the aircraft–engine combinations used corresponds to 46% of all takeoff roll activities and the specific aircraft types cover 69%. Under the assumption that the takeoff phase contributes approximately 22% of the total fuel consumed by ground level activities (Stettler et al., 2011), a 1.9% reduction in takeoff roll fuel consumption could achieve a reduction of around 0.42% of total aircraft ground level fuel consumed and CO₂ emissions. This would contribute towards the SESAR high-level target of a 2.8% reduction in the fuel consumption across the whole flight, but must be combined with other fuel saving strategies to achieve the target during ground operations. The takeoff roll phase contributes approximately 60% and 50% of total ground level NO_x and BC emissions respectively (Stettler et al., 2011). Consequently, the potential savings identified in this paper equate to a 3.5% reduction in total ground level NO_x and 3.3% reduction in total ground level BC emissions.

These recommendations are based on observed takeoff roll activities and are therefore achievable under the assumption of regular operating conditions. Given the empirical nature of the analysis, the suggested thrust settings will result in safe aircraft trajectories (aircraft acceleration, TIM and V speeds) and adhere to the limit value for thrust setting reduction as currently used at London Heathrow. Therefore, these findings facilitate the immediate adoption of the aforementioned recommendations by aircraft operators. It must be acknowledged that under certain circumstances, operational constraints will mean that the use of optimum thrust setting will not be possible.

The lack of recorded aircraft TOW is the primary limitation of the current research. While the current research used uncertainty analysis to quantify the potential error, future work should seek to validate the TOW estimation methodology against recorded data.

5. Conclusions

The use of reduced thrust takeoff at London Heathrow airport reduces fuel consumption, NO_x and BC emissions by 1.0–23.2%, 10.7–47.7% and 49.0–71.7% respectively, depending on the aircraft-engine combination, relative to 100% engine thrust setting. If reduced thrust takeoff were not used, increases in total ground level fuel consumption, NO_x and BC emissions of 3.3%, 31.9% and 71.3% are expected.

The thrust settings associated with minimum fuel consumption, NO_x and BC emissions from aircraft takeoff rolls for six aircraft-engine combinations have been presented as polynomial equations that are dependent on the relative aircraft TOW. If integrated into the takeoff roll thrust setting selection procedure by aircraft operators as part of the FMS, using the recommended thrust settings, average reductions of 1.9%, 5.8% and 6.5% for takeoff roll fuel consumption, NO_x and BC emissions respectively could be obtained. This equates to 0.4%, 3.5% and 3.3% reductions in total ground level fuel consumption, NO_x and BC emissions respectively. These reductions are a relatively small proportion of those currently being achieved due to the use of reduced thrust takeoff. Consequently, this paper concludes that reduced thrust takeoff is already implemented effectively at London Heathrow but that the optimum thrust settings could be of relevance to other airlines and airports.

This study overcomes the limitations of previous research, which relied on assumptions regarding aircraft trajectory and fuel flow rates, in calculating NO_x and BC emission rates due to the lack of empirical data and therefore failed to accurately represent aircraft activity and associated variability. Two main sources of error have been overcome through the use of a large number of FDRs; first, unreliable quantification of fuel consumption and pollutant emissions and second, the possible negligence of operational limitations and constraints. The results of this paper not only benefit the economics of airlines, but also quantify the contribution that reduced thrust operations may offer towards achieving the fuel efficiency and environmental targets set by SESAR and compliance with air quality regulations around airports.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.trd.2017.02.004>.

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