The impact of aircraft takeoff thrust setting on NOx emissions

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Abstract

Reduced thrust takeoff has the potential to reduce aircraft-related NOx emissions at airports, however this remains to be investigated using flight data. This paper analyses the effect of takeoff roll thrust setting variability on the magnitude and spatial distribution of NOx emissions using high-resolution data records for 497 Airbus A319 activities at London Heathrow. Thrust setting varies between 67 and 97% of maximum, and aircraft operating in the bottom 10th percentile emit on average 514 grams less NOx per takeoff roll (32% reduction) than the top 10th percentile, however this is dependent on takeoff roll duration. Spatial analysis suggests that peak NOx emissions, corresponding to the start of the takeoff roll, can be reduced by up to 25% by adopting reduced thrust takeoff activities. Furthermore, the length of the emission source also decreases. Consequently, the use of reduced thrust takeoff may enable improved local air quality at airports.

Keywords

Airport operations; NOx emissions; reduced thrust; aircraft takeoff; environmental impact.
Highlights

- Flight data analysis for 497 Airbus A319 aircraft takeoffs at London Heathrow.
- The adopted thrust setting during takeoff is found to vary between 67 and 97%.
- The 10th percentile of takeoff thrust settings emits 32% less NOx than the 90th.
- Reducing takeoff thrust also leads to a reduced NOx emission source spatial extent.

1. Introduction

1.1 Research context

Global aviation has grown at an average annual rate of 5% in recent years and this growth is forecast to continue (Airbus, 2015; Boeing, 2014), with the total passenger numbers expected to reach 12.2 billion in 2031 (ACI, 2013). As aviation contributes significantly to both worldwide connectivity and the global economy (Wolfe et al., 2016), many aviation stakeholders have sought to enable this growth. However, this is expected to lead to a considerable additional strain on the air transport network, as many of its components currently operate at, or near, maximum capacity. The airport has been identified as a potential bottleneck to any increase in air transport capacity (Gelhausen et al., 2013). However, plans for airport expansion are increasingly scrutinised with respect to their potential environmental impacts (both noise and air quality) (Mahashabde et al., 2011), as these can be harmful to human health (Yim et al., 2013). The aircraft landing and takeoff (LTO) operations contribute significantly to local pollutant concentrations at airports (Carslaw et al., 2012). It is expected that any airport expansion will increase pollutant emissions through an increase in the number of LTO operations (Levy et al., 2012; Masiol and Harrison, 2014), which may inhibit capacity growth. Consequently, in recent years airport stakeholders have shifted from simply demonstrating compliance with ambient air quality directives that outline pollutant concentration limits (European Commission, 2008), towards facilitating pollutant emission reduction through airport operation management (Fleuti and Maraini, 2012).

This approach is critical for airports such as London Heathrow airport (UK Government, 2010), which is the busiest two-runway airport in the world and is seeking to expand, given that it operates at near maximum capacity (DfT, 2013). Several areas surrounding Heathrow have been designated as Air Quality Management Areas (AQMA) (Suau-Sanchez et al., 2014) due to the exceedance of EU Air Quality Standards. Thus, reducing pollutant emissions is a key priority for the airport (Heathrow Airport Ltd., 2010). The main pollutants of concern in the AQMAs around Heathrow airport are the nitrogen oxides (NOx), which are harmful to human health (Masiol and Harrison, 2015). In 2015, aircraft operating at the airport were subject to a
charge of £8.57 per kilogram of NO\textsubscript{x} emitted (increasing to £16.51 per kilogram of NO\textsubscript{x} emitted in 2017), as a financial incentive to promote emission-reducing operating strategies for airlines (Heathrow Airport Ltd, 2015).

Within the LTO cycle, aircraft are reported to operate at the highest thrust setting during the takeoff phase, which corresponds to peak fuel flow, CO\textsubscript{2} and NO\textsubscript{x} emission rates (Fleuti and Polymeris, 2004). Despite a relatively short time-in-mode (TIM) compared to other LTO cycle phases, the takeoff roll contributes 60% of the total ground level NO\textsubscript{x} and 22% of CO\textsubscript{2} emissions at Heathrow (Stettler et al., 2011). The use of reduced thrust takeoff allows aircraft operators to takeoff with less than the maximum (100%) thrust (Sherry, 2014), which is expected to result in several benefits, including increased engine life due to less mechanical wear, decreased fuel consumption and reduced CO\textsubscript{2} and NO\textsubscript{x} emissions (Hall et al., 2003). Many airports have adopted such operating strategies to reduce pollutant emissions (Guo et al., 2014), however, the associated impacts remain uncertain due to the limitations of the emission modelling methods used (Unal et al., 2005).

Emission modelling has commonly been conducted using aggregated data, with a significant amount of activity simplification, primarily to demonstrate compliance with ambient air quality regulatory limits. Modelling approaches such as the International Civil Aviation Organisation (ICAO) Simple Approach, are associated with high uncertainty regarding estimated emissions, due to the reliance on assumptions resulting in the specification of constant thrust setting and TIM values for each LTO reference cycle phases (landing, taxi, takeoff and initial climb). These values are conservative estimates and may not reflect actual operations (Kurniawan and Khardi, 2011). While the use of airport and aircraft specific constant values can improve the ICAO Simple Approach estimate by up to 40% (Fleuti and Maraini, 2012; Romano et al., 1999), this approach still fails to incorporate the variability that is expected during actual activity (ICAO, 2011). For example Winther et al. (2015) used the ICAO Simple Approach to model aircraft emissions at Copenhagen Airport, though a shortcoming of their study is the failure to capture the variability within each LTO cycle phase due to the use of aggregated, phase-specific fuel flow rates and emission indices. In order to overcome the limitations for complex operations such as reduced thrust takeoff, the use of high-resolution data and emissions modelling techniques, such as the ICAO Sophisticated Approach is recommended (Khadilkar and Balakrishnan, 2012).

Whilst the ICAO Sophisticated Approach is more data intensive than the ICAO Simple Approach, it is able to yield more accurate pollutant emission estimates given its ability to
capture variability in aircraft trajectory and thrust setting. Using high-resolution data for analyses leads to a more granular representation of the spatial and temporal trends, and thereby enables a more precise estimation of the magnitude, duration, frequency and location of emission sources. This in turn leads to an improved understanding of the emission patterns from observed aircraft activity, which can be valuable when determining the precise location of NOx released by high emitting mobile sources (i.e. an aircraft) to identify and quantify areas of operational inefficiency with regards to air quality management. This may be used to reduce airport emissions through informed management; i.e. the selection of less polluting operations over other options or a reduction in the emissions produced by a certain operation (Nikoleris et al., 2011; Ravizza et al., 2013). Furthermore, the spatial distribution of the emission source is important given implications for the personal exposure of airport staff and residents, as well as the impact of pollutant dispersion and therefore the local air quality. However, such analyses are rarely conducted due to high level of data requirements and the difficulty in obtaining data for sensitivity reasons.

1.2 Outline of paper

This paper seeks to analyse the effects of reduced thrust on Airbus A319 takeoff NOx emissions. This will be achieved through four objectives: (i) the variables used to calculate takeoff roll NOx emissions (time-in-mode (TIM), fuel flow rate and thrust setting) will be compared to LTO reference cycle assumptions; (ii) the relationship between thrust setting and TIM will be investigated to identify corresponding impacts on NOx emissions; (iii) the characteristics of the top and bottom 10th percentile of thrust settings will be analysed to quantify the effect on takeoff roll NOx emissions; (iv) the impact of thrust setting on the spatial distribution of NOx emissions will be examined through a comparison of the distributions for the top and bottom 10th percentile of thrust setting activities.

This paper will be formed of three further sections. Section 2 presents the data availability and adopted NOx modelling method. Section 3 presents and discusses the analysis used to meet the research objectives, demonstrates the benefits of using high-resolution analysis and outlines avenues for future research. Finally, the conclusions in Section 4 highlight the contributions of this paper to the research field.

2. Methodology

2.1 Data and emission modelling

Analyses focus on a case study of aircraft takeoff roll activities at Heathrow airport and are supported by the availability of 497 takeoffs on runway 27R corresponding to Airbus A319
aircraft fitted with V2522-A5 engines. The methodology presented is designed to be transferable to other airports if the data requirements are met.

The primary data source for this research is high-resolution (1 Hz) Flight Data Records (FDR) recorded during a continuous two-week period in November 2012. Each raw FDR file contains spatial, temporal and engine data as shown in Table 1.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal</td>
<td>Date</td>
<td>dd/mm/yy</td>
</tr>
<tr>
<td>Temporal</td>
<td>Time</td>
<td>hh/mm/ss</td>
</tr>
<tr>
<td>Temporal</td>
<td>Time from engine start</td>
<td>s</td>
</tr>
<tr>
<td>Temporal</td>
<td>Ground speed</td>
<td>kts</td>
</tr>
<tr>
<td>Spatial</td>
<td>Latitude</td>
<td>°, ', &quot;</td>
</tr>
<tr>
<td>Spatial</td>
<td>Longitude</td>
<td>°, ', &quot;</td>
</tr>
<tr>
<td>Spatial</td>
<td>Radio altitude</td>
<td>ft</td>
</tr>
<tr>
<td>Ambient</td>
<td>Outside air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Engine information</td>
<td>Fuel flow (per engine)</td>
<td>kg/s</td>
</tr>
<tr>
<td>Engine information</td>
<td>Engine pressure ratio (per engine)</td>
<td>n/a</td>
</tr>
<tr>
<td>Aircraft information</td>
<td>Flight phase</td>
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</tr>
<tr>
<td>Modelled</td>
<td>Thrust (per engine)</td>
<td>% of max.</td>
</tr>
<tr>
<td>Modelled</td>
<td>NO\textsubscript{X} emission rate (per engine)</td>
<td>g/s</td>
</tr>
<tr>
<td>Modelled</td>
<td>CO\textsubscript{2} emission rate (per engine)</td>
<td>g/s</td>
</tr>
</tbody>
</table>

Table 1. Parameters available for each FDR record.

The thrust setting (relative to maximum rated thrust) and NO\textsubscript{X} emissions are calculated following the Boeing Fuel Flow Method II (BFFM2) (ICAO, 2011; Kim and Rachami, 2008). This has been widely used (e.g. (Simone et al., 2013; Stettler et al., 2011; Wasiuk et al., 2015)) and results in a high-resolution thrust and emission rate time series, calculated using recorded fuel flow rates and engine-specific input data from the ICAO Exhaust Emission Databank (EEDB).

The thrust is given by:

\[
\frac{F}{F_{00}} = A \cdot \dot{m}_f^2 + B \cdot \dot{m}_f + C, \tag{1}
\]

where \(F/F_{00}\) is the thrust setting as a ratio relative to rated thrust, \(\dot{m}_f\) is the recorded fuel flow rate, and \(A, B, C\) are engine specific constants derived by fitting a quadratic to data in the ICAO EEDB. The NO\textsubscript{X} emission rate is given by:

\[
E_i = \dot{m}_f \cdot E_i \cdot t, \tag{2}
\]
where $E_i \dot{t}$ is the emission rate, $\dot{m}_f$ is the fuel flow rate; and $E_i \ddot{t}$ is the engine-specific emission index at a known thrust setting. $E_i(\text{NO}_x)$ is derived by fitting a log-log curve to the $E_i(\text{NO}_x)$ data at $F/F_{\text{SO}}$ values of 7, 30, 85 and 100%, contained in the ICAO EEDB. Under complete combustion, $E_i(\text{CO}_2)$ is dependent on the hydrogen to carbon ratio of aviation fuel and is approximately 3160 g/kg (Stettler et al., 2011).

2.2 Data handling

To ensure the analysis of activities associated with the takeoff roll phase, an understanding of the theoretical aircraft performance (Midkiff et al., 2004) and a manual analysis of data trends were both used to inform the phase selection. The on-ground segment of this phase is known as the takeoff roll and is the period between engine power-up and wheels-off (International Aviation Standards, 2013). This takeoff roll phase is assumed to occur when the aircraft altitude is less than 35 feet, the ground speed is greater than 1 knot and the engine thrust setting is greater than 21%. The data was obtained from a relatively short time period (2 weeks) to limit the likelihood of severe meteorological changes (e.g. ambient temperature and air density), which can cause changes to both aircraft performance and their operations.

2.3 Spatial allocation of takeoff roll emissions

The high-resolution positional data corresponding to the aircraft takeoff roll emissions facilitates a visualisation of the NOx emission source spatial distribution. The NOx emissions are assigned to a grid, with a cell size of approximately 15m by 15m, relating to the sampling resolution of the recorded positional data. The plot is divided into three segments, covering approximately the start of roll (I), acceleration (II) and wheels off (III), to aid discussion.

The colour coding of each cell corresponds to the total NOx emissions produced by all takeoff roll activities occurring within that cell. Grid squares with no NOx emissions are omitted. Absolute values are masked from the results due to sensitivity agreements. The colour coding is at 10% intervals and is normalised as a percentage relative to the maximum NOx emissions across all cases.
3. Results and discussion

3.1 Variability in recorded data

The first analysis conducted in this paper investigates the assumption that the ICAO Simple Approach typically misrepresents aircraft takeoff roll activity. When modelling NO\textsubscript{X} emissions, as introduced in Section 2, two independent variables are identified: fuel flow rate and TIM.

Figure 1 shows that the LTO reference cycle (represented by the dashed line) overestimates the observed fuel flow rate for all activities, and underestimates the TIM for 67.2\% of activities. Furthermore, the use of aggregated data does not capture the variability in observed aircraft activities, as the factors are constant.

Total NO\textsubscript{X} emissions for aircraft takeoff can be estimated from the variables that describe thrust. The LTO reference cycle is found to overestimate the average thrust setting used during the takeoff roll, relative to observed activities. The mean average thrust setting is 78.9\% of maximum rated thrust, which is considerably lower than the 100\% thrust setting often assumed. Furthermore, the recorded data supports the assumption that a set of thrust settings, ranging from 67.3\% to 97.1\%, are used to achieve aircraft takeoff at Heathrow.

Figure 1 also shows that the adoption of aggregated thrust setting and trajectory data, which is widely used in industry for the quantification and analysis of airport emissions, can lead to the inaccurate estimation of aircraft NO\textsubscript{X} emissions. This research finds that aggregated values are conservative and therefore NO\textsubscript{X} emissions are overestimated, relative to estimates made using the recorded data.
Fig. 1. The distribution of takeoff roll activity values for (clockwise from top left) TIM, fuel flow rate, NO\textsubscript{X} emissions and thrust setting. With the ICAO Simple Approach estimate (dashed line).

3.2 Trends between NO\textsubscript{X} emissions, average thrust setting and time-in-mode

In Figure 2, the total NO\textsubscript{X} emissions for each observed Airbus A319 takeoff roll are plotted against the corresponding average thrust setting used to identify the general trend. To further analyse the impact of the underlying variables on total NO\textsubscript{X} emissions, the TIM is also considered. The points plotted are shaded to reflect the TIM of the takeoff roll, where darker shading represents shorter takeoff roll durations.

As expected, a positive correlation is observed between activities with increasing takeoff roll thrust settings and increasing total NO\textsubscript{X} emissions. Generally, reducing takeoff roll thrust setting results in reduced total NO\textsubscript{X} emissions, due to reduced fuel flow rate and reduced emission index. This suggests that a reduced thrust setting during takeoff can lead to a
reduction in the total NO\textsubscript{X} emissions produced. However, there is variation in the NO\textsubscript{X} emitted for constant thrust settings, indicating the existence of additional underlying variables. It is observed that for the same thrust setting, higher total NO\textsubscript{X} emissions are produced by takeoff rolls with a longer TIM. Therefore, reduced thrust setting may not cause a lower total of NO\textsubscript{X} emitted during the takeoff roll and, instead lead to increased emissions through increased TIM. As such, it may be possible to achieve a reduction in NO\textsubscript{X} emissions either by reducing the average thrust setting or the TIM. However, from this analysis it is not possible to assess which of the two variables has the most significant impact on NO\textsubscript{X} emissions.

Fig. 2. Impact of takeoff roll thrust setting and TIM on NO\textsubscript{X} emissions. Solid lines represent the top and bottom 10\% of average thrust settings.

3.3 NO\textsubscript{X} emissions for regular and reduced thrust takeoff operations

To analyse the impact of reduced thrust takeoff on NO\textsubscript{X} emissions, the data is categorised on the basis of the average thrust setting adopted during each takeoff roll. To facilitate this, the distribution of average takeoff rolls used in the data sample was plotted using the density function as shown in Figure 3. The curve is approximately Gaussian in distribution, which indicates a single mode of operations (i.e. no evidence of separate reduced and regular thrust setting modes). It is acknowledged that there is no quantified definition for reduced thrust takeoff in literature, therefore, the bottom and top 10\textsuperscript{th} percent of average thrust settings have been chosen as analogues for reduced and non-reduced (regular) thrust settings to illustrate the effects of reduced thrust takeoff.
Fig. 3. Density function indicating the bottom and top 10th percentiles of average thrust setting during takeoff roll, represented by grey shaded sections. The mean value of average thrust settings is plotted for reference and represented by the dashed line.

The distribution of the total NO\(_X\) emitted by the top and bottom 10\(^{th}\) percentiles of average thrust settings used during the takeoff roll is analysed and the categories are compared using the density plots shown in Figure 4. The mean values of the average thrust setting, the average TIM and the average total NO\(_X\) emitted for each category is shown in Table 2.

Table 2. Percentage contribution of LTO phase to airport aircraft related NO\(_X\) emission at Heathrow.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Average thrust setting (% of max.)</th>
<th>Average TIM (s)</th>
<th>Average total NO(_X) emitted (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom 10%</td>
<td>72.0</td>
<td>41.0</td>
<td>1106</td>
</tr>
<tr>
<td>Mean</td>
<td>78.9</td>
<td>43.7</td>
<td>1366</td>
</tr>
<tr>
<td>Top 10%</td>
<td>86.1</td>
<td>44.4</td>
<td>1620</td>
</tr>
</tbody>
</table>

The results show that the adoption of reduced thrust takeoff activity usually leads to a reduction in the total NO\(_X\) emitted by an aircraft during the takeoff roll. At Heathrow, a 14-percentage point reduction in the average takeoff roll thrust setting is identified between aircraft operating in the bottom and top 10\(^{th}\) percentiles. Aircraft operating in the top 10% of average thrust settings emit 1620 grams of NO\(_X\) during the takeoff roll on average compared to 1106 grams of NO\(_X\) emitted for aircraft operating in the bottom 10%. This corresponds to a reduction of 514 grams per takeoff roll (31.7%). However, there is an overlap in the total NO\(_X\)
emitted by the two categories, most likely caused by variations in the TIM; a takeoff roll with an average thrust setting in the bottom 10% and a relatively high takeoff roll duration has the potential to emit a similar volume of NO\textsubscript{X} to a takeoff roll in the top 10% of average thrust settings with a short takeoff roll duration.

Fig. 4. Difference in distribution of total NO\textsubscript{X} emitted by the top and bottom 10th percentiles.

Reduced thrust takeoff aims to utilise the benefits of adopting less than maximum thrust to reduce emissions during aircraft takeoff (Duchene, 2006). During this operating strategy, a pilot will use the minimum allowable thrust setting during the takeoff roll while maintaining the safety criteria, i.e. reaching the correct takeoff speed within the maximum length of runway. This is regularly carried out at major airports such as Heathrow (King and Waitz, 2005), however the allowable thrust setting for takeoff depends on several factors, which may limit the consistency to which reduced thrust takeoff can be adopted. These factors include: aircraft takeoff weight (TOW); headwind speed; ambient temperature; air density; runway conditions (e.g. surface type, slope); airframe contamination and aircraft flap setting. The impacts of these factors should be investigated in future work and may lead to the introduction of policy recommendations to maximise the implementation of reduced thrust takeoffs, for example by rewarding airlines by calculating NO\textsubscript{X} emissions charges based on flight records rather than on the ICAO reference LTO cycle.

These factors may explain the variation identified in takeoff roll operations. For example, if the minimum thrust allowable is limited by TOW, and assuming that aircraft use the lowest
possible thrust setting to achieve safe takeoff, the length of the takeoff roll and subsequently
the length of emission source are likely to be similar across all thrust settings. A reduced thrust
setting will correspond to a lower fuel flow rate and a corresponding reduction in the rate of
NO\textsubscript{X} emission, however it may also lead to reduced acceleration and a consequent increase in
the TIM. As the total NO\textsubscript{X} emitted is a function of both the fuel flow rate and the TIM, the thrust
setting reduction may increase NO\textsubscript{X} emissions due to increased aircraft takeoff roll TIM.
Models that rely on simplified input data will not capture these trends, and this supports the
requirement for high-resolution analysis. The effects of reduced thrust takeoff must be
understood to enable a balanced consideration of activity and therefore the planning of efficient
operations.

3.4 NO\textsubscript{X} emission source spatial distribution for regular and reduced thrust takeoff

This subsection seeks to identify the impact of reduced thrust takeoff on the spatial distribution
of the NO\textsubscript{X} emission source relative to regular takeoff operations, using the spatial allocation
of NO\textsubscript{X} emissions described in Section 2.3. The results of this spatial allocation are shown in
Fig. 5.

Fig. 5. Spatial distribution of modelled total NO\textsubscript{X} emissions for the top and bottom 10\textsuperscript{th} percentiles of
average takeoff roll thrust settings (activity occurs from right to left).

The first difference identified between reduced and regular thrust takeoff, is an area of peak
NO\textsubscript{X} emissions around the start of the takeoff roll seen in segment ‘I’. This is expected to be due
to the high thrust setting and the extended period of time aircraft spend in this position on the
runway with low ground speed while the aircraft accelerates from standing. As expected, the
peak value of total NO\textsubscript{X} emitted decreases when changing from regular thrust to reduced thrust
operations, however the location of the emission peak remains approximately constant. In
segment ‘II’, no significant variation between the spatial distributions of NO\textsubscript{X} emissions has
been identified for the different thrust setting categories, as the emission source area (length
and width) is approximately the same. In segment ‘III’, the emission source extends further to
the left for maximum thrust setting activity, which demonstrates that the takeoff roll is longer.
for higher thrust setting activities. This may be due to the interdependency between aircraft
TOW and average thrust setting. An aircraft with a lower TOW will require less thrust during
the takeoff roll to achieve the speed required for wheels-off than a heavier aircraft, furthermore
the required wheels-off speed is lower for lighter aircraft. Takeoff roll activity with an increased
average thrust setting, but also increased TOW, will accelerate at a similar rate and therefore
reach takeoff speed after an approximately equal length of takeoff roll.

The NOx spatial distribution identified with high-resolution analysis can be used to inform
mitigation methods. For example, if NOx emissions peak corresponding to the start of the
takeoff roll, this may be reduced if operations are modified to the stagger the takeoff roll
starting points. This would distribute the emissions over a larger area and consequently reduce
the peak. In situations where reduced thrust or staggered takeoff rolls cannot be employed, the
analysis presented can inform the introduction of mitigation strategies, such as managing
human activities to ensure minimal time spent in the vicinity of NOx emissions peaks or
introducing physical barriers to minimise emission dispersion over high-density populations.
Future work should include dispersion modelling to estimate the impact of reduced thrust
takeoffs on local pollutant concentrations.

To better examine the magnitude of these patterns, total NOx emissions are plotted against the
longitude (x-direction). This facilitates the visualisation of the distribution of emissions over
the length of emission source, as shown in Figure 6. Regular and reduced thrust activities are
represented by the red and blue curves respectively.

The use of reduced thrust takeoff leads to a reduction in peak NOx emissions (identified in
segment ‘I’) of up to 25% and generally in reduced emissions across the length of the takeoff
roll. In segment ‘II’, there is minimal difference identifiable in the spatial distribution of
emissions between the two thrust setting categories. However, in segment ‘III’, NOx emissions
are considerably lower for the reduced thrust setting activity than for the regular thrust setting
activity. It is noted that there is considerable variation in Figure 6, due to the FDR sampling
resolution, which results in some grid squares capturing more takeoff roll activities than others.
However, comparisons of the overall trend in the profile of NOx emissions can still be made.
The results presented in this section provide information regarding the changing rates of emissions across the length of the takeoff roll and therefore facilitates the identification of areas with high NOx emissions, which may cause increased harm to human health, relative to the equivalent emissions averaged over a larger area, if personal exposure is high. Previous analysis has been unable to identify these patterns, given the assumptions of constant thrust setting, emission rate, TIM and length of takeoff roll. The extent to which high-resolution data and analysis improves the ability to assess aircraft emissions serves as a new contribution to the research field.

4. Conclusions

This paper quantifies the impacts of using reduced thrust during takeoff activities at London Heathrow airport. It is shown that the adoption of reduced thrust provides reductions in the total mass of NOx emissions of 32% per takeoff roll on average, however this is dependent on the takeoff roll TIM. Additional benefits have been identified regarding the spatial distribution of NOx emissions, which includes a reduction in the size of the takeoff roll emission source. Furthermore, peak NOx emissions, around the start of the takeoff roll, may be reduced by up to 25%. However, the ability to use reduced thrust takeoff may be dependent on other factors such as wind speed, wind direction and TOW, which impact TIM.

The results of this paper were enabled by the use of high-resolution data and analysis, which leads to improved accuracy in NOx emissions quantification. This is the first case study using such analysis to quantify the impacts of aircraft-related NOx emission reduction strategies,
which is critical when assessing airport operations to minimise pollutant emissions. High-resolution analysis also facilitates the assessment of NOx emission spatial distributions. Applications of the current research may be to inform mitigation strategies, the evaluation of the impact of airport operations on local air quality, and the identification of optimal airport operations through comparisons of the emissions corresponding to contrasting operating techniques.

For airports where local air quality is of concern, such as Heathrow, the identification of aircraft operations that minimise aircraft NOx emissions is of importance for stakeholders as they could contribute to significant reductions in airport emissions. This may facilitate compliance with legally binding air quality standards at locations in the airport vicinity, which in turn, offers the potential to enable airport expansion to meet the forecasted future demand. As mentioned previously, aviation is regularly associated with considerable economic and social benefits, consequently these effects may be maximised if airport expansion is enabled through reduced pollutant emissions. However, the potential costs of airport expansion must also be considered, including additional noise and associated traffic.

Underlying factors, including aircraft TOW, may have an impact on the ability to utilise reduced thrust takeoff and may explain the variability between average thrust setting and TIM. Future research will seek to incorporate TOW variability into analyses in order to explore this dependency. Findings are specific to Airbus A319 (V2522-A5) operations on runway 27R this operating scenario. While these findings are valuable contributions to the field independently, the general technique presented may be adopted for similar analysis of other operational techniques and/or at other airports. Furthermore, it will be valuable to consider various additional airframe and engine type combinations in future. A final extension of the research presented in this paper is to consider the dispersion of aircraft related NOx emissions for reduced and regular thrust takeoff and their resultant impacts on local air quality.

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