Method for the Improvement of Aircraft Trajectory Simulation using Analysis of Variability

Mr. G. Koudis, Dr. R. North, Dr. A. Majumdar, Dr. W. Schuster, Dr. S. Hu
Centre for Transport Studies
Imperial College London
London, United Kingdom
g.koudis12@imperial.ac.uk

***Abstract*— Developments in operational strategy proposed by Single European Sky ATM Research (SESAR) require quantification of airport environmental impact using methods representative of actual operations. Methods suggested by the International Civil Aviation Organisation (ICAO) operate at either too high an aggregation to be representative, or require a substantial amount of data to be available. The use of a hybrid methodology is proposed; template second-by-second trajectories that use sparse, routinely collected data to accommodate the observed variability in aircraft landing and take-off (LTO) trajectories. High-resolution data for 3898 aircraft take-off events at London Heathrow airport are analysed to identify variability with respect to aircraft type, take-off weight and meteorological conditions. This research suggests that template trajectories be developed for each aircraft type, in line with the ICAO advanced approach, and then modified to account for the impact of additional factors such as take-off weight. The generic methodology proposed facilitates transferability between airports. In cases with limited data availability, this allows a more refined representation of actual trajectories than previously possible.**

Keywords-Airport; aircraft; emissions; modelling; take-off;

I. Introduction

Airports are highly complex operating environments where the surface operations are closely managed to achieve optimisation in capacity, cost-efficiency, safety and, increasingly, environmental performance areas [6]. The requirement to maximise performance in these areas is promoted by Single European Sky ATM Research (SESAR) in its Air Traffic Management Master Plan [20]. To meet these requirements, in each case a clear representation of aircraft movements is required. A variety of approaches exist, including trajectory prediction models [3], [15], [19], [23] and the use of recorded activity data [1], [8], [18]. However, these techniques require data at a volume and resolution that is rarely available. Therefore, models based on the assumptions of the International Civil Aviation Organisation (ICAO) reference landing and take-off (LTO) cycle [9] are frequently used [11], [14], particularly when considering the environmental impact.

The first contribution of this research proposes a hybrid method for using high-resolution data to inform simple LTO trajectory simulation, therefore reflecting a greater volume of actual operations with limited data and little additional computational expense. A large sample of aircraft movement data recorded in November 2012 at London Heathrow airport is used in this paper to investigate the levels of variability in aircraft LTO trajectories, with a focus on the parameters of interest for environmental impact. This paper develops a methodology to utilise sparse data routinely collected by airports (aircraft information, activity parameters and meteorology) to provide realistic estimates of trajectories.

This paper is structured into the following five sections. Section 2 reviews existing methods of environmental analyses for aircraft and airport operations and describes recent applications. The proposed transferable methodology is presented in section 3. Section 4 introduces data availability, characterisation and implements analyses. Discussion and application of results, and conclusions, are presented in sections 5 and 6 respectively.

II. Analysis Methods for Aircraft LTO Cycle Environmental Impact

Airport operations encompass some of the most heavily polluting phases of flight per unit time. The emission of aviation related pollutants often leads to elevated exposure levels in the vicinity of airports [7], which can have a detrimental effect on human health [2]. Several authors have found that aircraft landing and take-off (LTO) activity produces the majority of pollutants, therefore having the most significant impact on local air quality (LAQ) [7], [8], [24]. Emphasis has been placed on airports to monitor their environmental impact [3], and new objectives, presented in the SESAR Master Plan, include the implementation of new operating techniques to reduce the impact of aviation on LAQ [20]. Among the targets are minimization of aircraft holding, reduction of taxi time and ground rolling distances by pre-defining departure sequences, also the introduction of continuous climb and improvement of data availability (such as meteorological). The primary aim of this paper is to improve the levels of realism of actual activity in trajectory simulation, through an understanding of variability. Variability in the LTO trajectory can be seen in spatial and temporal activity, as well as in speeds, fuel flows, thrust setting and emission rates. It is a function of a number of underlying factors, operational, human and meteorological, which determine aircraft operations. To quantify the impact of operational changes in reaching the

Research sponsored by the Lloyds Register Foundation

SESAR objectives, a sufficiently detailed and representative model of aircraft activity must be available.

A. Environmental Modelling Approaches

There are three International Civil Aviation Organisation (ICAO) specified approaches to modelling aircraft LTO emissions, 'simple', 'advanced' and 'sophisticated' as presented in table I; the levels of input data for each have been summarised [4] and further detail is available [13]. Each approach aims to achieve an increasing level of accuracy respectively, through the representation of a greater level of variability in trajectory. Each approach uses increasingly specific information to model the trajectories and emissions, however, this often requires increased data input.

TABLE I – ICAO MODELLING APPROACHES

Approach	**Simple**	**Advanced**	**Sophisticated**
Aircraft and engine fit	Aircraft group	Aircraft type	Aircraft specific
Operational profile	Standard LTO TIM & thrust	LTO TIM & thrust per aircraft type	LTO TIM & thrust per specific aircraft
Emission indices	ICAO per group	ICAO per movement	ICAO per movement

When analysing the environmental impact of airport operations, aircraft trajectories are used to develop emissions inventories. The ICAO reference cycle is often used as the 4D trajectory basis for environmental analysis with the approaches presented in table I, in particular when limited data is available. It can be used independently or with data recorded by airports and airlines, and is useful in a variety of contexts (i.e. emission charges and simple emission inventories) but is inaccurate when calculating actual aircraft emissions [5]. The cycle is divided into operating modes, where each mode has a corresponding time-in-mode (TIM) and associated thrust setting, as presented in figure I.

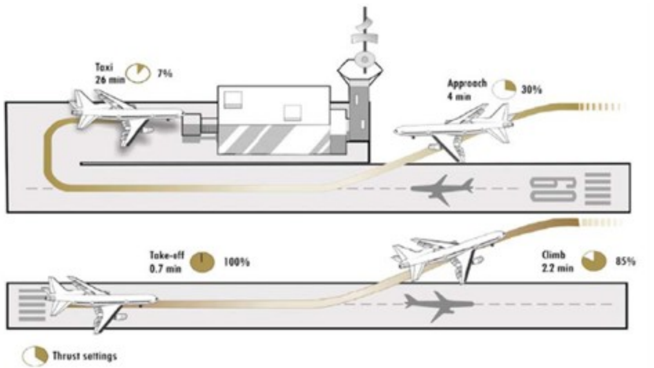

FIGURE I – ICAO REFERENCE LTO CYCLE [10]

There are many factors that introduce variability into LTO trajectories (see table II). Variability must be represented in simulation models when aiming to reflect real operations however, the TIM and thrust values suggested by ICAO does not capture this. To highlight these errors, aircraft data records have been compared to the reference cycle TIM and thrust during take-off, and indicate substantial differences [22]. The capture of variability is highly important when simulating aircraft movements, particularly when attempting to optimise airport operations in line with SESAR objectives. From an environmental impact perspective, variation in trajectory may impact fuel consumption, required thrust, consequent emissions and noise levels. It may also alter the spatial distribution of emissions and perceived noise levels. For these reasons, the current LTO cycle does not facilitate management and improvement of activity.

B. Application of ICAO Methods in Recent Studies

Regional environmental impact of aircraft activity often uses specific emissions as suggested in the ICAO simple approach [17], [24], or by using historic totals independent of space [16]. Aircraft type and mode-specific emissions inventory have been developed using the LTO cycle, and ICAO Exhaust Emissions Databank (EEDB) for emissions comparison [11], [21], representative of the advanced approach shown in table I. Variability in airport specific TIM has been introduced, but other variation is neglected. The failure to include detailed trajectory variation may reduce the realism reflected by the modelling. Data is aggregated to an extent where results become independent of actual individual trajectories These techniques are used for high-level quantification and do not have the ability to analyse, and consequently minimize, environmental impact of the aircraft LTO cycle in line with SESAR objectives.

The LTO reference cycle has been adapted for aircraft type and engine combinations have been used to develop emissions inventories with spatial and temporal distribution [14], [22]. Corrected TIM and thrust settings were generated using aircraft specific monitored data, and the uncertainty for each was quantified. However there was no variability in this rate within each mode and no attempt was made to include underlying factors. These have not been accounted for, but would be dependent on pilot operational decisions and aircraft performance characteristics [22]. These methods are still significantly aggregated relative to the ICAO sophisticated approach, which provides the best representation of actual aircraft emissions [13], but requires the use of actual operational data. Actual TIM and fuel flows are used to represent variability, and emissions calculated using a method such as the Boeing Fuel Flow Method 2 (BFFM2) [12]. This approach is seldom carried out due to the requirement for detailed operational data. However, the need to consider the trajectory variability must be recognised when attempting to manage environmental impact.

There is a significant methodological problem of representing the variability in aircraft LTO trajectories where limited detailed data is available. This research proposes that recorded operational data is used to understand the causes of variability in LTO trajectory. This knowledge can be used to inform approaches in quantifying environmental impact where limited detailed aircraft data is available, therefore increasing the level of realism reflected in the model. This will facilitate the analysis of a greater volume of aircraft LTO activities with reference to SESAR objectives.

III. PROPOSED TRANSFERABLE METHODOLOGY

These methods are variations on the same general approach, operating at different resolutions and with different accuracies of input data. The system diagram shown in figure II compares the simple and sophisticated approaches to the general procedure in order to identify similarities in methods. There are advantages and disadvantages in the use of both methods. The simple approach is less data intensive and more easily computed, however, the results are substantially less accurate and calculated at a higher aggregation. The sophisticated approach is much more data intensive, at a high computational expense, but generates substantially more accurate results at a higher resolution. This process highlights the methodology gap in the system and therefore the point at which this research can build upon the state-of-the art.

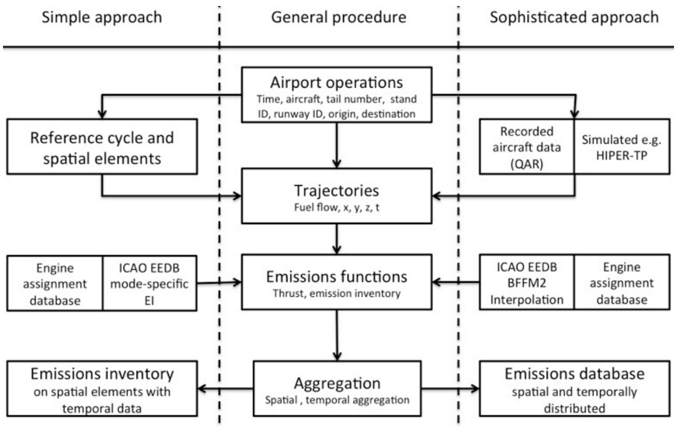

FIGURE II – GENERAL, SIMPLE AND SOPHISTICATED PROCEDURES FOR THE PREDICTION OF LTO ENVIRONMENTAL IMPACT

There is a desire to accurately represent aircraft LTO emissions at a high-resolution, at reduced computational expense, and given limited availability of aircraft specific data. The points at which high-resolution input data is required are when developing trajectories and emissions functions. In contrast to the data intensive technique employed by these approaches, it may be possible to assume trajectories based on sparse knowledge of operating techniques and the underlying factors that impact on these activities. This paper proposes the use of high-resolution input data to inform the analyses. Resulting in a less data intensive analysis of aircraft trajectory emissions and environmental impact. The system diagram for the suggested 'hybrid' approach is shown in figure III.

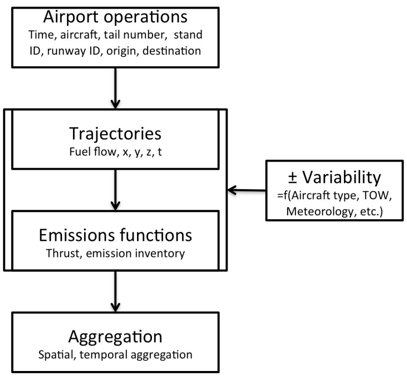

FIGURE III – PROPOSAL FOR HYBRID METHODOLOGY

There are a large number of factors that contribute to the variability in an aircraft's LTO trajectory, including operational, human and meteorological. An inexhaustive list of these factors is shown in table II, adapted from reference [3]. Improving the level of understanding of the impact of these factors on trajectory variability relies on high-resolution data availability. This can be either actual recorded data, or simulated, validated data. While it would be advantageous to have airport specific data, it may be possible to validate generic data for use with multiple airports.

TABLE II – FACTORS WITH IMPACT ON AIRCRAFT TRAJECTORY

Group	Specific factor	Comments
Operational	Take-off weight	Sensitive data; may be able to generate reliable proxy. Maximum take-off weight is more readily available.
	Airline operating choice	Airline dependent choice of operating scenario.
	Airport procedures	Airport operating procedures, often determined by infrastructure and safety/capacity constraints.
	Ageing of the aircraft	Readily available from third party sources.
	Aircraft maintenance	Sensitive data.
	Ageing of the engines	Readily available from third party sources.
	Engine maintenance	Sensitive data.
Meteorology	Wind direction	Regularly collected and available (varying resolutions).
	Wind speed	Regularly collected and available (varying resolutions).
	Temperature	Regularly collected and available (varying resolutions).
	Humidity	Regularly collected and available (varying resolutions).
Human	Pilot preference	Expert operator decision making within guidelines.
	ATC decision choices	Expert operator decision making within guidelines.

This research proposes that a template trajectory, such as suggested in the simple or advanced approach by ICAO be used as a baseline and modified to generate a more realistic representation of aircraft LTO trajectories. The theoretical approach, supported by the system diagram in figure III, relies on the assumption that a template trajectory can be adjusted based on a function, dependent on the factors that influence variability, to generate an accurate representation of any given activity. Subject to validation and calibration, a model such as the 'simple' approach could be modified to improve the accuracy of the representation of actual activity. Sparse input data, regarding factors of influence, would facilitate trajectory modification with minimal computational expense.

IV. APPLICATION OF METHOD USING LONDON HEATHROW CASE STUDY

Sample aircraft activity data will be used to reiterate the requirement to improve ICAO simple approach trajectories when calculating emissions, even under limited data availability conditions. This section then aims to identify factors that have an impact on the trajectory as specified by the ICAO LTO cycle, using variability in the take-off roll.

Data is arranged and analysed to identify potential impact of aircraft type, at the simple, advanced and sophisticated levels of specificity. Factors of take-off weight and wind conditions are also compared to take-off trajectory.

A. Data Availability

Summary data, shown in table III, is collected for aircraft activity at London Heathrow (LHR). Known as 'Business Objective Search System' (BOSS), it can provide basic information on the 4D trajectory of an aircraft. Both start and end locations of taxi activity can be inferred, along with the time that the activity (arrival or departure) and operating mode (idle, take-off or approach) has taken. Data regarding aircraft type, engine type, and MTOW can be used to give initial estimates of aircraft fuel flow and consequent emissions. It will form the 'index' for the development of high-resolution aircraft activity datasets.

TABLE III – DATA RECORDED IN BOSS

Group	Item
Temporal	Actual date/time
	Scheduled date/time
	Stand on or off time
Spatial	Type of activity (arrival or departure)
	Origin or destination
	Stand number
	Runway number
Aircraft information	Airline operator
	Aircraft (type specific)
	Engine type
	Aircraft tail number
	Maximum number of passengers
	Maximum take-off weight (MTOW)

On-board quick access recorder (QAR) data, summarised in table IV, is available at 1Hz resolution. The high level of data availability facilitates accurate analysis of activity. Multiple values for an item, e.g. from multiple engines, are shown in brackets. This, very large dataset, is analysed to identify high-resolution variability in aircraft trajectories.

TABLE IV – DATA RECORDED IN QAR

Group	Item	Units
Temporal	Date	dd/mm/yy
	Time	hh/mm/ss
	Time from engine start	s
	Ground speed	kts
Spatial	Latitude	° ' "
	Longitude	° ' "
	Pressure altitude	ft
	Radio altitude	ft
Ambient	Outside air temperature	^{o}C
	Total pressure	hPa
Engine information	Fuel flow (1,2,3,4)	kg/s
	Engine pressure ratio (1,2,3,4)	n/a
	Turbine gas temperature (1,2,3,4)	n/a
	Thrust (1,2,3,4)	% (of max)
Aircraft information	Flight phase	n/a
	APU usage (1,2)	n/a

The latitude and longitude for destination airports were exported from www.openflights.org. Meteorological data were collected at the Air Quality Monitoring Station LHR2, which is situated near to runway 27R, available at an hourly resolution.

B. Data Processing

A series of steps for quality control (QC) of the sample data were used, to remove clearly erroneous values; these values were identified as points where ground surface movement occurred outside the airport boundaries, indicating an error in GPS recording. Assessment of recorded latitudes and longitudes showed significant data loss (>50% of values) for Boeing 767 aircraft. All B767 data were therefore deemed unreliable and removed from the analysis. Flight records with unrealistic values of ground speed and unrealistic step changes in elevation (>100m) were also removed. The remaining dataset (3898 take-off events) was used in the analysis. Table V summarises these data.

TABLE V– SUMMARY OF POST-QC DATA

Aircraft type	Aircraft jet size	Total number pre-QC	Total number post-QC	Percentage loss
A319	Small	1412	1398	1.0
A320	Small	1145	1122	2.0
A321	Small	425	416	2.1
B767	N/A	287	0	100.0
B77A	Medium	387	387	0.0
B772	Medium	67	67	0.0
B77W	Medium	55	54	1.8
B747	Large	470	453	3.6
TOTAL		4248	3898	8.2

A Java Script was used to normalise the sampling frequency of the data, in order to provide consistency when comparing activity recorded at different frequencies. A 'PostgreSQL' database was constructed containing the QAR and BOSS datasets to allow efficient querying of the data. Statistical analysis of the data was conducted using 'R'.

There are many aspects of this data that would improve the general understanding of variability in aircraft activity, however this section focuses on the variability of trajectories. In particular, the trajectory of the take-off roll, defined as the segment of activity including and between the cut-points 'start of take-off roll' and 'wheels off' was specified (see table VI). Note that the wheels off cut-off point cannot occur before the start of the take-off roll. The QAR data facilitates characterisation of the activity that occurred during the sample period at LHR, including characterisation of variability.

TABLE VI – CUT-OFF POINT DEFINITIONS

Cut-off point	Criteria used for the data cut
Start of take-off roll	Thrust = 14% (ICAO idle thrust x2) & speed > 100kts 60s later
Wheels-off	Elevation > 10ft (above datum)

C. Analysis of Take-off Roll Variability

To analyse significance between aircraft trajectories the data is firstly identified as being non-normal on the basis of the Kolmogorov-Smirnov test (P~0). Mean values are therefore rejected in favour of median, as a better measure of central tendency. The ICAO simple approach trajectory assumes homogeneity of activity between different aircraft types; however, figure IV suggests that there are significant differences between the ground speed reached by different aircraft types at wheels off. The R^2 correlation coefficient between maximum take-off weight (aircraft type dependent) and the median values of ground speed and wheels off is 0.79. This implies a significant dependence of trajectory on aircraft type. Generally, heavier aircraft reach higher speeds before wheels off, however, there is substantial variability in this trend and the range of speeds often overlaps. Table VII shows that the minimum ground speed at 'wheels off' for a heavy (B747) aircraft is less than the maximum for a small (A319) jet (LQ and UQ refer to the lower and upper quartiles respectively). This implies that there are additional factors governing the required wheels off speed.

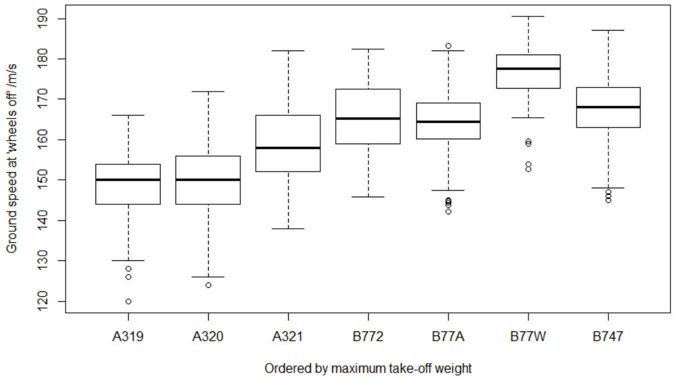

FIGURE IV – AIRCRAFT TYPE SEPARATED BOXPLOTS FOR GROUND SPEEDS AT WHEELS OFF

TABLE VII – SUMMARY TABLE OF AIRCRAFT TYPE SEPARATED GROUND SPEEDS AT WHEELS OFF

	Av. TOW /kg	Min. /m	LQ /m	Median /m	Mean /m	UQ /m	Max. /m
A319	63949	120	144	150	148	154	166
A320	73491	124	144	150	150	156	172
A321	84950	138	152	158	159	166	182
B77A	281311	142	160	165	165	169	183
B772	271268	146	159	165	166	173	183
B77W	340194	153	173	178	176	181	191
B747	395417	145	163	168	168	173	187

In addition to the variability in ground speed at wheels off, there is a large range of values for length of take-off roll, summarised in table VIII. These summary data indicate that the use of a single trajectory, i.e. the simple approach, will result in a significant loss of information. This will lead to insensitivity to potentially activity changes because of an inaccurate representation of activity.

TABLE VIII – LENGTH OF TAKE-OFF ROLL FOR ALL ACTIVITY

	Min. /m	LQ /m	Median /m	Mean /m	UQ /m	Max. /m
ALL	857	1512	1691	1733	1869	3106

Figure V spatially represents the 'start of take-off roll' and 'wheels off' cut points, for all Airbus A319 departure activity. The arrowed line represents the direction of take-off. Relative to the 'wheels off' position, the majority of 'start of roll' activity happens within a small range. There are several values that fall outside this range, which may be indicative of human operating choice, where the start position is adjusted as a result of additional factors. The large spread of distances required to 'wheels off' could be as a result of required ground speed being achieved at different points (variable acceleration) however, referring back to figure IV suggests that there is enough variation in the speed at 'wheels off' to make this theory unlikely. It is expected to be an operational choice based on external factors, or human operator preference. Clearly, these factors need identifying and quantifying to improve the accuracy of a simplified template trajectory.

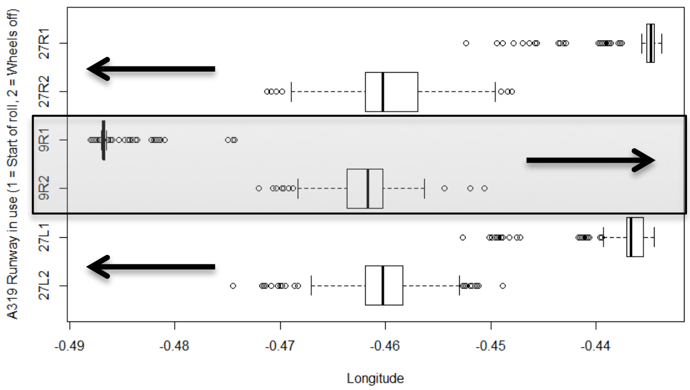

FIGURE V – VARIABILITY IN START AND END POINTS OF TAKE-OFF ROLL

Figure VI shows the relationship between length of take-off roll and the ground speed at wheels off, for each event during the sample period. A linear trend line for the data is superimposed on the plots. The quantised nature of the ground speed data is a manifestation of the recording resolution for certain aircraft. There is a strong correlation between these two factors (Pearson correlation coefficient 'r' = 0.853), which confirms that to achieve higher ground speeds a longer take-off roll is needed. This suggests only moderate variation in acceleration across aircraft types but may also be due to airline specific desired thrust settings. Further analysis is required to indicate the reasons for requiring higher ground speed at wheels off, but there is a clear link between the ground speed required and the length of runway to achieve it. This has consequences when planning departure activity and for spatial distribution of emissions. If the necessary ground speed at wheels off is known, it is possible to simulate the take-off roll more accurately.

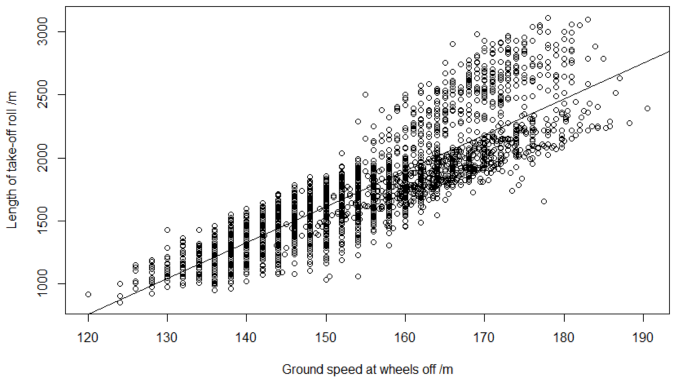

FIGURE VI - SCATTER PLOT OF LENGTH OF GROUND SPEED AT WHEELS OFF AGAINST LENGTH OF TAKE-OFF ROLL

Boxplots 1 to 6 in figure VII represent the activity of specific aircraft with a take-off roll sample size >40 during the sample period at LHR. The A319 boxplot uses all A319 activity data, and 'all' represents all aircraft activity. Shapiro-Wilk test classifies the data series as non-normal at $P<0.05$ and the Wilcoxon Rank Sum test is used with the null hypothesis that there is no significant difference in the distributions of these ground speeds the statistical distribution must be defined. This is accepted at $P>0.05$ when testing aircraft 1-6 against each other. The range of P values is from 0.107 to 0.907 with an average of 0.499. There is a significant difference between A319 and 'all' activity ($P<<0.05$). There is some variability in individual activity, but generally this is captured by the aircraft type (A319) activity. Therefore, modifying the template trajectory requires explicit inclusion of aircraft type, but not specific aircraft.

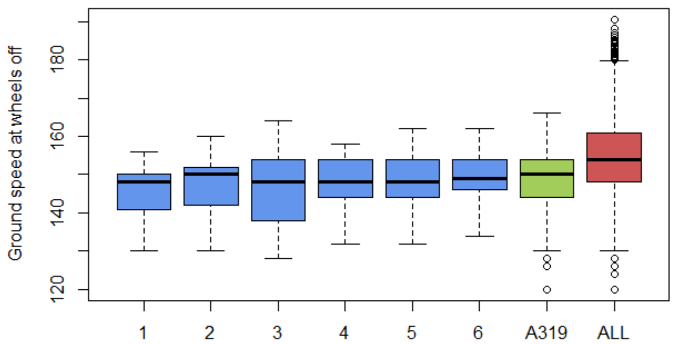

FIGURE VII - VARIATION IN GROUND SPEED AT WHEELS OFF OF SAME AIRCRAFT

Take-off weight is known to have a significant impact on fuel consumption, thrust and emissions for a constant trajectory [3]. It is a function of airframe weight and aircraft loading (passenger, freight and fuel). For this analysis it is assumed that there is little variation in the load factors for the same aircraft on similar routes. There is expected to be minimal difference between the airframe weights of the same aircraft type. Therefore the variability in take-off weight may be estimated as a function of fuel loading. The trade-off between fuel loading and fuel consumption is heavily correlated to the distance between origin and destination airport. There is an additional safety margin that requires the aircraft carry sufficient fuel to stay airborne for an additional ¾ hour; this is often increased when expecting poor meteorological conditions at the destination airport. In each jet size case (small, medium and large), the distance to the destination airport is correlated against length of take-off roll and ground speed at wheels off. For each jet size, a positive relationship is seen with Pearson's 'r', as shown in table IX. There is weak-moderate correlation for small jet sizes; this may be due to the additional ¾ hour safety margin fuel loading (higher in poor weather conditions), which forms a bigger proportion of overall fuel loaded and reduces the correlation. For medium and large aircraft the correlation is moderate-strong, indicating that the distance between origin and destination airport has a significant impact on the aircraft trajectory. This suggests that the assumption that fuel loading, and consequently take-off weight, has an impact on aircraft trajectory. The inclusion of aircraft TOW, or suitable proxy, is therefore, a requirement when conducting modification of a template trajectory.

TABLE IX– CORRELATIONS BETWEEN LENGTH OF TAKE-OFF ROLL AND WHEELS OFF GROUND SPEED TO JOURNEY DISTANCE

Aircraft jet size	Length of take-off roll	Ground speed at wheels off
Small	r = 0.273	r = 0.417
Medium	r = 0.598	r = 0.565
Large	r = 0.629	r = 0.664

Aircraft activity at airports is often constrained by meteorological conditions. Wind speed, wind direction, temperature, pressure and humidity can all cause variability in aircraft LTO trajectories due to impacts on aircraft performance or required operational changes. True Air Speed (TAS), which determines aircraft lift, is determined by the aircraft mass. Required ground speed may be a function of required TAS and wind conditions. Heathrow airport operates with a westerly preference, and switches to easterly when the tailwind exceeds 3m/s. Meteorological factors are often seasonal. However, all of the analysis dataset was recorded during November 2012, therefore seasonal variability is unlikely to be captured. Figure VIII compares ground speed at wheels off and wind speed to the wind direction for activity on runway 27R. Activity on this runway usually operates from east to west, into the headwind (270^o wind bearing). Operations are allowed to continue on this runway unless the tail wind (90^o wind bearing) exceeds 3m/s. The scatter plot shows little correlation between the two factors, either with headwind (270^o) or tailwind (90^o). Two potential reasons have been identified. The wind speed during the time period was relatively low, which may mean that any impact of wind direction had minimal impact on the take-off roll trajectory. Correlation with wind direction may only be observed with direct respect to head- or tailwind where the effect on TAS is greatest. Secondly, wind direction data was aggregated at an hourly resolution, which may be inadequate when attempting to capture dynamic aircraft trajectory responses.

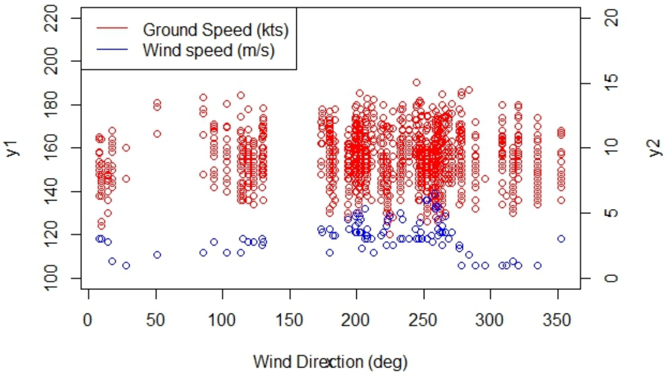

FIGURE VIII – GROUND SPEED AT WHEELS OFF (y1) AND WIND SPEED (y2) AGAINST WIND DIRECTION

V. Discussion and Application

Analyses indicate significant variability in the trajectory of aircraft LTO activity at London Heathrow airport. The primary objective was to promote the use of a template trajectory, such as the ICAO reference LTO cycle, modified by factors that impact variability, to represent all activity.

This paper finds that there is significant variability in the take-off roll, in terms of ground speed at wheels off and length of take-off roll, which strongly correlates to aircraft type. Variability in start position of take-off roll is relatively small, but there is high variability in wheels off points. Analysis shows that the length of take-off roll is highly correlated to speed at wheels off, which has been found to correlate closely with aircraft type, through MTOW. Insignificant variability is found when analysing take-off rolls of the same aircraft. Generally, this variability takes the same form as the larger sample for the same aircraft type and is therefore captured in the aircraft type trajectory. This research concludes that a significantly improved simulation will be achieved by using aircraft type defined template trajectories. This information should be taken from airport summary data, such as BOSS, and used to generate the trajectory. The use of exact aircraft specific trajectories may be unnecessary depending on the detail required in the analyses being conducted.

Two factors, take-off weight (TOW) and wind conditions, both widely expected to have an impact on the LTO trajectory of aircraft, were then analysed. The calculated correlation coefficients suggest that TOW is an important factor in determining LTO trajectory. Inclusion of TOW, or use of journey distance as a proxy for fuel loading, may significantly improve the realism reflected in trajectory simulation. When analysing wind conditions, normalised by runway 27R, there does not appear to be a relationship between wind direction, wind speed and ground speed at wheels off. The analyses prove inconclusive and further research should be conducted using data with larger variation in wind speed recorded at a higher resolution.

Following the quantification of the relationship of these factors, the template trajectory for each LTO trajectory can be modified based on sparse information regarding that factor. This data is more readily available than the high-resolution data used in the ICAO sophisticated approach.

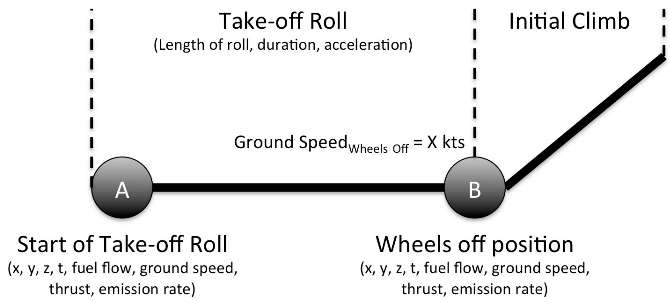

FIGURE IX - TAKE-OFF ROLL TEMPLATE

Using the example shown in figure IX, the wheels off point of a B747 take-off is most likely to occur at a ground speed of X knots, but could fall within the range of 0.86X and 1.29X knots. There is a moderately strong correlation between TOW and B747 ground speed at wheels off, therefore, the ground speed to be used in the trajectory can be modified within the above range accordingly. Over a shorter journey distance, ground speed at wheels off is likely to be lower; the opposite is true for longer journey distances. For example, a journey of 5,000km is likely to have a ground speed at wheels off between 0.86X and 1.04X knots while a journey of 10,000km will fall within the range of 0.98X and 1.10X knots. A similar relationship has been identified for the length of take-off roll. While it was expected that wind conditions would impact aircraft LTO trajectory, this was not supported in the analysis conducted. There are clearly other factors that impact LTO trajectory, shown in table II, and these should be considered in future analyses.

VI. Conclusions and Future Work

When representing airport emissions, the simple approach suggested by ICAO does not capture the high level of variability in aircraft take-off rolls at London Heathrow airport. This limits the capability of analysing the impact of measures proposed by SESAR, when optimising operations for environmental impact. The more detailed, sophisticated approach is seldom used due to the high-level of data requirement and computational expense. This report has argued for the use of available high-level data to inform the modification of a template trajectory, such as the ICAO LTO reference cycle. Sparse data regarding the factors that impact an aircraft LTO trajectory, such as aircraft type, take-off weight, meteorology, may be used to modify this template trajectory. This would represent aircraft activity more realistically and reflect the actual levels of variability in the trajectory simulation, without the requirement of high-level data and with less impact on computational expense.

High-resolution aircraft data has been used to identify and quantify potential relationships between aircraft take-off roll trajectories and factors expected to have an impact on them. This paper suggests that it is possible to improve the accuracy of simulated take-off rolls, in a period of activity with limited data availability, by using a template trajectory for each aircraft type, as suggested in the ICAO advanced approach. Sparse data, regarding factors such as TOW and wind conditions, should be used to modify this template trajectory, to provide improved levels of accuracy and realism.

These findings may be used to improve the ability of airport stakeholders to realistically simulate aircraft LTO trajectories given limited data and resources. This would allow a greater volume of activity to be analysed with minimal additional computational expense. The importance of variability consideration, when simulating aircraft LTO trajectories, lies in minimising uncertainty. Which, is an objective specified by SESAR. This can be beneficial to all airport stakeholders; airport operators can better forecast activity requirements to develop more optimal planning procedures and more efficient management of take-off speeds to reduce thrust and consequent emissions. Airlines may be able to manage fuel consumption based on factors such as take-off weight, by modifying take-off speed and/or length of take-off. Passengers may see reduced costs, as airlines and airports begin to minimise the factors that contribute to uncertainty.

A. Future work

There are several areas for future work that would build on the research presented in this paper. There are more variables in aircraft trajectory than the spatial and ground speeds considered here. Temporal, fuel flow, thrust and emissions analysis vary depending on activity and may also facilitate a significant improvement of efficiency in aircraft airport take-off rolls. The comparison of ground speed to true air speed may also assist in the interpretation of the results presented. Further segments of aircraft activity should be considered and their variability assessed, for example taxi, landing and initial climb. Analysis should be conducted to assess scope of variability. This would allow validation of the above findings for other airports, aircraft types and seasons.

ACKNOWLEDGMENTS

Thanks also go to the members of the Sensor Network for Air Quality (SNAQ) at London Heathrow consortium members, including data providers. Finally, thanks go to Jacintha Mack-Smith for valuable assistance in data processing and David Williams in statistical analysis.

REFERENCES

[1] ARNALDO VALDÉS, R. M., GÓMEZ COMENDADOR, F., MIJARES GORDÚN, L. & SÁEZ NIETO, F. J. 2011. The development of probabilistic models to estimate accident risk (due to runway overrun and landing undershoot) applicable to the design and construction of runway safety areas. *Safety Science,* 49**,** 633-650.

[2] COHEN, B. S. & BRONZAFT, A. L. 2011. Air Transportation and Human Health. *In:* EDITOR-IN-CHIEF: JEROME, O. N. (ed.) *Encyclopedia of Environmental Health.* Burlington: Elsevier.

[3] DUCHENE, N. 2006. The impact of aircraft weight on aircraft take-off emissions. *EUROCONTROL*.

[4] FLEUTI, E. & MARAINI, S. 2012. Air Quality Assessment Sensitivities - Zurich Airport Case Study.

[5] FLEUTI, E. & POLYMRIS, J. 2004. Aircraft NOx-Emissions Within the Operational LTO Cycle. *Unique (Flughafen Zrich AG) and Swiss Flight Data Services*.

[6] GELHAUSEN, M. C., BERSTER, P. & WILKEN, D. 2013. Do airport capacity constraints have a serious impact on the future development of air traffic? *Journal of Air Transport Management*.

[7] HSU, H.-H., ADAMKIEWICZ, G., ANDRES HOUSEMAN, E., VALLARINO, J., MELLY, S. J., WAYSON, R. L., SPENGLER, J. D. & LEVY, J. I. 2012. The relationship between aviation activities and ultrafine particulate matter concentrations near a mid-sized airport. *Atmospheric Environment,* 50**,** 328-337.

[8] HSU, H.-H., ADAMKIEWICZ, G., HOUSEMAN, E. A., ZARUBIAK, D., SPENGLER, J. D. & LEVY, J. I. 2013. Contributions of aircraft arrivals and departures to ultrafine particle counts near Los Angeles International Airport. *Science of The Total Environment,* 444**,** 347-355.

[9] ICAO 2011. Airport Air Quality Manual (Doc 9889).

[10] ICAO 2013. Environmental Report: Destination Green. 92 - 94.

[11] KESGIN, U. 2006. Aircraft emissions at Turkish airports. *Energy,* 31**,** 372-384.

[12] KIM, B. & RACHAMI, J. Aircraft emissions modeling under low power conditions. Proceedings of the A &WMA's 101st annual conference and exhibition, Portland, OR, USA, 2008.

[13] KURNIAWAN, J. S. & KHARDI, S. 2011. Comparison of methodologies estimating emissions of aircraft pollutants, environmental impact assessment around airports. *Environmental Impact Assessment Review,* 31**,** 240-252.

[14] MAZAHERI, M., JOHNSON, G. R. & MORAWSKA, L. 2011. An inventory of particle and gaseous emissions from large aircraft thrust engine operations at an airport. *Atmospheric Environment,* 45**,** 3500-3507.

[15] MORI, R. 2013. Aircraft ground-taxiing model for congested airport using cellular automata. *Intelligent Transportation Systems, IEEE Transactions on,* 14**,** 180-188.

[16] MOUSSIOPOULOS, N., SAHM, P., KARATZAS, K., PAPALEXIOU, S. & KARAGIANNIDIS, A. 1997. Assessing the impact of the New Athens airport to urban air quality with contemporary air pollution models. *Atmospheric Environment,* 31**,** 1497-1511.

[17] PEACE, H., MAUGHAN, J., OWEN, B. & RAPER, D. 2006. Identifying the contribution of different airport related sources to local urban air quality. *Environmental Modelling & Software,* 21**,** 532-538.

[18] SCHÄFER, K., JAHN, C., STURM, P., LECHNER, B. & BACHER, M. 2003. Aircraft emission measurements by remote sensing methodologies at airports. *Atmospheric Environment,* 37**,** 5261-5271.

[19] SCHUSTER, W., PORRETTA, M. & OCHIENG, W. 2012. High-accuracy four-dimensional trajectory prediction for civil aircraft. *Aeronautical Journal,* 116**,** 45-66.

[20] SESAR 2012. The Roadmap for Sustainable Air Traffic Management: European ATM Masterplan.

[21] SIDIROPOULOS, C., IKONOMOPOULOS, A., STRATIOTI, A. & TSILINGIRIDIS, G. Comparison of typical LTO-Cycle emissions with aircraft engine-and airport-specific emissions for Greek airports. Proc. 9th Int. Conference on Environmental Science and Technology, 2005. B865-B870.

[22] STETTLER, M. E. J., EASTHAM, S. & BARRETT, S. R. H. 2011. Air quality and public health impacts of UK airports. Part I: Emissions. *Atmospheric Environment,* 45**,** 5415-5424.

[23] TASTAMBEKOV, K., PUECHMOREL, S., DELAHAYE, D. & RABUT, C. 2014. Aircraft trajectory forecasting using local functional regression in Sobolev space. *Transportation Research Part C: Emerging Technologies,* 39**,** 1-22.

[24] UNAL, A., HU, Y., CHANG, M. E., TALAT ODMAN, M. & RUSSELL, A. G. 2005. Airport related emissions and impacts on air quality: Application to the Atlanta International Airport. *Atmospheric Environment,* 39**,** 5787-5798.