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Ricardo Energy & Environment

Heathrow Airport 2017 Emission Inventory

Report for Heathrow Airport Limited

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Glossary

APU	Auxiliary Power Unit
AUWR	All Up Weight Return – Heathrow's database that provides information on aircraft engine fits and maximum take-off weights
CAEP	Committee on Aviation Environmental Protection
EFPS	Electronic Flight Processing Strips
ICAO	International Civil Aviation Organisation
LTO	Landing and Take-Off
mppa	million passengers per annum
NATS	National Air Traffic Services
NTK	Noise and Track-Keeping
nvPM	non-volatile particulate matter
OPR	Overall Pressure Ratio
OSI	Operational Safety Instruction

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1 Introduction

This report presents the results of an air quality emission study of Heathrow Airport for the year 2017, concentrating on aircraft related emissions. It is the latest in a series of annual updates, which are based on the methodology for a study of the 12-month period April 2008 to March 2009. The 2008/9 study included an emission inventory[i], a dispersion modelling study[ii] and a model evaluation study[iii], which compared model results with measured concentrations. For 2013 there was a thorough update of the inventory and dispersion modelling[iv] and a new model evaluation study[v]. Subsequent annual updates for the calendar years 2014[vi], 2015[vii] and 2016[viii] have included specific components of the HAL 2013 emission inventory.

1.1 Aircraft and APU emissions

The motivation for the updates is that total aircraft emissions from the airport will change from one twelve-month period to another. There are a variety of reasons for this, and it is useful to identify two components to the overall change:

a) The change in the number of movements of aircraft of various types
b) The change in the operational parameters (times-in-mode, thrust settings, etc.) applicable to aircraft of a given type

Changes to times-in-mode might arise, for example, as a result of infrastructure changes on the airport affecting taxiing routes. Changes in thrust might arise, for example, as a result of a systematic change in load factors or in the distribution of destinations served by a given aircraft type.

It is judged that variations of type “b” above will be modest on the timescale of a few years unless the airport undergoes a major reorganisation, although average parameters may drift slowly over a period of several years. Thus, two timescales can be considered in the process of annual updating of the aircraft emission inventory: aircraft movement and fleet mix data are updated on an annual basis to refer to the actual set of flights that used the airport in the relevant year, while operational parameters (e.g. taxiing time by aircraft type) are updated on a longer timescale. This concept is applied here to generate the 2017 calendar year aircraft emissions inventory by retaining operational parameters derived from data for 2013 but updating the aircraft movement and fleet mix data.

However, for this update, data on taxi and hold times, derived from the electronic flight processing strips (EFPS) used by controllers, were available for 2017. These data have been analysed and the effects on the calculated emissions determined. Results using previous (2013), suitably averaged, taxi and hold times are presented as an alternative estimate to the main results.

For APUs, new observations of running times were made during 2017; the new APU data have been analysed and the effects on the calculated emissions determined. Results using previous (2013) APU data are presented as an alternative estimate to the main results.

The main results constitute an enhanced annual update and the alternative estimates a more basic update. A full update would include the following:

- Updated times-in-mode for take-off roll, initial climb, climb-out, approach and landing roll
- Updated thrust settings for take-off roll, initial climb and climb-out
- Updated reverse thrust settings for landing roll
- Updated climb and approach profiles
- Inclusion of reduced-engine taxiing in the modelling
- Updated source data for other airport sources:
    - Ground Support Equipment
    - Heating Plant
    - Car Parks
- Updated source data for off-airport sources:
    - Landside Roads

Such a comprehensive update to the modelling would require updated data on the elements such as times-in-mode, use of reduced-engine taxiing, etc., potentially from surveys. The updated climb and approach profiles would need to be derived from records of radar-based track data (e.g. from the noise and track-keeping (NTK) data).

The details of the methodology for quantifying aircraft emissions were presented in the 2008/9 report quoted earlier[i], and are not discussed further in this report.

1.2 Reduced-engine taxi

Heathrow have started to record the use of reduced-engine taxiing for departures. However, they do not record the duration of its use nor the associated APU use off-stand. Although not included in the main inventory, alternative results are presented that take account of reduced-engine taxiing, albeit making assumptions regarding the duration of its use and the associated APU use off-stand.

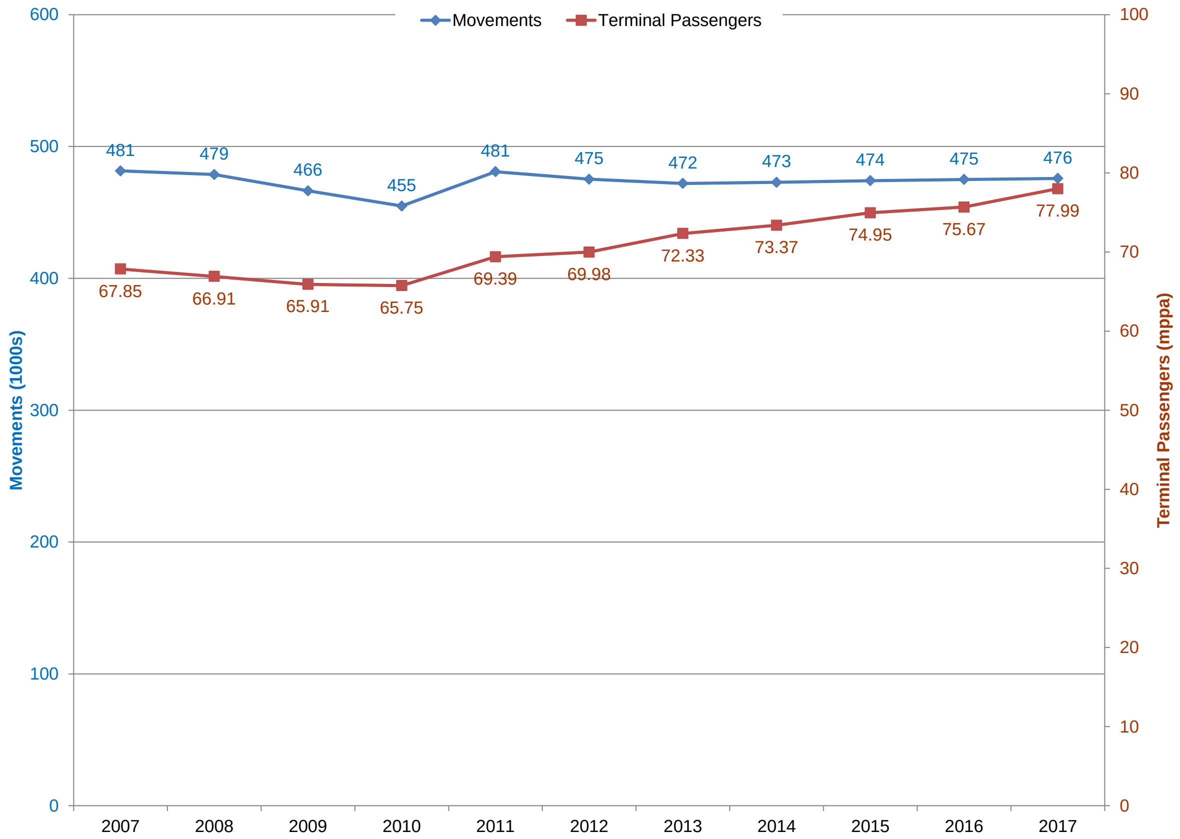
Additionally, Heathrow have undertaken a survey of the airlines to understand their procedures for the use of reduced-engine taxi on both arrival and departure.

2 Input data

2.1 Movements and passenger numbers

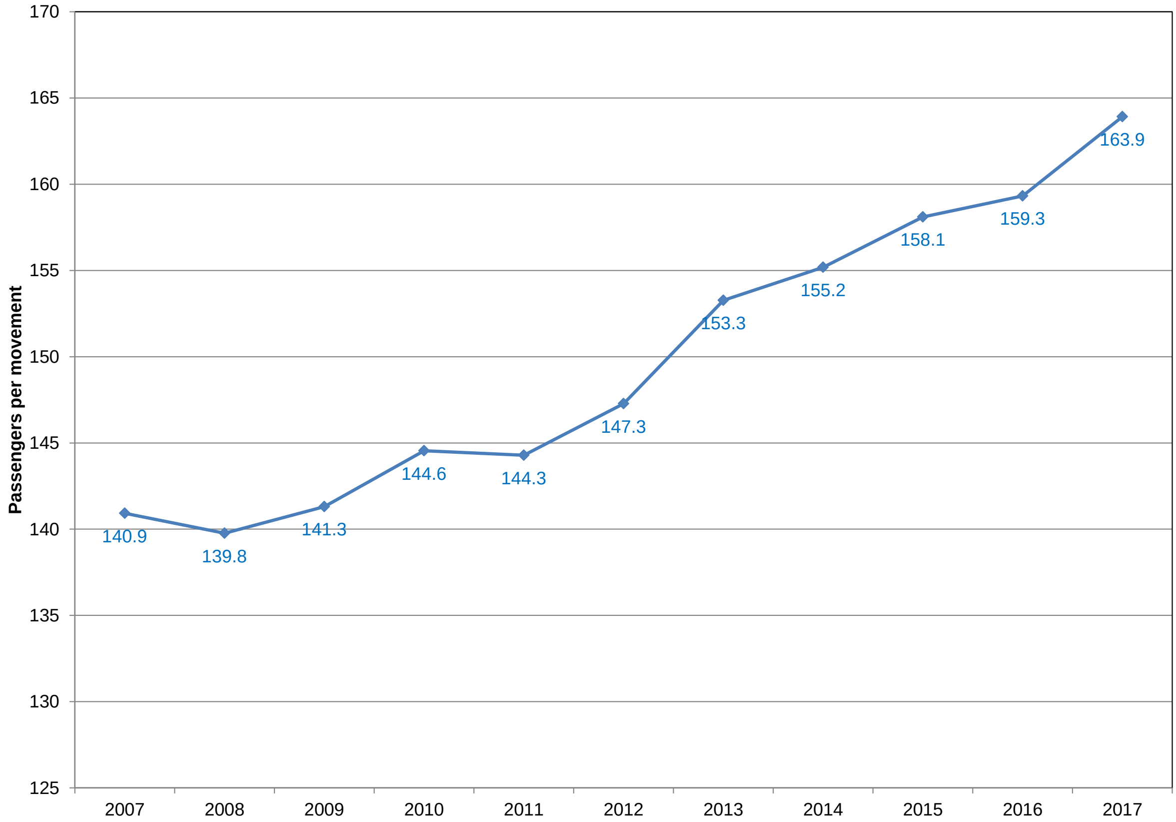
Figure 1 shows the trend in the number of aircraft movements and passengers over the last ten years. The number of aircraft movements has remained broadly constant, reflecting the fact that the airport is operating close to maximum capacity. However, the number of passengers has risen steadily over the period, accommodated by a larger number of passengers per movement on average (Figure 2).

Figure 1 Aircraft movement[1] and passenger numbers[2]



[1] ATMs and non-ATMs
[2] Terminal passengers

Figure 2 Average number of passengers[1] per movement[2]



[1] Terminal passengers
[2] ATMs and non-ATMs

2.2 Aircraft data

Aircraft movement data for the calendar year 2017 were provided by Heathrow Airport as an extract from their BOSS (Business Objective Search System) database. For each aircraft movement in the 2017 period, the following data fields are used in the emissions inventory:

- aircraft registration number (which allows an engine type to be assigned to the movement)
- flight date and time (which allows effects of meteorological parameters on emissions to be calculated)
- runway identifier and whether arrival or departure
- stand number (with the last two items used to determine taxiing and other times-in-mode)

The inventory includes emissions from non-ATMs (non-Air Transport Movements) – for example, positioning movements and private flights. The original 2008/9 study did not include non-ATMs, but the 2009 annual update report[ix] includes 2008/9 emissions recalculated to include non-ATMs, so that the results can be compared on a like-for-like basis.

Table 1 gives a breakdown of the movements by aircraft type alongside the equivalent breakdown for 2013 to 2016. The annual increase in movements seen in 2017 was 937. This represents a growth of 0.2% (from 474,978 in 2016 to 475,915 in 2017). The annual growth in passenger numbers seen in 2017 was 3.1% (from 75.67 mppa in 2016 to 77.99 mppa in 2017).

Figure 3 shows the trend in the number of aircraft movements broken down by aircraft type.

There have been some significant changes in the fleet mix from 2016 to 2017. The Boeing 787 (B787) has increased its share from 5.8% of the movements (27,591) in 2016 to 7.7% of the movements (36,484) in 2017. This appears to have been partially at the expense of the Boeing 767 (B767), whose share has reduced from 5.5% (25,949 movements) in 2016 to 5.0% (23,749 movements) in 2017. The “Other Heavy” category, which includes the Airbus A330 and A340, has also seen a significant decrease in its share, from 6.1% of the movements (28,986) in 2016 to 5.5% of the movements (26,079) in 2017.

Turning to medium sized aircraft, the A321 and the B737 have seen significant decreases in their shares from 9.1% (43,040 movements) and 3.9% (18,712 movements) in 2016, respectively, to 8.1% (38,541 movements) and 3.2% (15,174 movements) in 2017, respectively. Conversely, other medium and small aircraft have seen their shares increase.

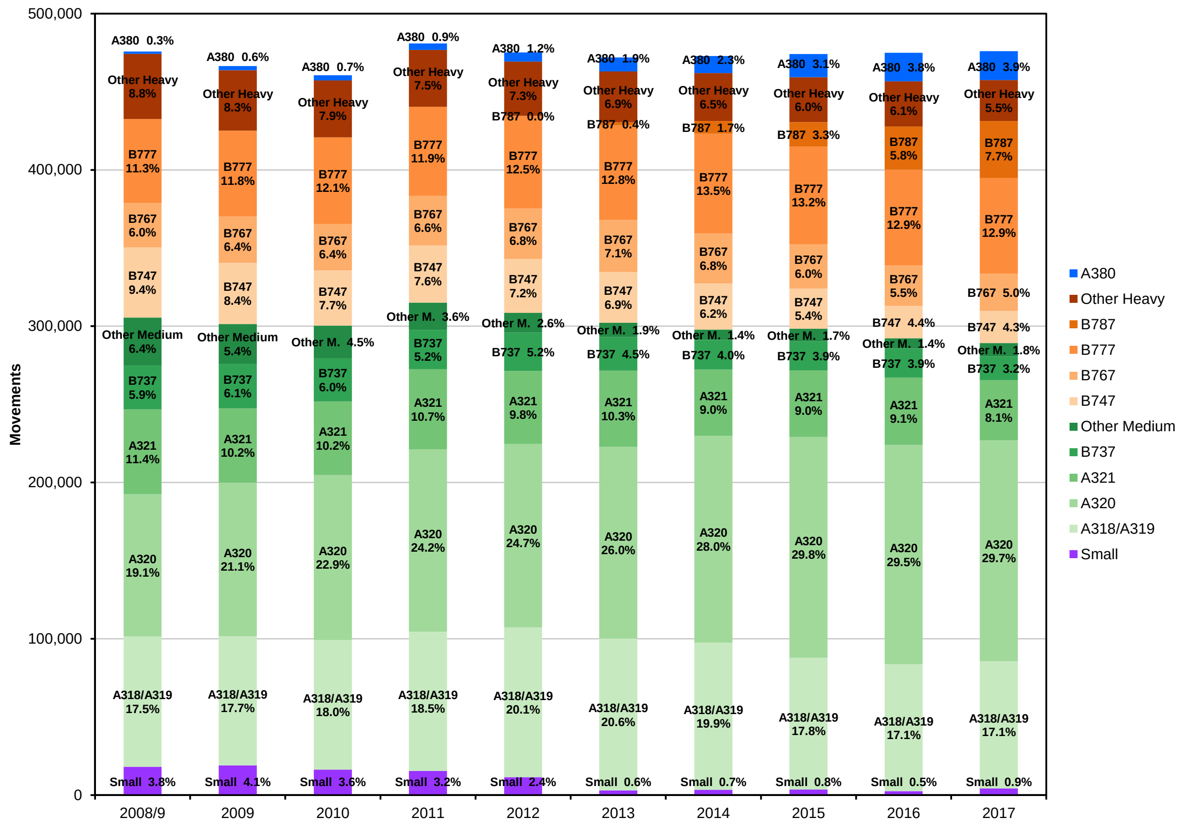
Overall, there has been a reduction of 4,792 movements (1.7%) by medium-sized aircraft and an increase of 3,747 movements (2.3%) by heavy aircraft (excluding the A380, whose movements increased by 218 (1.2%)), illustrating how the increase in the average passengers per movement (Figure 2) has been achieved without a significant change in the total number of movements.

Table 1 Aircraft movements[1] by aircraft type: comparison of 2017 with 2013 to 2016

Aircraft Type	2013	2014	2015	2016	2017	Change (%)			
						2013[a]	2014[b]	2015[c]	2016[d]
Small	3,038	3,405	3,556	2,504	4,268	40.5	25.3	20.0	70.4
Medium	299,219	294,438	294,843	289,774	284,982	-4.8	-3.2	-3.3	-1.7
A318/A319	97,108	94,057	84,352	81,196	81,371	-16.2	-13.5	-3.5	0.2
A320	122,638	132,490	141,169	140,303	141,347	15.3	6.7	0.1	0.7
A321	48,837	42,324	42,765	43,040	38,541	-21.1	-8.9	-9.9	-10.5
B737	21,459	18,898	18,376	18,712	15,174	-29.3	-19.7	-17.4	-18.9
Others	9,177	6,669	8,181	6,523	8,549	-6.8	28.2	4.5	31.1
Heavy	160,750	164,161	160,869	164,435	168,182	4.6	2.4	4.5	2.3
B747	32,378	29,510	25,662	20,668	20,564	-36.5	-30.3	-19.9	-0.5
B767	33,322	31,990	28,342	25,949	23,749	-28.7	-25.8	-16.2	-8.5
B777	60,542	63,774	62,611	61,241	61,306	1.3	-3.9	-2.1	0.1
B787	2,012	8,134	15,601	27,591	36,484	1713.3	348.5	133.9	32.2
Other	32,496	30,753	28,653	28,986	26,079	-19.7	-15.2	-9.0	-10.0
A380	8,931	10,813	14,826	18,265	18,483	107.0	70.9	24.7	1.2
Total	471,938	472,817	474,094	474,978	475,915	0.8	0.7	0.4	0.2

[1] ATMs and non-ATMs
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Figure 3 Number of movements[1] by aircraft type: 2008/9 to 2017



[1] ATMs and non-ATMs

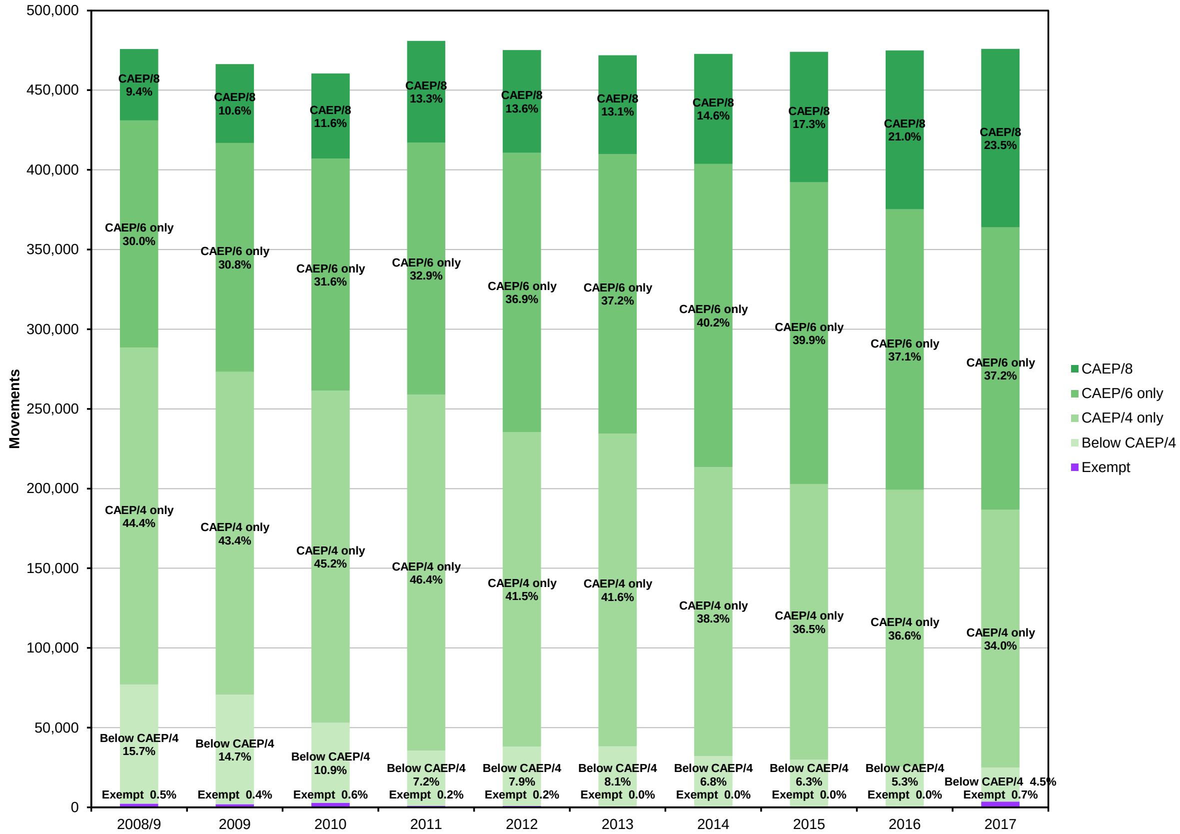
2.3 Engine assignment

Aircraft engine assignments have been taken directly from the airlines via Heathrow's AUWR database.

Prior to 2014 the inventories took aircraft engine assignments from JP Airline Fleets. However, for 2012 and 2013 this introduced a problem with certain engines (CFM56-5B1 to CFM56-5B9, GEnx-1B64 and GEnx-1B70) as their precise combustor variants were no longer reported. This led to difficulties in the assignment of engine types to the relevant records in the ICAO engine emissions databank and the fraction of engines meeting the CAEP/8 emission standard being overestimated.

Figure 4 shows the trend in the number of movements by aircraft meeting the various CAEP emission standards. The values for 2012 and 2013 have been revised from those reported in the 2013 study[iv], in line with Heathrow's AUWR database.

Figure 4 Total movements[1] by CAEP standard[2]



[1] ATMs and non-ATMs
[2] "CAEP/4 only" means engines that meet the CAEP/4 standard but **not** the CAEP/6 standard. Similarly, "CAEP/6 only" means engines that meet the CAEP/6 standard but **not** the CAEP/8 standard. Jet engines below 26.7 kN (6,000 lb) thrust and turboprops are exempt from the CAEP regulations.

These results show a continuing trend of an increasing number of aircraft that meet the most recent CAEP NO_x standards (CAEP/6 and CAEP/8) and a reducing number of aircraft that do not meet the older standard (CAEP/4). This is the natural result of normal fleet replacement as more modern aircraft are more likely to meet the latest standards. (All newly manufactured engines since 01 January 2013 must comply with the CAEP/6 standard, while all new engines types since 01 January 2014 must comply with the CAEP/8 standard.)

2.4 APU running times

The APU running times for this 2017 emission inventory update are derived from new observations of running times made during 2017. The new APU data were supplied by Heathrow Airport in the same form as that provided for previous inventories since 2013. These data have been analysed using the same methodology as used in the previous work to extract average running times on arrival and on departure, for narrow and wide-bodied aircraft types. The Airbus A380 was analysed separately from other wide-bodied aircraft as its APU is generally run for longer and the number of APU running times recorded were significant enough to warrant separate analysis. (Heathrow's Operational Safety Instruction "OSI/21/11" allows for longer running times for the A380 compared with other wide-bodied aircraft.)

The 2013 inventory only considered APU use on-stand. However, if aircraft operate using reduced-engine taxi, they usually keep their APUs running during taxiing. At the time of the 2013 inventory no data were available regarding the deployment of reduced-engine taxi at Heathrow, so it was not considered in the inventory. However, anecdotal information now indicates that single- (or reduced-) engine taxiing is widely used during taxi-in after landing and is beginning to be used more widely during taxi-out for take-off. The inclusion of reduced-engine taxiing in the modelling, based on information on its frequency of use from surveys of airlines, would be a useful enhancement to the analysis.

To remain consistent with previous annual updates (where only aircraft movement data were updated), APU running times taken from the 2013 assessment have been used to generate 'alternative' inventories.

The results presented make comparisons with the emissions calculated using the 'alternative' APU running times, allowing the effect on emissions of updating the times to be quantified.

Table 2 shows the APU running times derived from data for the year 2013 to 2017.

The 2017 data suggest that total running times for narrow-bodied aircraft are similar to 2016. However, the 2017 data suggest that total running times for wide-bodied aircraft, excluding the A380, are about 30% higher than for 2016 and that total running times for the A380 are about a factor of 3.5 higher than for 2016. It should be noted that the 2016 times have been revised slightly since the publication of the 2016 report[viii]., as more complete data for 2016 were provided alongside the data for 2017.

The increase in APU running time seen for wide-bodied aircraft is likely to relate to issues with PCA use, which first became apparent in 2016. Increased running times for the A380 could also be an artefact of the small sample size.

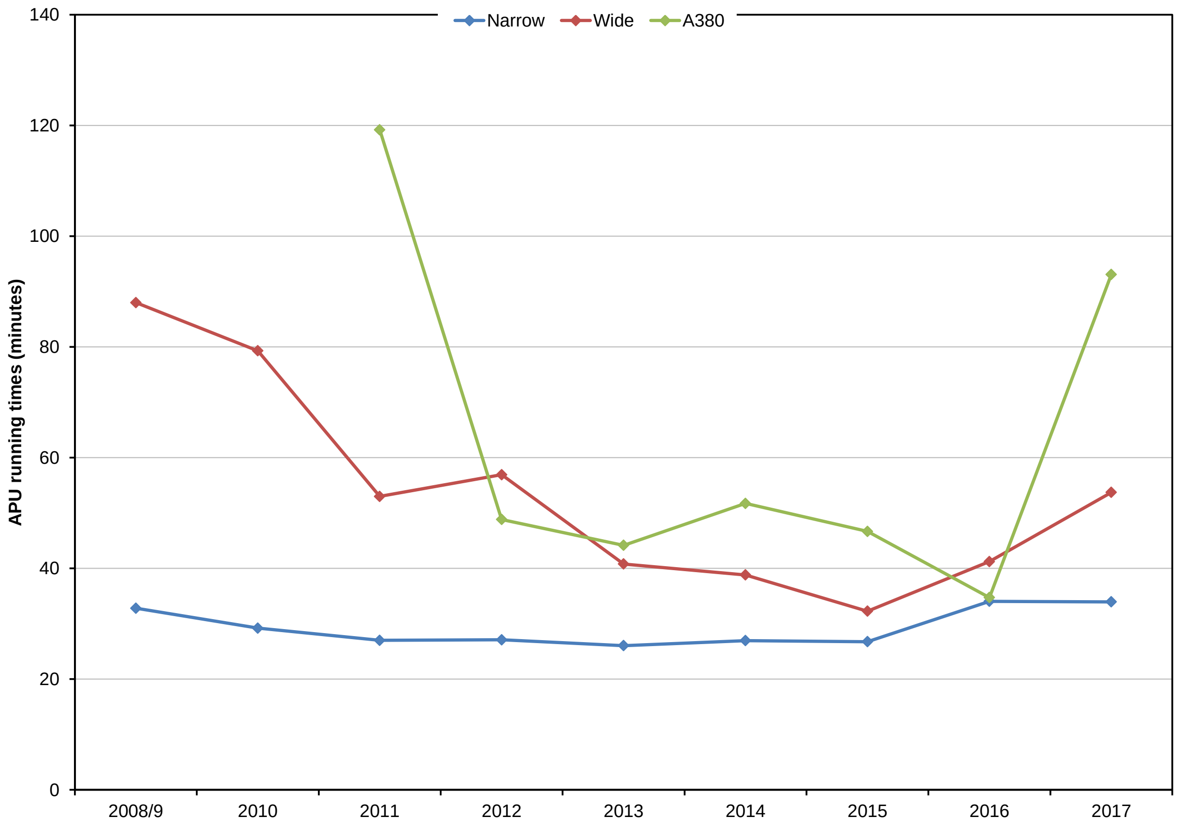
Figure 5 shows the trend in the APU running times since 2008/9. There is clearly a downward trend for wide-bodied aircraft until 2015. However, increases in 2016 and again in 2017 have seen APU running times for wide-bodied aircraft return to levels seen in 2011 and 2012. APU running times for narrow-bodied aircraft have remained more or less constant over the five years to 2015. However, the times for 2016 and 2017 stand clearly above the long-term trend.

Table 2 APU running times: comparison of 2017 with 2013 to 2016

		APU running time (minutes)					Change from (%)			
		2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Narrow-bodied	Arrival	6.7	6.8	6.9	9.9	8.8	31.3	28.8	27.9	-11.5
	Departure	19.4	20.1	19.9	24.1	25.2	30.0	25.1	26.6	4.4
	Total	26.1	26.9	26.8	34.0	34.0	30.3	26.0	26.9	-0.3
Wide-bodied	Arrival	12.0	8.9	8.2	11.1	10.4	-13.0	16.7	26.8	-5.9
	Departure	28.8	29.9	24.0	30.1	43.3	50.3	44.9	80.1	43.6
	Total	40.8	38.8	32.3	41.2	53.7	31.7	38.4	66.5	30.3
A380	Arrival	18.2	11.9	11.2	16.1	27.1	49.1	128.4	142.5	68.6
	Departure	26.0	39.9	35.5	18.7	66.0	153.8	65.5	85.9	253.6
	Total	44.2	51.7	46.7	34.7	93.1	110.8	79.9	99.5	168.0

[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Figure 5 APU running times



2.5 Taxi and hold times

The taxi and hold times for this 2017 emission inventory update are taken from data, for 2017, extracted from a NATS database that is populated using electronic flight processing strips (EFPS).

For departures, the EFPS database records time of pushback, time at hold, and actual time of departure, to 1 second precision[1]. It therefore includes times for hold, line-up and pilot reaction as well as taxi-out, and these have also been incorporated. For arrivals, it records actual time of arrival and time on-stand, again to 1 second precision; taxi-in times were obtained by subtracting landing roll times[2].

It was possible to match 99% of departures with an EFPS record so that they had individual taxi-out and hold times, and similarly for 99% of arrivals. For the other movements which could not be matched, times were taken from tables of times by runway/apron combination derived by averaging the EFPS data.

To remain consistent with previous annual updates (where only aircraft movement data were updated), average taxi and hold times taken from the 2013 assessment have been used to generate ‘alternative’ inventories.

The results presented make comparisons with the emissions calculated using the ‘alternative’ taxi and hold times, allowing the effect on emissions of updating the times to be quantified.

Table 3 shows taxi-in times derived from data for the years 2013 to 2017, by runway and terminal. Table 4 and Table 5 show similar data for taxi-out and hold respectively.

Table 6 shows that overall, the 2017 taxi and hold times are very similar to previous years. However, there is considerable variation in the differences between runway and terminal pairings.

[1] The EFPS system records the time when controllers react to an observation or perform an action, so times are not necessarily accurate to 1 second.
[2] Landing-roll times were assumed to be unchanged from the 2013 assessment.

Table 3 Aircraft taxi-in times: comparison of 2017 with 2013 to 2016

Runway	Terminal	Taxi-in (s)					Change from (%)			
		2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
09L	T1[e]	256	253	246	N/A	N/A	N/A	N/A	N/A	N/A
09L	T2	327	406	435	407	437	33.6	7.5	0.5	7.4
09L	T3	389	399	407	419	455	17.0	14.1	11.8	8.5
09L	T4	732	722	718	694	705	-3.7	-2.3	-1.9	1.5
09L	T5	493	493	478	456	446	-9.5	-9.6	-6.7	-2.2
09L	Cargo	669	667	687	670	677	1.2	1.5	-1.4	1.1
09R	T1[e]	517	397	431	N/A	N/A	N/A	N/A	N/A	N/A
09R	T2	471	315	306	308	315	-33.1	0.1	3.1	2.5
09R	T3	383	395	409	417	476	24.2	20.4	16.2	14.0
09R	T4	291	289	268	262	281	-3.3	-2.6	5.1	7.2
09R	T5	639	586	582	578	651	1.9	11.1	11.9	12.7
09R	Cargo	307	306	318	260	295	-3.8	-3.5	-7.0	13.6
27L	T1[e]	484	486	499	N/A	N/A	N/A	N/A	N/A	N/A
27L	T2	576	411	367	339	378	-34.4	-8.1	3.1	11.5
27L	T3	328	329	323	350	387	18.0	17.6	19.8	10.6
27L	T4	398	398	359	345	362	-9.0	-9.1	0.8	4.8
27L	T5	423	430	424	447	448	5.8	4.0	5.6	0.1
27L	Cargo	223	221	200	185	214	-4.0	-3.2	7.0	15.9
27R	T1[e]	272	273	285	N/A	N/A	N/A	N/A	N/A	N/A
27R	T2	402	494	521	498	525	30.6	6.3	0.8	5.4
27R	T3	329	339	369	389	409	24.4	20.6	10.9	5.1
27R	T4	719	728	734	764	749	4.2	2.9	2.0	-2.0
27R	T5	428	423	403	424	409	-4.4	-3.2	1.4	-3.6
27R	Cargo	667	654	667	640	642	-3.8	-1.9	-3.8	0.4

[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)
[e] T1 closed in 2015. However, there remain a small numbers of movements to remote stands previously associated with T1.

Table 4 Aircraft taxi-out times: comparison of 2017 with 2013 to 2016

Runway	Terminal	Taxi-out (s)					Change from (%)			
		2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
09L	T1[e]	734	681	518	N/A	N/A	N/A	N/A	N/A	N/A
09L	T2	907	848	845	734	794	-12.4	-6.3	-6.0	8.2
09L	T3	840	714	712	747	652	-22.4	-8.8	-8.4	-12.8
09L	T4	874	871	935	723	886	1.4	1.7	-5.2	22.5
09L	T5	628	558	637	607	641	2.1	14.8	0.7	5.6
09L	Cargo	854	681	763	606	612	-28.3	-10.0	-19.8	1.1
09R	T1[e]	717	719	803	N/A	N/A	N/A	N/A	N/A	N/A
09R	T2	853	658	604	638	672	-21.2	2.2	11.3	5.3
09R	T3	608	592	609	642	653	7.4	10.3	7.3	1.7
09R	T4	619	604	596	614	610	-1.4	1.1	2.4	-0.6
09R	T5	508	503	530	527	518	1.9	2.8	-2.3	-1.7
09R	Cargo	572	562	541	536	558	-2.4	-0.8	3.2	4.1
27L	T1[e]	544	541	577	N/A	N/A	N/A	N/A	N/A	N/A
27L	T2	573	485	463	458	459	-19.9	-5.5	-0.8	0.3
27L	T3	634	622	661	676	677	6.7	8.8	2.3	0.1
27L	T4	519	531	544	556	528	1.7	-0.5	-2.9	-5.0
27L	T5	751	765	815	832	821	9.3	7.4	0.7	-1.4
27L	Cargo	743	719	656	703	681	-8.4	-5.2	3.8	-3.2
27R	T1[e]	455	460	519	N/A	N/A	N/A	N/A	N/A	N/A
27R	T2	526	565	568	563	561	6.6	-0.8	-1.2	-0.5
27R	T3	702	713	747	726	726	3.4	1.8	-2.8	-0.1
27R	T4	512	516	513	504	496	-3.1	-3.9	-3.2	-1.5
27R	T5	786	826	852	779	779	-0.8	-5.6	-8.5	0.0
27R	Cargo	785	718	678	644	696	-11.3	-3.0	2.6	8.1

[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)
[e] T1 closed in 2015. However, there remain a small numbers of movements from remote stands previously associated with T1.

Table 5 Aircraft hold[1] times: comparison of 2017 with 2013 to 2016

Runway	Terminal	Hold (s)					Change from (%)			
		2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
09L	T1[e]	722	480	113	N/A	N/A	N/A	N/A	N/A	N/A
09L	T2	819	458	589	421	450	-45.1	-1.7	-23.6	7.0
09L	T3	817	655	546	350	424	-48.2	-35.3	-22.4	21.0
09L	T4	1109	638	806	753	738	-33.4	15.8	-8.4	-1.9
09L	T5	765	559	670	419	528	-30.9	-5.6	-21.1	26.0
09L	Cargo	830	473	674	1015	615	-25.9	30.0	-8.8	-39.4
09R	T1[e]	605	628	631	N/A	N/A	N/A	N/A	N/A	N/A
09R	T2	642	646	642	665	631	-1.8	-2.4	-1.8	-5.1
09R	T3	668	687	697	713	677	1.3	-1.5	-2.9	-5.2
09R	T4	666	660	676	704	684	2.6	3.5	1.1	-2.9
09R	T5	689	695	690	713	691	0.3	-0.6	0.2	-3.1
09R	Cargo	531	577	517	500	508	-4.3	-12.0	-1.7	1.7
27L	T1[e]	569	589	595	N/A	N/A	N/A	N/A	N/A	N/A
27L	T2	593	578	554	593	587	-1.1	1.6	5.8	-1.1
27L	T3	609	627	621	653	644	5.7	2.7	3.6	-1.3
27L	T4	558	554	553	577	586	5.1	5.8	6.0	1.7
27L	T5	584	604	591	618	615	5.3	1.9	4.0	-0.6
27L	Cargo	484	559	551	505	505	4.2	-9.8	-8.5	-0.1
27R	T1[e]	532	541	539	N/A	N/A	N/A	N/A	N/A	N/A
27R	T2	555	527	537	589	563	1.4	6.8	4.7	-4.4
27R	T3	587	575	579	631	614	4.5	6.7	5.9	-2.7
27R	T4	801	802	828	881	862	7.7	7.6	4.1	-2.1
27R	T5	560	561	560	620	613	9.5	9.3	9.4	-1.2
27R	Cargo	807	746	748	758	775	-4.0	3.9	3.6	2.3

[1] Includes time for line-up and pilot reaction
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)
[e] T1 closed in 2015. However, there remain a small numbers of movements from remote stands previously associated with T1.

Table 6 Weighted average[1] taxi and hold[2] times

Mode	2013	2014	2015	2016	2017	Change from (%)			
						2013[a]	2014[b]	2015[c]	2016[d]
Taxi-In	434	438	429	434	444	2.3	1.5	3.5	2.4
Taxi-Out	657	651	673	664	662	0.8	1.7	-1.7	-0.4
Hold	592	604	603	642	629	6.1	4.0	4.1	-2.1

[1] Derived from movements in 2017
[2] Includes time for line-up and pilot reaction
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

3 Taxiing emissions

3.1 Conventional taxiing

Taxiing is assigned a thrust setting of 7% in the standard ICAO LTO cycle. There has been evidence available for some years (e.g. the Loughborough study at Gatwick[x]) that actual taxiing thrust settings are on average less than this. However, it was unclear how emission indices would behave at lower thrust settings. For the products of incomplete combustion, such as CO and HC, the emission indices (g pollutant per kg fuel burned) are likely to be higher for lower thrust settings, with the reverse likely to be true for NO_x; the position for Smoke Number and PM_{10} emission indices is unclear.

For taxi-out and for taxi-in on all engines, the PSDH recommended that idle thrust settings lower than 7% should be taken into account. FDR data compiled for the PSDH indicate that in most cases the ground-idle thrust setting used during most of taxiing and hold is around 5% except for aircraft fitted with Rolls Royce engines, for which 3% thrust is nearer the mark. Clearly, there will be brief periods of higher thrust (perhaps 10% to 15%) to get the aircraft rolling or to negotiate sharp turns, but superimposed on much longer periods at the ground idle setting, so the average thrust level will be significantly below 7%.

It is easier to estimate the impact of these lower thrust settings on fuel flow than on emission indices. Considering the available data as a whole, the PSDH recommended that fuel flow rates for engine types other than Rolls Royce be set 15% - 20% lower than the ICAO 7% value and for Rolls Royce engines be set 30% - 35% lower than the ICAO 7% value, and these recommendations were implemented for Heathrow by using the mid-point of the ranges, i.e. 17.5% and 32.5% respectively, with the values applied to all periods of taxiing and hold. The PSDH further recommended that the NO_x and PM_{10} emission indices at the lower fuel flow rate be held the same as the value at 7% thrust. As noted earlier, this is likely to yield a somewhat conservative estimate (i.e. overestimate) of taxiing NO_x emissions; current information[xi], albeit more uncertain, suggests that this assumption is also likely to be conservative for PM_{10}. These recommendations have been applied to LHR inventories since 2008/9.

3.2 Reduced-engine taxi

Reduced-engine taxiing is the practice of shutting down an engine during taxi operations, which helps reduce fuel use, emissions, and noise. In theory, reductions of 20% to 40% of the ground level fuel burn and CO_2, and 10% to 30% of ground level NO_x emissions, may be realised dependant on aircraft type and operator technique[3].

The estimation of taxiing emissions is made potentially more complex by the practice of reduced-engine taxiing. At the time of the PSDH there were no robust statistical data on the practice at Heathrow, although the PSDH expert panel report estimated it was used for around 25% or less of arrivals. Reduced-engine taxiing for departures was not common practice at the time. In light of this, the PSDH report made no specific recommendation for taking account of reduced-engine taxiing on NO_x and PM emissions.

Since the publication of the PSDH report the practice of reduced-engine taxiing has become more widespread, due in part to the achieved fuel savings. Since the summer of 2014, Heathrow have recorded the use of reduced-engine taxiing for departures. During 2017 about 18% of departures used reduced-engine taxiing. The use of reduced-engine taxiing on arrival is expected to be more common than on departures. However, systems to record its use on arrival are not yet available at Heathrow or any other major airport, generally. Currently, Heathrow only record if reduced-engine taxiing is used on departure. They do not record the duration of its use or the associated APU use off-stand.

3.2.1 Taxi-out

In the assessment of reduced-engine taxiing we have assumed that aircraft using reduced-engine taxiing will operate on all engines for the final 2-3 minutes of taxi-out; this is to allow for the engines to fully warm-up prior to take-off. During reduced-engine taxiing we have assigned the standard ICAO thrust setting of 7%. We have also assumed that airlines will operate their APUs whilst taxiing using reduced engines. It is likely that the APU would be needed to provide on-board power to the aircraft and to start the remaining engine(s).

3.2.2 Taxi-in

Anecdotal evidence suggests the use of reduced-engine taxi on arrival is much more common than for departures. Although reduced-engine taxiing was not recorded for arrivals, a survey of the airlines

[3] http://www.sustainableaviation.co.uk/wp-content/uploads/2015/09/Departures-Code-of-Practice-June-2012.pdf

was undertaken. Of the airlines that responded, all of those who used reduced-engine taxiing on departure also used it on arrival. Additionally, some airlines that did not use reduced-engine taxiing on departure did use it on arrival.

We have therefore extended the methodology to cover the arrivals corresponding to the reduced-engine departures of the turnarounds and to airlines that responded positively to the use of reduced-engine taxiing on arrival (78% of arrivals). We have conservatively assumed that aircraft using reduced-engine taxiing will operate on all engines for the first 2-3 minutes of taxi-in; this is to allow for engine cool-down and runway clearance. Anecdotal evidence suggests that pilots shut down one or more engines prior to 2 minutes after touch-down.

4 Results

4.1 NO_x

Table 7 shows aircraft emissions broken down by mode (i.e. phase of the LTO cycle), using the same categories as in the 2008/9 inventory report and the subsequent annual updates. The 2017 values have been compared with equivalent reported values for 2013 to 2016. The calculated total aircraft NO_x emissions (up to 1000 m altitude) for 2017 are 2.2% higher than the equivalent value for 2016, for a 3.1% increase in the number of passengers.

The majority (four-fifths) of this increase is explained by the changes in APU running times. The remaining fraction is due principally to meteorological effects (an increase in average ambient temperature and a decrease in average ambient humidity) offset slightly by a reduction due to aircraft fleet changes.

Table 7 Breakdown of aircraft NO_x emissions by mode: comparison of 2017 with 2013 to 2016

Mode	Annual NO_x emissions (tonnes)					Change from (%)			
	2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Ground-level									
Landing roll	41.04	43.91	44.42	45.71	46.85	14.2	6.7	5.5	2.5
Taxi-in	153.51	163.60	163.51	162.24	163.02	6.2	-0.4	-0.3	0.5
Taxi-out	237.53	251.18	259.11	252.36	257.45	8.4	2.5	-0.6	2.0
Hold	225.63	235.80	234.50	246.16	245.74	8.9	4.2	4.8	-0.2
Take-off roll	681.80	741.75	726.78	729.50	735.52	7.9	-0.8	1.2	0.8
APU	182.05	185.24	190.02	255.45	338.67	86.0	82.8	78.2	32.6
Engine testing[1]	2.80	2.80	2.80	2.80	2.80	0.0	0.0	0.0	0.0
Total ground-level	**1524.36**	**1624.28**	**1621.14**	**1694.21**	**1790.04**	**17.4**	**10.2**	**10.4**	**5.7**
Elevated									
Approach	594.64	628.51	623.51	616.99	626.87	5.4	-0.3	0.5	1.6
Initial climb	773.17	838.77	825.12	830.53	830.33	7.4	-1.0	0.6	0.0
Climb out	1393.60	1452.24	1427.51	1445.07	1441.40	3.4	-0.7	1.0	-0.3
Total elevated	**2761.41**	**2919.52**	**2876.14**	**2892.59**	**2898.61**	**5.0**	**-0.7**	**0.8**	**0.2**
Total	**4285.76**	**4543.80**	**4497.28**	**4586.80**	**4688.66**	**9.4**	**3.2**	**4.3**	**2.2**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Table 8 shows the values of annual aircraft LTO NO_x emissions normalised by the number of passengers and movements. The NO_x per passenger for 2017 is 0.8% lower than for 2016 and the NO_x per movement is 2.0% higher.

Table 8 LTO NO_x emissions per passenger and per movement: comparison of 2017 with 2013 to 2016

	2013	2014	2015	2016	2017	Change from (%)			
						2013[a]	2014[b]	2015[c]	2016[d]
LTO NO_x (tonnes per year)	4285.76	4543.80	4497.28	4586.80	4688.66	9.4	3.2	4.3	2.2
Passengers[1] (mppa)	72.33	73.37	74.95	75.67	77.99	7.8	6.3	4.0	3.1
LTO NO_x (g per passenger[1])	59.25	61.93	60.00	60.61	60.12	1.5	-2.9	0.2	-0.8
Movements[2] (1000s)	471.94	472.80	474.09	474.96	475.78	0.8	0.6	0.4	0.2
LTO NO_x (kg per movement[2])	9.08	9.61	9.49	9.66	9.85	8.5	2.5	3.9	2.0

[1] Excludes transit passengers
[2] ATMs and non-ATMs
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

From a local air quality perspective, emissions from aircraft on the ground have a greater impact than elevated emissions. The calculated value of ground-level aircraft NO_x emissions (including APU emissions and engine testing emissions) for 2017 is 5.7% higher than the equivalent value for 2016, for a 0.2% increase in the total number of movements (3.1% increase in total number of passengers). The majority of this 5.7% increase in NO_x emissions is due to the increase in APU emissions. The other modes make only a small contribution to the increase in emissions. Compared with 2016, the fractional range for the individual ground-level modes (excluding engine testing) shown in Table 7 vary from -0.2% (for Hold) to +32.6% (for APU). The variability reflects the changes in times-in-mode, particularly the increases in APU running times. Changes in the fleet will also affect the individual modes differently, as the emission rates vary with thrust settings.

Table 9 gives a breakdown of ground-level aircraft NO_x emissions (omitting APUs and engine testing) by aircraft type, comparing the distribution in 2017 with the equivalent distribution in 2016. As expected from the movement breakdowns in Table 1 the A320 aircraft family (A318/A319, A320 and A321) account for a significant fraction of the emissions in both years (23.8% in 2017 and 24.5% in 2016). However, the larger aircraft types, B747, B777 and A380, together contribute approximately half of the emissions in each period (50.6% in 2017 and 50.7% in 2016), despite accounting for less than a quarter of the total movements.

Table 9 also gives ground-level emissions per movement (excluding APU and engine testing emissions) for each aircraft type, comparing values for 2017 with those for 2016. There is variability in emissions from year-to-year, due to the changeable effects of ambient meteorological conditions. For a given aircraft type, the emissions per movement are also affected by changes to the distribution of sub-aircraft types and/or engine models, which have different emission characteristics. The table shows that the values of ground-level emissions per movement for the large aircraft types (B747 and B777) are around a factor of five higher than the average for A318/A319/A320/A321 or B737 aircraft. Of course, the larger types carry more passengers than the A320/B737 families, but only around twice as many passengers, so the NO_x per passenger ratio is roughly double that of the A320/B737 families. The reasons for this are well understood and result from two main causes:

- The larger aircraft types tend to be operated on long-haul rather than short-haul flights, so fuel comprises a much greater proportion of the aircraft take-off mass, requiring significantly higher take-off thrust (per passenger).
- Engine manufacturers have previously concentrated their efforts on fuel efficiency on larger engines (as fitted to these larger aircraft types) as, globally, they consume more fuel than the smaller types. A key technology for increasing fuel efficiency is the use of higher overall pressure ratios (OPR) and the CAEP standards allow engines with higher OPRs to emit more NO_x than those with lower OPRs (after normalising by the engine rated thrust).

Table 9 Breakdown of ground-level aircraft NO_x emissions[1] by aircraft type

Aircraft Type	2016			2017		
	NO_x (t/year)	%	NO_x (kg/mvt)	NO_x (t/year)	%	NO_x (kg/mvt)
Small	1.53	0.1	0.61	1.55	0.1	0.36
Medium	380.72	26.5	1.31	372.63	25.7	1.31
A318/A319	99.88	7.0	1.23	99.17	6.8	1.22
A320	176.98	12.3	1.26	177.86	12.3	1.26
A321	74.51	5.2	1.73	67.60	4.7	1.75
B737	19.96	1.4	1.07	16.51	1.1	1.09
Others	9.38	0.7	1.44	11.49	0.8	1.34
Heavy	878.66	61.2	5.34	896.40	61.9	5.33
B747	156.61	10.9	7.58	151.22	10.4	7.35
B767	76.94	5.4	2.96	70.61	4.9	2.97
B777	397.07	27.7	6.48	403.44	27.9	6.58
B787	109.96	7.7	3.99	147.62	10.2	4.05
Other	138.08	9.6	4.76	123.51	8.5	4.74
A380	175.07	12.2	9.58	178.00	12.3	9.63
Total	1435.97	100.0	3.02	1448.58	100.0	3.04

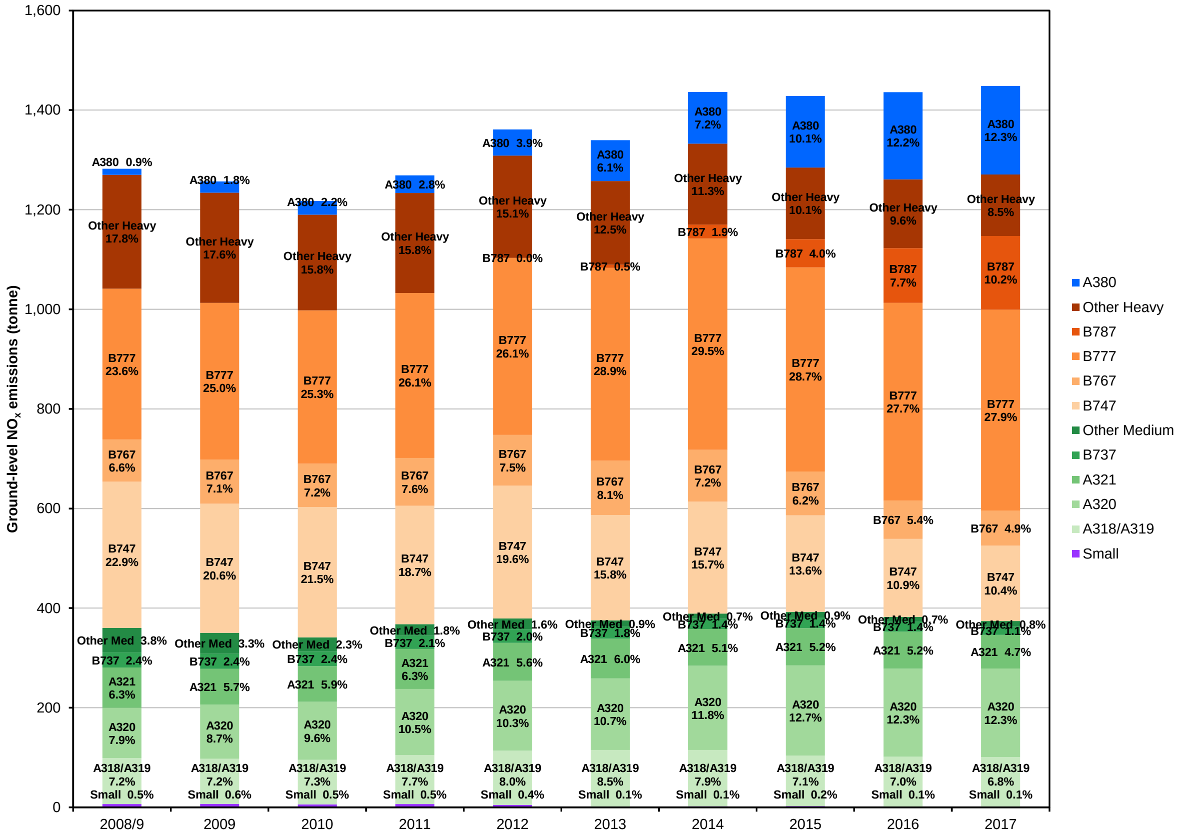
[1] Ground–level emissions from main engines only (omitting APU and engine testing)

Overall, the fleet-averaged value of ground-level aircraft NO_x emissions per movement, excluding APUs and engine testing, has risen by 0.7% between the 2016 inventory and the 2017 inventory, from 3.02 kg per movement in 2016 to 3.04 kg per movement in 2017.

Including APUs and engine testing, the increase from the 2016 inventory is 5.4%, from 3.57 kg per movement in 2016 to 3.76 kg per movement in 2017.

Figure 6 shows the trend in ground-level aircraft NO_x emissions broken down by aircraft type since 2008/9.

Figure 6 Breakdown of ground-level aircraft NO_x emissions[1] by aircraft type: 2008/9 to 2017



[1] Ground–level emissions from main engines only (omitting APU and engine testing)

4.1.1 Alternative operating times

Table 10 presents NO_x emissions for the 2017 aircraft movements calculated using the 'alternative' 2013 operating times (APU running, taxi and hold), comparing them with the emissions calculated for 2013 to 2016 (also calculated using the 'alternative' 2013 operating times, so the differences between the analyses are restricted to the numbers of movements, the frequency of use of terminals and runways and the fleet mix). This table is the 'alternative' equivalent of Table 7. Table 10 shows that calculated aircraft emissions for the whole LTO cycle (including elevated) were 0.4% higher in 2017 than in 2016 and ground-level aircraft emissions were 0.7% higher than in 2016.

For comparison using the specific year times, the whole LTO cycle emissions were 2.2% higher in 2017 than in 2016 and ground-level aircraft emissions were 5.7% higher than in 2016.

Table 10 Aircraft NO_x emissions using 'alternative' operating times: comparison of 2017 with 2013 to 2016 (all calculated using 2013 operating times)

Mode	Annual NO_x emissions (tonnes)					Change from (%)			
	2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Landing roll	41.04	43.91	44.42	45.71	46.85	14.2	6.7	5.5	2.5
Taxi-in	153.51	159.61	161.92	159.29	157.65	2.7	-1.2	-2.6	-1.0
Taxi-out	237.53	242.53	244.33	240.96	245.71	3.4	1.3	0.6	2.0
Hold	225.63	225.52	229.41	222.90	221.37	-1.9	-1.8	-3.5	-0.7
Take-off roll	681.80	741.75	726.78	729.50	735.52	7.9	-0.8	1.2	0.8
APU	182.05	187.00	211.63	221.43	223.88	23.0	19.7	5.8	1.1
Engine testing[1]	2.80	2.80	2.80	2.80	2.80	0.0	0.0	0.0	0.0
Total ground-level	**1524.36**	**1603.12**	**1621.29**	**1622.59**	**1633.78**	**7.2**	**1.9**	**0.8**	**0.7**
Total aircraft LTO[2]	**4285.76**	**4522.64**	**4497.43**	**4515.18**	**4532.39**	**5.8**	**0.2**	**0.8**	**0.4**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[2] Elevated emissions are unchanged from Table 7 .
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

4.1.2 Reduced-engine taxi

Table 11 presents NO_x emissions taking account of reduced-engine taxi. It compares emissions that account for reduced-engine taxiing on both departure and arrival with emissions calculated assuming conventional taxi. As can be seen, the reduction in main engine emissions achieved during taxi-out and taxi-in is largely offset by the associated increase in APU emissions.

Table 11 Breakdown of aircraft NO_x emissions by mode – 2017: comparison of reduced-engine taxi with conventional taxi

Mode	Annual NO_x emissions (tonnes)		Change (%)[a]
	Conventional	RET	
Landing roll	46.85	46.85	0.0
Taxi-in	163.02	134.28	-17.6
Taxi-out	257.45	247.97	-3.7
Hold	245.74	245.74	0.0
Take-off roll	735.52	735.52	0.0
APU	338.67	371.27	9.6
Engine testing[1]	2.80	2.80	0.0
Total ground-level	**1790.04**	**1784.43**	**-0.3**
Total aircraft LTO[2]	**4688.66**	**4683.04**	**-0.1**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[2] Elevated emissions are unchanged from Table 7 .
[a] Change % = 100 * (RET value – Conventional value) / (Conventional value)

4.2 PM_{10} and $PM_{2.5}$

Table 12 shows aircraft PM_{10} emissions broken down by mode (phase of the LTO cycle), using the same categories as in the 2008/9 inventory report and the subsequent annual updates. Table 13 shows the equivalent comparison for $PM_{2.5}$. The 2017 values have been compared with equivalent reported values for 2013 to 2016. The calculated total aircraft PM_{10} ($PM_{2.5}$) emissions (up to 1000 m) for 2017 are 0.2% (0.4%) lower than the equivalent value for 2016, for a 0.2% increase in the number of movements.

It should be noted that for aircraft exhaust emissions all the mass has been assumed to be associated with particles less than 2.5 µm in diameter (as it is widely understood that all particulate matter emitted by aircraft engines is smaller than this size), so PM_{10} and $PM_{2.5}$ exhaust emissions are the same. However, not all of the particulate matter generated by brake and tyre wear is associated with particles of less than 2.5 µm in diameter (see Reference i for details).

Table 12 Breakdown of aircraft PM_{10} emissions by mode: comparison of 2017 with 2013 to 2016

Mode	Annual PM_{10} emissions (tonnes)					Change from (%)			
	2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Ground-level									
Landing roll	0.55	0.53	0.53	0.54	0.54	-2.1	1.9	1.1	-1.0
Taxi-in	3.18	3.12	3.16	3.17	3.09	-2.9	-1.1	-2.1	-2.4
Taxi-out	4.90	4.75	4.93	4.87	4.87	-0.6	2.6	-1.3	0.0
Hold	4.62	4.47	4.46	4.75	4.66	0.7	4.1	4.3	-2.0
Take-off roll	3.34	3.07	2.99	2.99	2.92	-12.6	-5.1	-2.6	-2.5
Brake wear	9.25	9.45	9.58	9.74	9.82	6.2	3.9	2.5	0.9
Tyre wear	6.10	6.27	6.38	6.51	6.59	8.0	5.0	3.2	1.1
APU	3.52	3.47	3.15	4.33	4.72	34.0	36.0	49.7	8.9
Engine testing[1]	0.06	0.06	0.06	0.06	0.06	0.0	0.0	0.0	0.0
Total ground-level	**35.51**	**35.19**	**35.24**	**36.96**	**37.25**	**4.9**	**5.8**	**5.7**	**0.8**
Elevated									
Approach	5.69	5.50	5.50	5.50	5.39	-5.2	-2.0	-2.0	-1.9
Initial climb	3.27	3.01	2.95	2.95	2.84	-13.0	-5.5	-3.7	-3.8
Climb out	6.50	5.99	5.86	5.92	5.75	-11.6	-4.0	-1.9	-2.9
Total elevated	**15.46**	**14.50**	**14.32**	**14.38**	**13.98**	**-9.5**	**-3.5**	**-2.3**	**-2.7**
Total	**50.97**	**49.69**	**49.56**	**51.34**	**51.23**	**0.5**	**3.1**	**3.4**	**-0.2**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Table 13 Breakdown of aircraft $PM_{2.5}$ emissions by mode: comparison of 2017 with 2013 to 2016

Mode	Annual $PM_{2.5}$ emissions (tonnes)					Change from (%)			
	2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Ground-level									
Landing roll	0.55	0.53	0.53	0.54	0.54	-2.1	1.9	1.1	-1.0
Taxi-in	3.18	3.12	3.16	3.17	3.09	-2.9	-1.1	-2.1	-2.4
Taxi-out	4.90	4.75	4.93	4.87	4.87	-0.6	2.6	-1.3	0.0
Hold	4.62	4.47	4.46	4.75	4.66	0.7	4.1	4.3	-2.0
Take-off roll	3.34	3.07	2.99	2.99	2.92	-12.6	-5.1	-2.6	-2.5
Brake wear	3.68	3.76	3.81	3.88	3.91	6.2	3.9	2.5	0.9
Tyre wear	4.27	4.39	4.47	4.56	4.61	8.0	5.0	3.2	1.1
APU	3.52	3.47	3.15	4.33	4.72	34.0	36.0	49.7	8.9
Engine testing[1]	0.06	0.06	0.06	0.06	0.06	0.0	0.0	0.0	0.0
Total ground-level	**28.11**	**27.62**	**27.56**	**29.14**	**29.36**	**4.4**	**6.3**	**6.5**	**0.7**
Elevated									
Approach	5.69	5.50	5.50	5.50	5.39	-5.2	-2.0	-2.0	-1.9
Initial climb	3.27	3.01	2.95	2.95	2.84	-13.0	-5.5	-3.7	-3.8
Climb out	6.50	5.99	5.86	5.92	5.75	-11.6	-4.0	-1.9	-2.9
Total elevated	**15.46**	**14.50**	**14.32**	**14.38**	**13.98**	**-9.5**	**-3.5**	**-2.3**	**-2.7**
Total	**43.57**	**42.12**	**41.88**	**43.52**	**43.34**	**-0.5**	**2.9**	**3.5**	**-0.4**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Table 14 shows the values of annual aircraft LTO PM_{10} and $PM_{2.5}$ emissions normalised by the number of passengers and movements. The PM_{10} per passenger is 3.2% lower than in 2016 and the PM_{10} per movement is 0.4% lower than in 2016. The $PM_{2.5}$ per passenger is 3.4% lower than in 2016 and the $PM_{2.5}$ per movement is 0.6% lower than in 2016.

Table 14 LTO PM emissions per passenger and per movement: comparison of 2017 with 2013 to 2016

	2013	2014	2015	2016	2017	Change from (%)			
						2013[a]	2014[b]	2015[c]	2016[d]
LTO PM_{10} (tonnes per year)	50.97	49.69	49.56	51.34	51.23	0.5	3.1	3.4	-0.2
LTO $PM_{2.5}$ (tonnes per year)	43.57	42.12	41.88	43.52	43.34	-0.5	2.9	3.5	-0.4
Passengers[1] (mppa)	72.33	73.37	74.95	75.67	77.99	7.8	6.3	4.0	3.1
LTO PM_{10} (g per passenger[1])	0.70	0.68	0.66	0.68	0.66	-6.8	-3.0	-0.6	-3.2
LTO $PM_{2.5}$ (g per passenger[1])	0.60	0.57	0.56	0.58	0.56	-7.7	-3.2	-0.5	-3.4
Movements[2] (1000s)	471.94	472.80	474.09	474.96	475.78	0.8	0.6	0.4	0.2
LTO PM_{10} (kg per movement[2])	0.11	0.11	0.10	0.11	0.11	-0.3	2.5	3.0	-0.4
LTO $PM_{2.5}$ (kg per movement[2])	0.09	0.09	0.09	0.09	0.09	-1.3	2.3	3.1	-0.6

[1] Excludes transit passengers
[2] ATMs and non-ATMs
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

From a local air quality perspective, emissions from aircraft on the ground have a greater impact than elevated emissions. The calculated value of ground-level aircraft PM_{10} emissions (including brake and tyre wear, APU and engine testing emissions) for 2017 is 0.8% (0.7% for $PM_{2.5}$) higher than the equivalent value for 2016, for a 0.2% increase in the total number of movements.

For APUs, PM emissions were 8.9% higher than in 2016, reflecting the increases in APU running times, having accounted for the large variations in PM emission rates between different APU models.

For the main engine exhaust emissions, the difference from 2015 ranges from -2.5% (Take-off roll) to 0.0% (Taxi-out). PM exhaust emission factors are derived from Smoke Numbers given in the ICAO emissions databank. The maximum Smoke Number of an engine is subject to CAEP regulatory control although, unlike the situation for NO_x, the standard has not become more stringent over time. Modern jet engines usually have Smoke Numbers well below the CAEP limit, so there is no regulatory pressure for continuous improvement. As a result, there can be large non-systematic variations (albeit below the limit) from engine to engine, so the variation in total airport PM emissions over time is sensitive to the specific engines fitted to the principal aircraft types in the fleet.

It is known that the International Civil Aviation Organisation (ICAO) Committee on Aviation Environmental Protection (CAEP) is currently working to develop a new standard for non-volatile particulate matter (nvPM) emissions from aircraft engines, with agreement expected in 2019. This will bring the regulatory approach more in line with that of NO_x and may result in more regulatory pressure on PM emissions, either immediately or over time as more stringent subsequent standards are brought in. It will also lead to new data for nvPM mass emissions from engines (and particle numbers) becoming available and will result in new approaches for calculating PM emissions for airport inventories (replacing the current, smoke number-based, approaches).

For PM, non-exhaust emissions (aircraft brake and tyre wear) are a significant contributor to the ground-level aircraft emissions, together accounting for 44.0% of the ground-level PM_{10} emissions in 2017 (29.0% for $PM_{2.5}$). The increase in this combined contribution from 2016 to 2017 is 1.0% for both PM_{10} and $PM_{2.5}$.

Table 15 gives a breakdown of ground-level aircraft exhaust PM emissions (omitting brake and tyre wear, APUs and engine testing) by aircraft type, comparing the distribution in 2017 with the equivalent distribution in 2016. As expected from the movement breakdowns in Table 1, the A320 aircraft family (A318/A319, A320 and A321) account for a significant fraction of the emissions in both years (44.6% in 2017 and 45.3% in 2016). The larger aircraft types, B747, B777 and A380, together contribute over one third of the emissions in each year (36.8% in 2017 and 35.5% in 2016), despite accounting for less than a quarter of the total movements.

Table 15 also gives ground-level emissions per movement (excluding APU, engine testing and brake and tyre wear emissions) for each aircraft type, comparing values for 2017 with those for 2016. As explained in the NO_x discussion, this value may change over time even for a given aircraft type as a result of changes in sub-series and/or engine models in the fleet. Typically, the values for the larger aircraft types (B747, B777 and A380) are around a factor of 2 to 3 times those for the single-aisle jets.

Table 15 Breakdown of ground-level aircraft PM[1] emissions[2] by aircraft type

Aircraft Type	2016			2017		
	PM (t/year)	%	PM (g/mvt)	PM (t/year)	%	PM (g/mvt)
Small	0.06	0.4	22.9	0.02	0.1	5.2
Medium	7.78	47.7	26.9	7.52	46.8	26.4
A318/A319	2.51	15.4	30.9	2.46	15.3	30.2
A320	3.56	21.8	25.4	3.50	21.8	24.7
A321	1.32	8.1	30.6	1.22	7.6	31.7
B737	0.29	1.8	15.4	0.23	1.4	15.0
Others	0.10	0.6	15.9	0.12	0.7	14.0
Heavy	7.21	44.2	43.8	7.22	45.0	43.0
B747	1.58	9.7	76.2	1.63	10.1	79.1
B767	0.94	5.8	36.3	0.91	5.7	38.4
B777	2.95	18.1	48.2	2.99	18.6	48.8
B787	0.58	3.6	21.1	0.76	4.7	20.8
Other	1.16	7.1	40.0	0.93	5.8	35.8
A380	1.27	7.8	69.6	1.30	8.1	70.3
Total	16.32	100.0	34.4	16.07	100.0	33.8

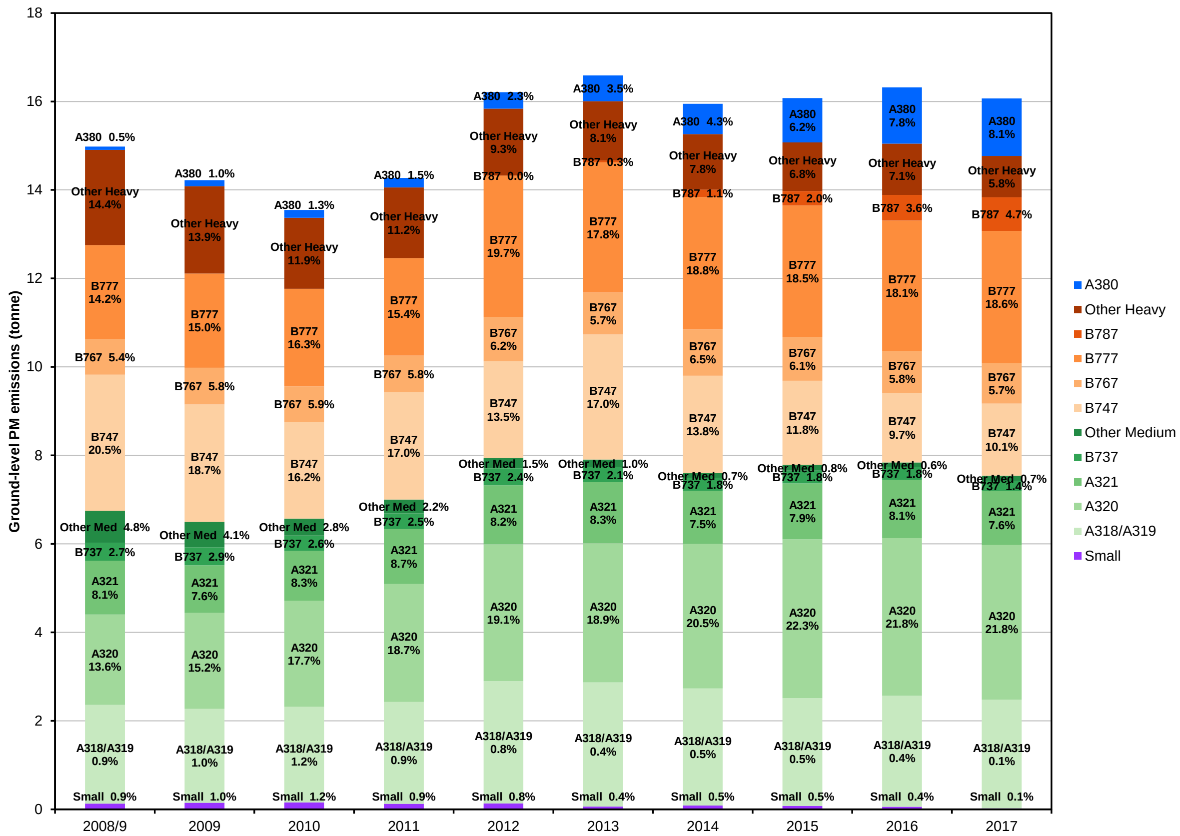
[1] For exhaust emissions, PM_{10} and $PM_{2.5}$ have been taken to be the same.
[2] Ground–level emissions from main engines only (omitting APU, engine testing, brake wear and tyre wear)

Overall, the fleet-averaged value of ground-level aircraft PM emissions per movement, excluding APUs, engine testing, brake wear and tyre wear, has fallen by 1.7% between the 2016 inventory and the 2017 inventory, from 34.4 grams per movement in 2016 to 33.8 grams per movement in 2017.

Including APUs, engine testing, brake wear and tyre wear, the decrease in ground-level aircraft PM_{10} emissions per movement from the 2016 inventory is 0.6% (0.6% for $PM_{2.5}$), from 77.8 grams of PM_{10} (61.4 grams of $PM_{2.5}$) per movement in 2016 to 78.3 grams of PM_{10} (61.7 grams of $PM_{2.5}$) per movement in 2017.

Figure 7 shows the trend in ground-level aircraft PM emissions broken down by aircraft type since 2008/9.

Figure 7 Breakdown of ground-level aircraft PM[1] emissions[2] by aircraft type: 2008/9 to 2017



[1] For exhaust emissions, PM_{10} and $PM_{2.5}$ have been taken to be the same.
[2] Ground–level emissions from main engines only (omitting APU, engine testing, brake wear and tyre wear)

4.2.1 Alternative operating times

Table 16 and Table 17 present PM_{10} and $PM_{2.5}$ emissions, respectively, for the 2017 aircraft movements calculated using the 'alternative' 2013 operating times, comparing them with the emissions calculated for 2013 to 2016 (also calculated using the 'alternative' 2013 operating times). These tables are the 'alternative' equivalents of Table 12 and Table 13. Table 16 and Table 17 show that calculated aircraft emissions of PM_{10} ($PM_{2.5}$) for the whole LTO cycle were 1.1% (1.5%) lower in 2017 than in 2016 and ground-level aircraft emissions were 0.4% (0.8%) lower than in 2016.

For comparison using the specific year times, the whole LTO cycle emissions were 0.2% (0.4%) lower in 2017 than in 2016 and ground-level aircraft emissions were 0.8% (0.7%) higher than in 2016.

Table 16 Aircraft PM_{10} emissions using 'alternative' operating times: comparison of 2017 with 2013 to 2016 (all calculated using 2013 operating times)

Mode	Annual PM_{10} emissions (tonnes)					Change from (%)			
	2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Landing roll	0.55	0.53	0.53	0.54	0.54	-2.1	1.9	1.1	-1.0
Taxi-in	3.18	3.10	3.17	3.16	3.05	-4.2	-1.6	-3.9	-3.4
Taxi-out	4.90	4.64	4.71	4.70	4.70	-4.0	1.4	-0.2	0.1
Hold	4.62	4.32	4.42	4.35	4.22	-8.8	-2.3	-4.7	-3.0
Take-off roll	3.34	3.07	2.99	2.99	2.92	-12.6	-5.1	-2.6	-2.5
Brake wear	9.25	9.45	9.58	9.74	9.82	6.2	3.9	2.5	0.9
Tyre wear	6.10	6.27	6.38	6.51	6.59	8.0	5.0	3.2	1.1
APU	3.52	3.49	3.47	3.46	3.47	-1.4	-0.5	-0.1	0.2
Engine testing[1]	0.06	0.06	0.06	0.06	0.06	0.0	0.0	0.0	0.0
Total ground-level	**35.51**	**34.92**	**35.32**	**35.51**	**35.35**	**-0.4**	**1.2**	**0.1**	**-0.4**
Total aircraft LTO[2]	**50.97**	**49.42**	**49.64**	**49.88**	**49.34**	**-3.2**	**-0.2**	**-0.6**	**-1.1**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[2] Elevated emissions are unchanged from Table 12.
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Table 17 Aircraft $PM_{2.5}$ emissions using 'alternative' operating times: comparison of 2017 with 2013 to 2016 (all calculated using 2013 operating times)

Mode	Annual $PM_{2.5}$ emissions (tonnes)					Change from (%)			
	2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Landing roll	0.55	0.53	0.53	0.54	0.54	-2.1	1.9	1.1	-1.0
Taxi-in	3.18	3.10	3.17	3.16	3.05	-4.2	-1.6	-3.9	-3.4
Taxi-out	4.90	4.64	4.71	4.70	4.70	-4.0	1.4	-0.2	0.1
Hold	4.62	4.32	4.42	4.35	4.22	-8.8	-2.3	-4.7	-3.0
Take-off roll	3.34	3.07	2.99	2.99	2.92	-12.6	-5.1	-2.6	-2.5
Brake wear	3.68	3.76	3.81	3.88	3.91	6.2	3.9	2.5	0.9
Tyre wear	4.27	4.39	4.47	4.56	4.61	8.0	5.0	3.2	1.1
APU	3.52	3.49	3.47	3.46	3.47	-1.4	-0.5	-0.1	0.2
Engine testing[1]	0.06	0.06	0.06	0.06	0.06	0.0	0.0	0.0	0.0
Total ground-level	**28.11**	**27.35**	**27.64**	**27.69**	**27.46**	**-2.3**	**0.4**	**-0.6**	**-0.8**
Total aircraft LTO[2]	**43.57**	**41.84**	**41.95**	**42.07**	**41.45**	**-4.9**	**-0.9**	**-1.2**	**-1.5**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[2] Elevated emissions are unchanged from Table 13.
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

4.2.2 Reduced-engine taxi

Table 18 and Table 19 present PM_{10} and $PM_{2.5}$ emissions, respectively, taking account of reduced-engine taxi. They compare emissions that account for reduced-engine taxi on both departure and arrival with emissions calculated assuming conventional taxi.

Table 18 Breakdown of aircraft PM_{10} emissions by mode - 2017: comparison of reduced-engine taxi with conventional taxi

Mode	Annual PM_{10} emissions (tonnes)		Change (%)[a]
	Conventional	RET	
Landing roll	0.54	0.54	0.0
Taxi-in	3.09	2.51	-18.9
Taxi-out	4.87	4.59	-5.7
Hold	4.66	4.66	0.0
Take-off roll	2.92	2.92	0.0
Brake wear	9.82	9.82	0.0
Tyre wear	6.59	6.59	0.0
APU	4.72	5.26	11.6
Engine testing[1]	0.06	0.06	0.0
Total ground-level	**37.25**	**36.93**	**-0.8**
Total aircraft LTO[2]	**51.23**	**50.92**	**-0.6**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[2] Elevated emissions are unchanged from Table 12.
[a] Change % = 100 * (RET value – Conventional value) / (Conventional value)

Table 19 Breakdown of aircraft $PM_{2.5}$ emissions by mode - 2017: comparison of reduced-engine taxi with conventional taxi

Mode	Annual $PM_{2.5}$ emissions (tonnes)		Change (%)[a]
	Conventional	RET	
Landing roll	0.54	0.54	0.0
Taxi-in	3.09	2.51	-18.9
Taxi-out	4.87	4.59	-5.7
Hold	4.66	4.66	0.0
Take-off roll	2.92	2.92	0.0
Brake wear	3.91	3.91	0.0
Tyre wear	4.61	4.61	0.0
APU	4.72	5.26	11.6
Engine testing[1]	0.06	0.06	0.0
Total ground-level	**29.36**	**29.04**	**-1.1**
Total aircraft LTO[2]	**43.34**	**43.03**	**-0.7**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[2] Elevated emissions are unchanged from Table 13.
[a] Change % = 100 * (RET value – Conventional value) / (Conventional value)

4.3 CO_2

In contrast to NO_x and PM, the emissions index (quantity of emission per kg of fuel burnt) for CO_2 is not a function of the engine type, but is a constant[4] (3.15 kg/kg). Therefore, the CO_2 emissions are calculated simply by multiplying the calculated fuel burn by that emissions index. Table 20 shows aircraft emissions of CO_2 broken down by mode (i.e. phase of the LTO cycle), using the same categories as in the 2008/9 inventory report and the subsequent annual updates. The 2017 values have been compared with equivalent values for 2013 to 2016. The calculated total aircraft CO_2

[4] Strictly, the emissions index for CO2 is a function of the chemistry of the fuel; it is slightly different for other fuels such as gasoline or diesel.

emission (up to 1000m) for 2017 is 2.0% higher than the equivalent value for the 2016, for a 3.1% increase in the number of passengers.

APU emissions were 27.6% higher than in 2016, reflecting the increases in APU running times, having accounted for the large variations in fuel consumption rates between different APU models.

Table 20 Breakdown of aircraft CO_2 emissions by mode: comparison of 2017 with 2013 to 2016

Mode	Annual CO_2 emissions (kilotonnes)					Change from (%)			
	2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Ground-level									
Landing roll	19.77	20.07	20.25	20.78	20.80	5.2	3.6	2.7	0.1
Taxi-in	105.45	108.87	109.48	110.26	109.81	4.1	0.9	0.3	-0.4
Taxi-out	161.15	165.34	171.25	169.39	171.18	6.2	3.5	0.0	1.1
Hold	152.63	154.55	154.46	164.99	163.39	7.0	5.7	5.8	-1.0
Take-off roll	92.26	92.09	91.89	92.43	92.63	0.4	0.6	0.8	0.2
APU	63.98	64.41	64.14	84.36	107.61	68.2	67.1	67.8	27.6
Engine testing[1]	1.21	1.21	1.21	1.21	1.21	0.0	0.0	0.0	0.0
Total ground-level	**596.46**	**606.53**	**612.69**	**643.42**	**666.62**	**11.8**	**9.9**	**8.8**	**3.6**
Elevated									
Approach	184.96	184.59	184.47	185.19	185.14	0.1	0.3	0.4	0.0
Initial climb	89.27	88.63	88.72	89.35	88.71	-0.6	0.1	0.0	-0.7
Climb out	177.13	174.27	174.13	177.84	176.86	-0.1	1.5	1.6	-0.5
Total elevated	**451.36**	**447.49**	**447.32**	**452.38**	**450.71**	**-0.1**	**0.7**	**0.8**	**-0.4**
Total	**1047.82**	**1054.02**	**1060.01**	**1095.80**	**1117.34**	**6.6**	**6.0**	**5.4**	**2.0**

[1] Engine testing emissions were not recalculated for 2016. However, they represent a small fraction of the total.
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Table 21 shows the values of annual aircraft LTO CO_2 emissions normalised by the number of passengers and movements. The CO_2 per passenger has fallen by 1.1% since 2016 whereas the CO_2 per movement is 1.8% higher than in 2016.

Table 21 LTO CO_2 emissions per passenger and per movement: comparison of 2017 with 2013 to 2016

	2013	2014	2015	2016	2017	Change from (%)			
						2013[a]	2014[b]	2015[c]	2016[d]
LTO CO_2 (kilotonnes per year)	1047.82	1054.02	1060.01	1095.80	1117.34	6.6	6.0	5.4	2.0
Passengers[1] (mppa)	72.33	73.37	74.95	75.67	77.99	7.8	6.3	4.0	3.1
LTO CO_2 (kg per passenger[1])	14.49	14.37	14.14	14.48	14.33	-1.1	-0.3	1.3	-1.1
Movements[2] (1000s)	471.94	472.80	474.09	474.96	475.78	0.8	0.6	0.4	0.2
LTO CO_2 (tonnes per movement[2])	2.22	2.23	2.24	2.31	2.35	5.8	5.3	5.0	1.8

[1] Excludes transit passengers
[2] ATMs and non-ATMs
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Table 22 gives a breakdown of LTO aircraft CO_2 emissions (omitting APUs and engine testing) by aircraft type, comparing the distribution in 2017 with the equivalent distributions in 2016. As expected from the movement breakdowns in Table 1, the A320 aircraft family (A318/A319, A320 and A321) account for a significant fraction of the emissions in both years (30.0% in 2017 and 30.7% in 2016). However, the larger aircraft types, B747, B777 and A380, together contribute almost half of the emissions in each period (44.8% in 2017 and 44.5% in 2016), despite accounting for less than a quarter of the total movements.

Table 22 also gives LTO emissions per movement (excluding APU and engine testing emissions) for each aircraft type. Emissions of CO_2 have global impacts on climate change, rather than the more local effects of pollutants such as NO_x and PM. Therefore, the values are presented for the complete movement (up to 1,000 m altitude) rather than just the ground-level emissions as presented for the other pollutants. The table shows that the values of LTO emissions per movement for the large aircraft types (B747 and B777) are around a factor of four higher than the average for A318/A319/320/321 or B737 aircraft. Of course, the large types carry more passengers than the A320/B737 families, but only around twice as many passengers, so the CO_2 /passenger ratio is roughly double that of the A320/B737 families.

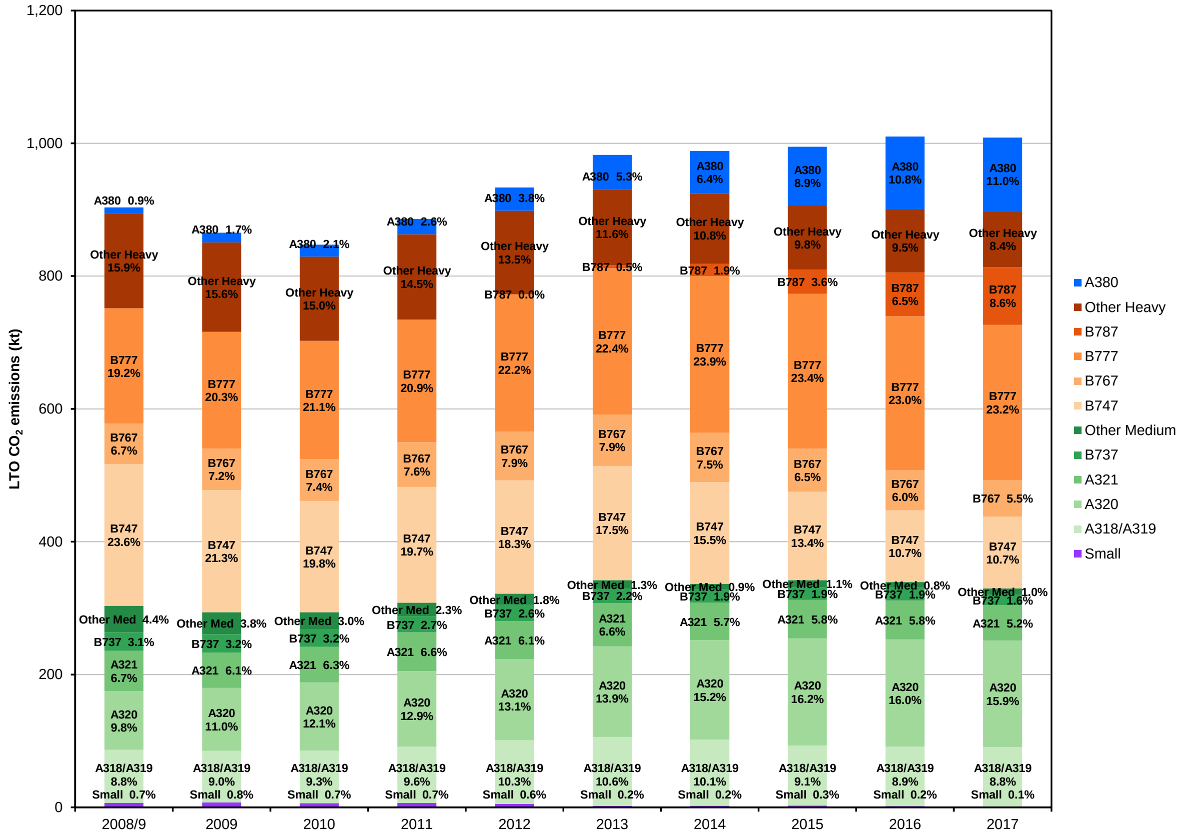
Table 22 Breakdown of LTO aircraft CO_2 emissions[1] by aircraft type

Aircraft Type	2016			2017		
	CO_2 (kt/year)	%	CO_2 (t/mvt)	CO_2 (kt/year)	%	CO_2 (t/mvt)
Small	1.78	0.2	0.71	1.41	0.1	0.33
Medium	337.34	33.4	1.16	328.14	32.5	1.15
A318/A319	89.72	8.9	1.10	89.10	8.8	1.09
A320	161.42	16.0	1.15	160.79	15.9	1.14
A321	58.72	5.8	1.36	52.90	5.2	1.37
B737	19.15	1.9	1.02	15.64	1.6	1.03
Others	8.33	0.8	1.28	9.70	1.0	1.13
Heavy	561.89	55.6	3.42	568.51	56.4	3.38
B747	108.26	10.7	5.24	108.07	10.7	5.26
B767	60.26	6.0	2.32	55.46	5.5	2.34
B777	231.96	23.0	3.79	233.50	23.2	3.81
B787	65.87	6.5	2.39	86.95	8.6	2.38
Other	95.54	9.5	3.30	84.53	8.4	3.24
A380	109.22	10.8	5.98	110.46	11.0	5.98
Total	1010.23	100.0	2.13	1008.52	100.0	2.12

[1] LTO emissions from main engines only (omitting APU and engine testing).

Figure 8 shows the trend in LTO aircraft CO_2 emissions broken down by aircraft type since 2008/9.

Figure 8 Breakdown of LTO aircraft CO_2 emissions[1] by aircraft type: 2008/9 to 2017



[1] LTO emissions from main engines only (omitting APU and engine testing)

4.3.1 Alternative operating times

Table 23 presents CO_2 emissions for the 2017 aircraft movements calculated using the 'alternative' 2013 operating times, comparing them with the emissions calculated for 2013 to 2016 (also calculated using the 'alternative' 2013 operating times). This table is the 'alternative' equivalent of Table 20. Table 23 shows that calculated aircraft emissions for the whole LTO cycle (including elevated) in 2016 were 0.4% lower than in 2016.

For comparison using the specific year times, the whole LTO cycle emissions were 2.0% higher in 2017 than in 2016.

Table 23 Aircraft CO_2 emissions using 'alternative' operating times: comparison of 2017 with 2013 to 2016 (all calculated using 2013 operating times)

Mode	Annual CO_2 emissions (kilotonnes)					Change from (%)			
	2013	2014	2015	2016	2017	2013[a]	2014[b]	2015[c]	2016[d]
Landing roll	19.77	20.07	20.25	20.78	20.80	5.2	3.6	2.7	0.1
Taxi-in	105.45	106.43	108.79	108.64	106.33	0.8	-0.1	-2.3	-2.1
Taxi-out	161.15	159.90	162.20	162.27	163.79	1.6	2.4	1.0	0.9
Hold	152.63	148.67	152.28	150.27	147.73	-3.2	-0.6	-3.0	-1.7
Take-off roll	92.26	92.09	91.89	92.43	92.63	0.4	0.6	0.8	0.2
APU	63.98	65.20	71.44	73.29	74.10	15.8	13.7	3.7	1.1
Engine testing[1]	1.21	1.21	1.21	1.21	1.21	0.0	0.0	0.0	0.0
Total ground-level	**596.46**	**593.55**	**608.07**	**608.90**	**606.59**	**1.7**	**2.2**	**-0.2**	**-0.4**
Total aircraft LTO[2]	**1047.82**	**1041.05**	**1055.38**	**1061.27**	**1057.31**	**0.9**	**1.6**	**0.2**	**-0.4**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[2] Elevated emissions are unchanged from Table 20.
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

4.3.2 Reduced-engine taxi

Table 24 presents CO_2 emissions taking account of reduced-engine taxi. It compares emissions that account for reduced-engine taxi on both departure and arrival with emissions calculated assuming conventional taxi.

Table 24 Breakdown of aircraft CO_2 emissions by mode - 2017: comparison of reduced-engine taxi with conventional taxi

Mode	Annual CO_2 emissions (kilotonnes)		Change (%)[a]
	Conventional	RET	
Landing roll	20.80	20.80	0.0
Taxi-in	109.81	90.50	-17.6
Taxi-out	171.18	164.81	-3.7
Hold	163.39	163.39	0.0
Take-off roll	92.63	92.63	0.0
APU	107.61	117.58	9.3
Engine testing[1]	1.21	1.21	0.0
Total ground-level	**666.62**	**650.92**	**-2.4**
Total aircraft LTO[2]	**1117.34**	**1101.63**	**-1.4**

[1] Engine testing emissions were not recalculated for 2017. However, they represent a small fraction of the total.
[2] Elevated emissions are unchanged from Table 20.
[a] Change % = 100 * (RET value – Conventional value) / (Conventional value)

5 Summary and conclusions

The total annual emissions of NO_x, PM_{10}, $PM_{2.5}$ and CO_2 from aircraft movements at Heathrow have been calculated for the 2017 calendar year, based on detailed flight records held by Heathrow Airport. This updates the aircraft component of the published 2013, 2014, 2015 and 2016 Heathrow Airport emissions inventories. With the exception of APU running times and taxi and hold times, the update makes the assumption that the set of aircraft operational parameters (such as the time that aircraft spend in various operational phases of the LTO cycle) derived for the 2008/9 and 2013 inventories were also applicable in 2017.

Table 25 shows some summary information about total emissions from the LTO (including APUs, engine testing and brake and tyre wear), while Table 26 presents the same information for ground-level emissions only. Figure 9 to Figure 12 show some trends over the years from 2008/9 to 2017. Note that in these graphs, the vertical scales are chosen to exaggerate the trends, which are typically of the order of one percent per year.

The number of movements in 2017 was 0.2% higher than in 2016, whereas the number of passengers was 3.1% higher than in 2016. There is no discernible trend in the number of movements over the last ten years (refer to Figure 1). This is because there is little room for growth as the airport is already operating close to the cap of 480,000 ATMs. Instead much of the year-to-year variation can be explained by external events such as the weather or (in 2010) the Eyjafjallajökull eruption. Despite this, the number of passengers shows an increase over the period, averaging 1.4% per year (2.2% per year over the last 5 years), and the number of passengers per movement is increasing steadily (refer to Figure 2).

The calculated value of total aircraft NO_x emissions in the Landing and Take-Off (LTO) cycle (up to 1000 m height) is 2.2% higher for 2017 than for 2016. For PM_{10} ($PM_{2.5}$), the 2016 value for total LTO emissions is 0.2% (0.4%) lower than for 2016. The calculated value of ground-level aircraft NO_x emissions (which are more important than elevated emissions from the perspective of local air quality) is 5.7% higher for 2017 than for 2016. The calculated value of ground-level aircraft PM_{10} ($PM_{2.5}$) the emissions is 0.8% (0.7%) higher than for 2016. Ground-level emissions since 2008/9 are plotted in Figure 9.

The main reason for these increases is changes in APU running times. In the case of NO_x, meteorological effects also influence the increases.

Figure 10 shows the ground-level NO_x emissions per movement and per passenger. The calculated values of NO_x emissions per movement in 2016 and 2017 stand clearly above the long term trend, which had been relatively constant. Prior to 2014 NO_x emissions per passenger had been falling. However, they have now been rising since 2015 and in 2017 they reverted to levels last seen in 2012.

Figure 11 and Figure 12 show the ground-level emissions per movement and per passenger, for PM_{10} and $PM_{2.5,}$ respectively. As for NOx, emissions per movement in 2016 and 2017 stand clearly above the long term trend. Prior to 2016 emissions per passenger had been falling. However, they showed a localised peak in 2016 before falling again in 2017.

Table 25 Summary of total LTO emissions

	2013	2014	2015	2016	2017	Change from (%)			
						2013[a]	2014[b]	2015[c]	2016[d]
NO_x (t/year)	4285.76	4543.80	4497.28	4586.80	4688.66	9.4	3.2	4.3	2.2
NO_x (g/pax[1])	59.25	61.93	60.00	60.61	60.12	1.5	-2.9	0.2	-0.8
NO_x (kg/mvt[2])	9.08	9.61	9.49	9.66	9.85	8.5	2.5	3.9	2.0
PM_{10} (t/year)	50.97	49.69	49.56	51.34	51.23	0.5	3.1	3.4	-0.2
PM_{10} (g/pax[1])	0.70	0.68	0.66	0.68	0.66	-6.8	-3.0	-0.6	-3.2
PM_{10} (kg/mvt[2])	0.11	0.11	0.10	0.11	0.11	-0.3	2.5	3.0	-0.4
$PM_{2.5}$ (t/year)	43.57	42.12	41.88	43.52	43.34	-0.5	2.9	3.5	-0.4
$PM_{2.5}$ (g/pax[1])	0.60	0.57	0.56	0.58	0.56	-7.7	-3.2	-0.5	-3.4
$PM_{2.5}$ (kg/mvt[2])	0.09	0.09	0.09	0.09	0.09	-1.3	2.3	3.1	-0.6
CO_2 (kt/year)	1047.82	1054.02	1060.01	1095.80	1117.34	6.6	6.0	5.4	2.0
CO_2 (kg/pax[1])	14.49	14.37	14.14	14.48	14.33	-1.1	-0.3	1.3	-1.1
CO_2 (t/mvt[2])	2.22	2.23	2.24	2.31	2.35	5.8	5.3	5.0	1.8

[1] Excludes transit passengers
[2] ATMs and non-ATMs
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Table 26 Summary of ground-level emissions

	2013	2014	2015	2016	2017	Change from (%)			
						2013[a]	2014[b]	2015[c]	2016[d]
NO_x (t/year)	1524.36	1624.28	1621.14	1694.21	1790.04	17.4	10.2	10.4	5.7
NO_x (g/pax[1])	21.07	22.14	21.63	22.39	22.95	8.9	3.7	6.1	2.5
NO_x (kg/mvt[2])	3.23	3.44	3.42	3.57	3.76	16.5	9.5	10.0	5.5
PM_{10} (t/year)	35.51	35.19	35.24	36.96	37.25	4.9	5.8	5.7	0.8
PM_{10} (g/pax[1])	0.49	0.48	0.47	0.49	0.48	-2.7	-0.4	1.6	-2.2
PM_{10} (kg/mvt[2])	0.08	0.07	0.07	0.08	0.08	4.1	5.2	5.3	0.6
$PM_{2.5}$ (t/year)	28.11	27.62	27.56	29.14	29.36	4.4	6.3	6.5	0.7
$PM_{2.5}$ (g/pax[1])	0.39	0.38	0.37	0.39	0.38	-3.1	0.0	2.4	-2.2
$PM_{2.5}$ (kg/mvt[2])	0.06	0.06	0.06	0.06	0.06	3.6	5.6	6.1	0.6

[1] Excludes transit passengers
[2] ATMs and non-ATMs
[a] Change % = 100 * (2017 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2017 value – 2014 value) / (2014 value)
[c] Change % = 100 * (2017 value – 2015 value) / (2015 value)
[d] Change % = 100 * (2017 value – 2016 value) / (2016 value)

Figure 9 Ground-level emissions of NO_x, PM_{10} and $PM_{2.5}$

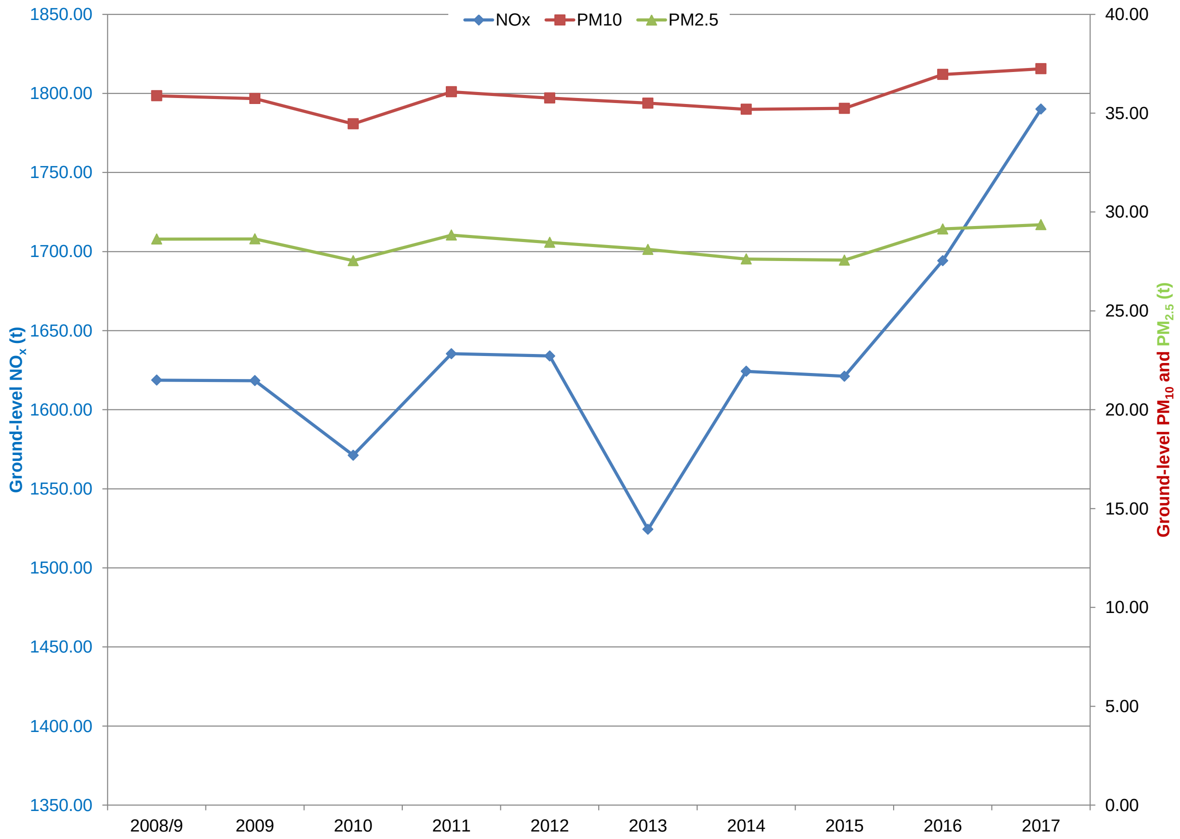


Figure 10 Ground-level NO_x emissions per movement and per passenger

Figure 11 Ground-level PM_{10} emissions per movement and per passenger

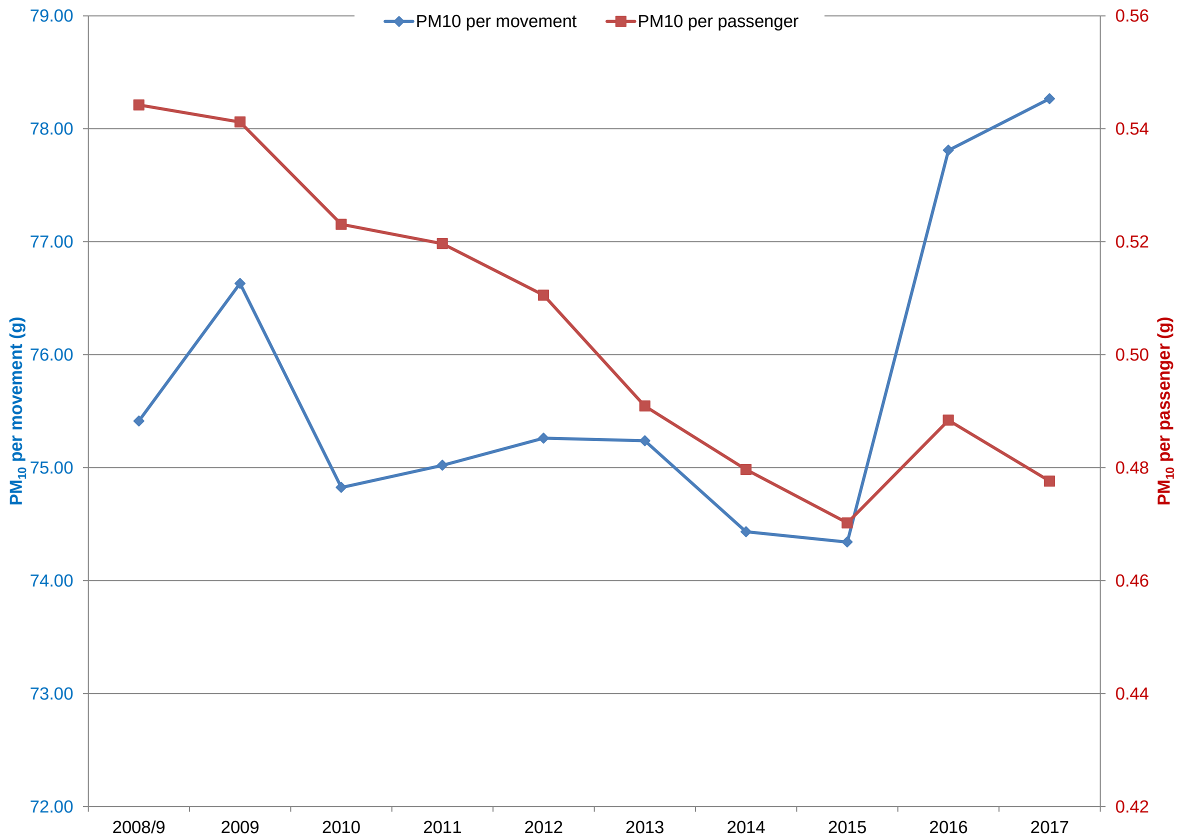
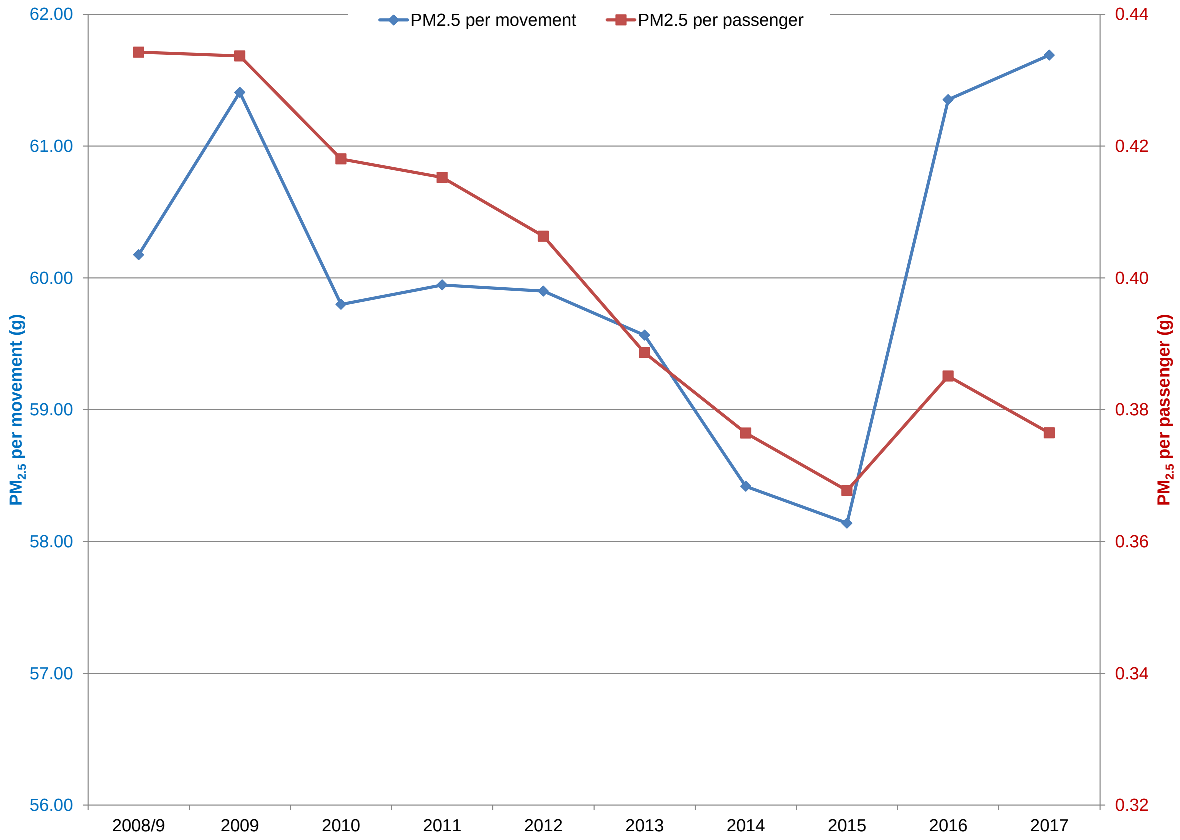


Figure 12 Ground-level $PM_{2.5}$ emissions per movement and per passenger



5.1 Reduced-engine taxi

Reduced-engine taxing at current levels (18% of departures and an estimated 78% of arrivals) offers only modest savings over conventional taxiing. Savings from reduced-engine taxiing in 2017 were almost completely offset by increased emissions from APUs. The net effect is that with reduced-engine taxi ground-level NO_x, PM_{10} and $PM_{2.5}$ are 0.3%, 0.8% and 1.1% lower than with conventional taxi, respectively.

We recommend that Heathrow should continue to record the use of reduced-engine taxiing for departures and implement a new system to record use on arrivals. They should also consider recording the duration of reduced-engine taxiing and off-stand APU use.

Emissions from APUs and aircraft main engines (during taxiing) have different dispersion characteristics, so any air quality modelling should take account of reduced-engine taxiing.

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