Heathrow Airport 2015 Emission Inventory

Report for Heathrow Airport Limited

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Glossary

APU	Auxiliary Power Unit
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 2015, 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]. A subsequent annual update for the calendar year 2014[vi] has 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, whereas operational parameters (e.g. taxiing time by aircraft type) are updated on a longer timescale. This concept is applied here to generate the 2015 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 2015. 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 2015, and 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 be derived from records of radar-based track data (i.e. from the noise and track-keeping (NTK) data).

The details of the methodology for quantifying aircraft emissions have been given in the report quoted earlier[i], and are not discussed further in this report.

1.2 Reduced-engine taxi

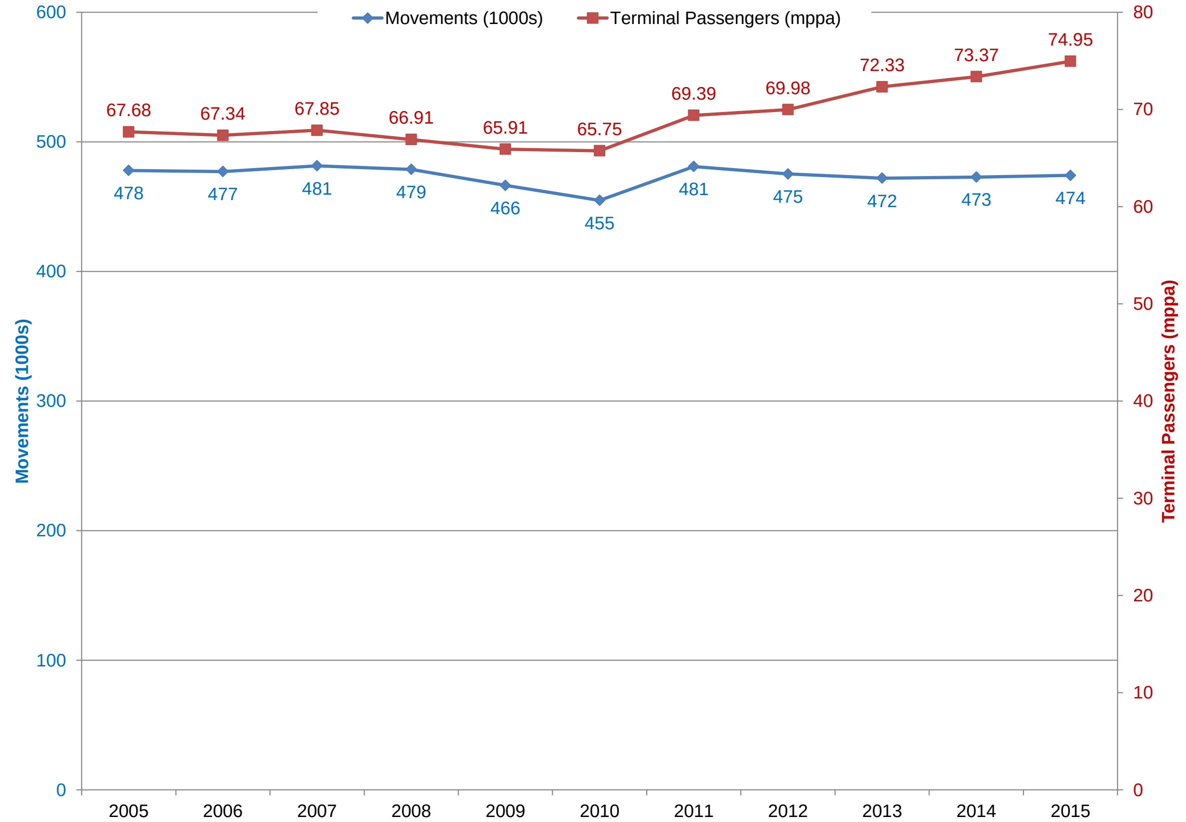
Heathrow have started to record the use of reduced-engine taxiing. However, they do not record the duration of its use nor the associated APU use off-stand. Although not included in the main inventory, alternative results are presented that take account of reduced-engine taxiing, albeit making assumptions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

2 Input data

2.1 Movements and passenger numbers

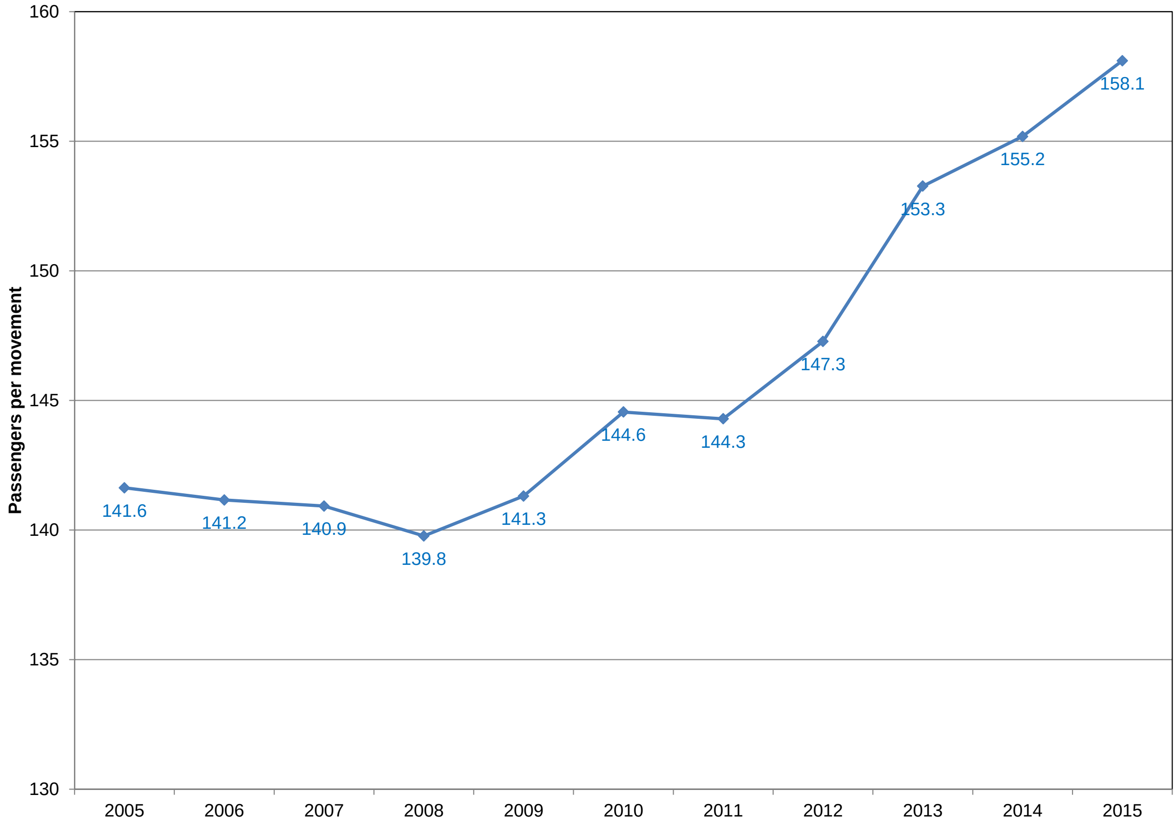
Figure 1 shows the trend in the number of aircraft movements and passengers over the last ten years. The number of aircraft movements has remained broadly constant, reflecting the fact that the airport is operating close to maximum capacity. The number of passengers has however risen steadily over the 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 2015 were provided by Heathrow Airport as an extract from their BOSS (Business Objective Search System) database. For each aircraft movement in the 2015 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 and 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 2009 annual update report[vii] 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 and 2014. The total number of movements has increased slightly from 471,938 in 2013 to 472,817 in 2014 and 474,094 in 2015. Over the same period, passenger numbers increased from 72.33 mppa in 2013 to 73.37 mppa in 2014 and 74.95 mppa in 2015.

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

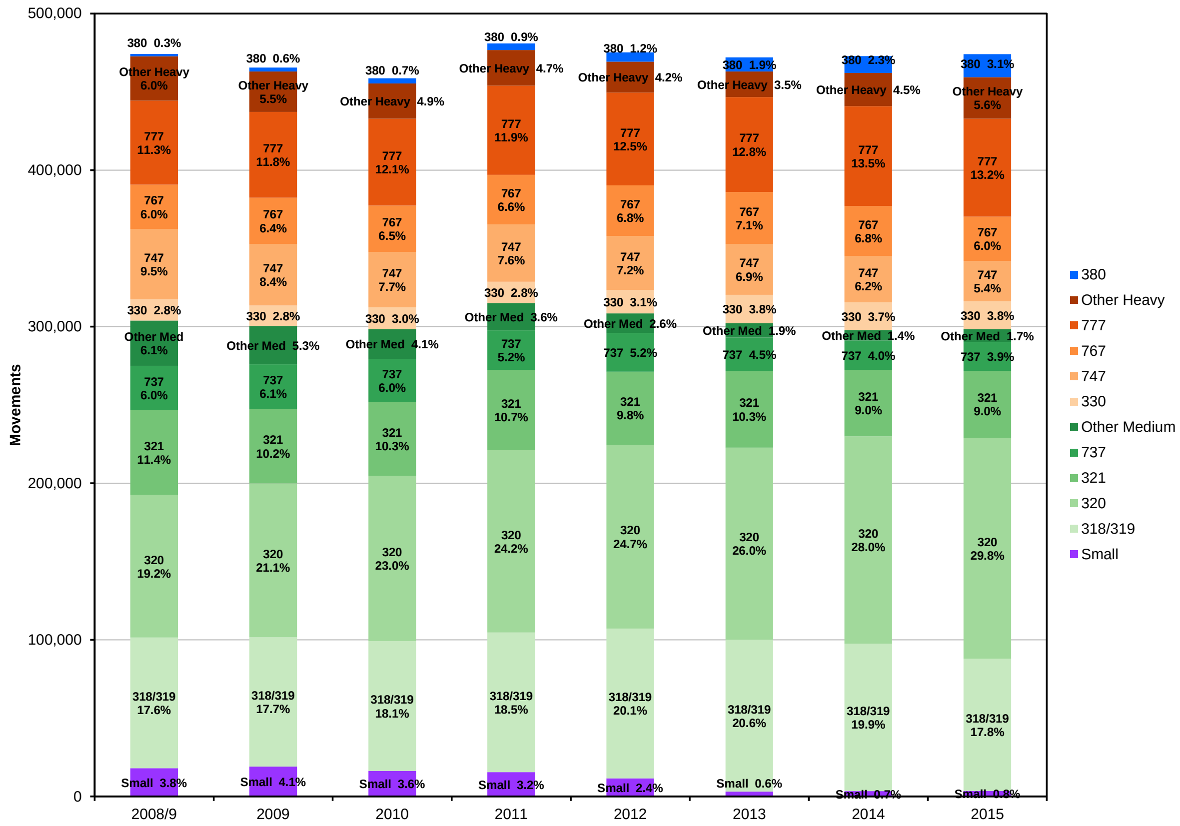
There have been some significant changes in the fleet mix from 2014 to 2015. The A320 increased its share from 28.0% of the movements (132,490) in 2014 to 29.8% of the movements (141,169) in 2015. This seems to have been partially at the expense of the A318/319, whose share has reduced from 19.9% (94,057 movements) in 2014 to 17.8% (84,352 movements) in 2015. The “Other Heavy” group, which includes the Boeing 787, has also seen a significant increase in its share from 4.5% (21,192 movements) in 2014 to 5.6% (26,404 movements) in 2015.

Table 1 Aircraft movements[1] by aircraft type: comparison of 2015 with 2013 and 2014

Aircraft Type	2013	2014	2015	Change		Change (%)	
				2013[a]	2014[b]	2013[c]	2014[d]
Small	3,050	3,415	3,562	512	147	16.8	4.3
Medium	299,207	294,428	294,837	-4,370	409	-1.5	0.1
A318/319	97,108	94,057	84,352	-12,756	-9,705	-13.1	-10.3
A320	122,638	132,490	141,169	18,531	8,679	15.1	6.6
A321	48,837	42,324	42,765	-6,072	441	-12.4	1.0
B737	21,459	18,898	18,376	-3,083	-522	-14.4	-2.8
Others	9,165	6,659	8,175	-990	1,516	-10.8	22.8
Heavy	160,750	164,161	160,869	119	-3,292	0.1	-2.0
A330	18,106	17,695	17,850	-256	155	-1.4	0.9
B747	32,378	29,510	25,662	-6,716	-3,848	-20.7	-13.0
B767	33,322	31,990	28,342	-4,980	-3,648	-14.9	-11.4
B777	60,542	63,774	62,611	2,069	-1,163	3.4	-1.8
Other	16,402	21,192	26,404	10,002	5,212	61.0	24.6
A380	8,931	10,813	14,826	5,895	4,013	66.0	37.1
Total	471,938	472,817	474,094	2,156	1,277	0.5	0.3

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

Figure 3 Number of movements[1] by aircraft type: 2008/9 to 2015



[1] ATMs and non-ATMs

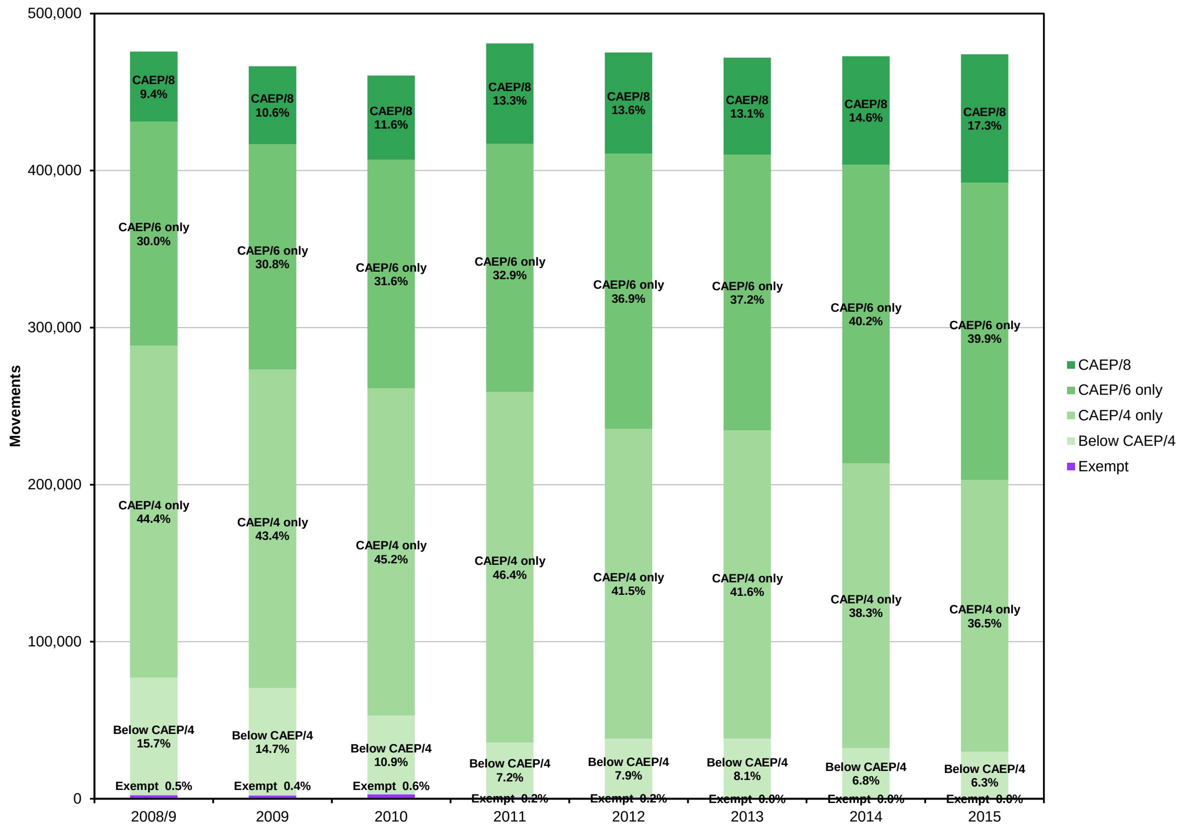
2.3 Engine assignment

Aircraft engine assignments have been taken directly from the airlines via Heathrow's AWUR 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 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, in line with Heathrow's AWUR database, from those reported in the 2013 study[iv].

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.

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 fail to 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 aircraft since 01 January 2013 must comply with the CAEP/6 standard, while all new aircraft types since 01 January 2014 must comply with the CAEP/8 standard.)

2.4 APU running times

The APU running times for this 2015 emission inventory update are derived from new observations of running times made during 2015. The new APU data were supplied by Heathrow Airport in the same form as that provided for the 2013 and 2014 inventories. These data have been analysed using the same methodology as used in the 2013 and 2014 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 then they will 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 2013, 2014 and 2015. For narrow-bodied aircraft, the new data suggest total running times that are about 2.7% higher than the 2013 data, but 0.7% lower than the 2014 data. For wide-bodied aircraft, excluding the A380, the new data suggest total running times that are about 20.9% lower than the 2013 data and 16.9% lower than the 2014 data. The new data suggest total running times for the A380 that are about 5.7% higher than the 2013 data, but 9.8% lower than the 2014 data.

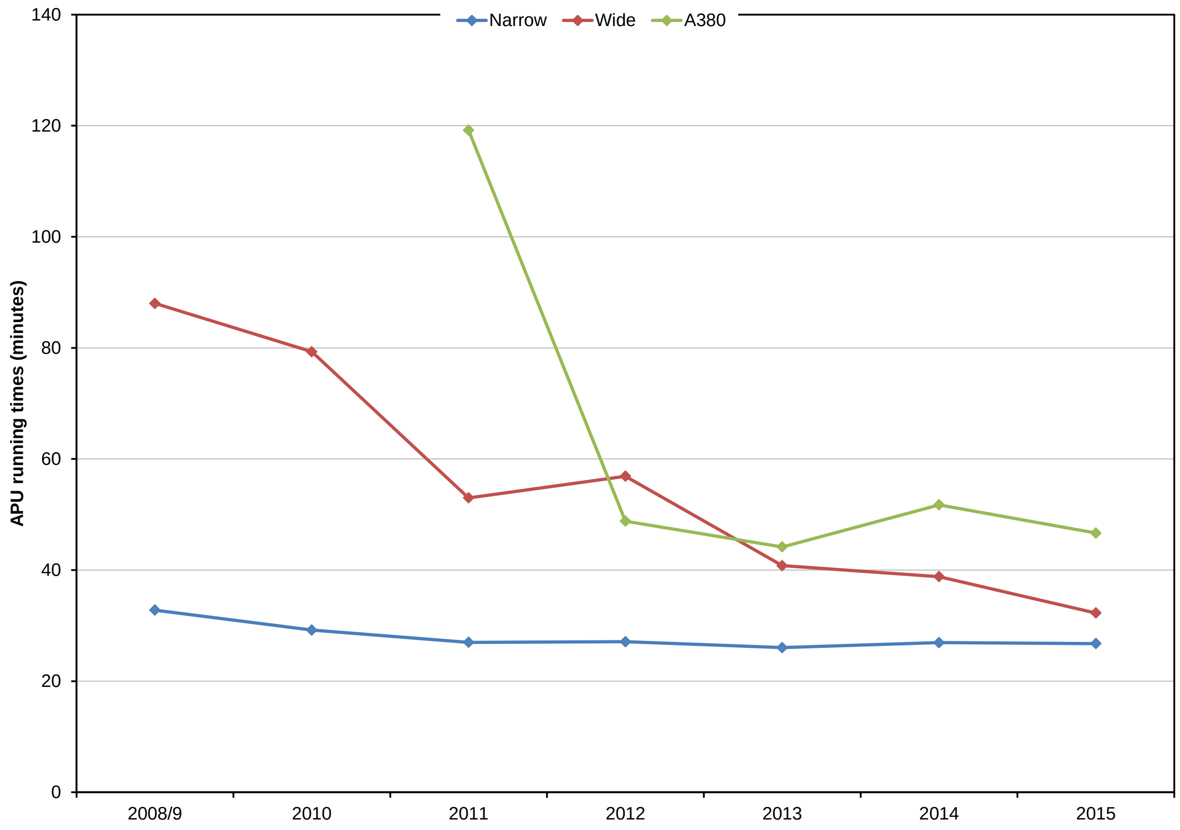
Figure 5 shows the trend in the APU running times since 2008/9. There is clearly a downward trend for wide-bodied aircraft. However APU running times for narrow-bodied aircraft have remained more or less constant over the last five years.

Table 2 APU running times: comparison of 2015 with 2013 and 2014

		APU running time (minutes)			Change from (%)	
		2013	2014	2015	2013[a]	2014[b]
Narrow-bodied	Arrival	6.7	6.8	6.9	2.7	0.7
	Departure	19.4	20.1	19.9	2.7	-1.2
	Total	26.1	26.9	26.8	2.7	-0.7
Wide-bodied	Arrival	12.0	8.9	8.2	-31.4	-8.0
	Departure	28.8	29.9	24.0	-16.5	-19.5
	Total	40.8	38.8	32.3	-20.9	-16.9
A380	Arrival	18.2	11.9	11.2	-38.5	-5.8
	Departure	26.0	39.9	35.5	36.5	-11.0
	Total	44.2	51.7	46.7	5.7	-9.8

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

Figure 5 APU running times



2.5 Taxi and hold times

The taxi and hold times for this 2015 emission inventory update are taken from data, for 2015, 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.

It was possible to match 98% of departures with an EFPS record so that they had individual taxi-out and hold times, and similarly for 98% 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 show taxi-in times derived from data for 2013, 2014 and 2015, by runway and terminal. Table 4 and Table 5 show similar data for taxi-out and hold respectively. Table 6 shows that overall, the 2015 taxi and hold times are very similar to the 2013 and 2014 times. However, there is considerable variation in the differences between runways and terminals 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.

Table 3 Aircraft taxi-in times: comparison of 2015 with 2013 and 2014

Runway	Terminal	Taxi-in (s)			Change from (%)	
		2013	2014	2015	2013[a]	2014[b]
09L	T1	256	253	246	-3.9	-2.6
09L	T2	327	406	435	32.9	7.0
09L	T3	389	399	407	4.6	2.0
09L	T4	732	722	718	-1.9	-0.5
09L	T5	493	493	478	-3.1	-3.2
09L	Cargo	669	667	687	2.6	2.9
09R	T1	517	397	431	-16.7	8.5
09R	T2	471	315	306	-35.1	-3.0
09R	T3	383	395	409	6.9	3.6
09R	T4	291	289	268	-8.0	-7.3
09R	T5	639	586	582	-9.0	-0.7
09R	Cargo	307	306	318	3.5	3.7
27L	T1	484	486	499	3.0	2.6
27L	T2	576	411	367	-36.3	-10.9
27L	T3	328	329	323	-1.5	-1.8
27L	T4	398	398	359	-9.8	-9.8
27L	T5	423	430	424	0.3	-1.5
27L	Cargo	223	221	200	-10.2	-9.5
27R	T1	272	273	285	4.7	4.3
27R	T2	402	494	521	29.6	5.5
27R	T3	329	339	369	12.1	8.7
27R	T4	719	728	734	2.1	0.9
27R	T5	428	423	403	-5.8	-4.5
27R	Cargo	667	654	667	0.0	2.0

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

Table 4 Aircraft taxi-out times: comparison of 2015 with 2013 and 2014

Runway	Terminal	Taxi-out (s)			Change from (%)	
		2013	2014	2015	2013[a]	2014[b]
09L	T1	734	681	518	-29.4	-23.9
09L	T2	907	848	845	-6.9	-0.4
09L	T3	840	714	712	-15.3	-0.4
09L	T4	874	871	935	7.0	7.4
09L	T5	628	558	637	1.4	14.0
09L	Cargo	854	681	763	-10.6	12.2
09R	T1	717	719	803	12.0	11.8
09R	T2	853	658	604	-29.2	-8.2
09R	T3	608	592	609	0.1	2.8
09R	T4	619	604	596	-3.7	-1.3
09R	T5	508	503	530	4.3	5.3
09R	Cargo	572	562	541	-5.4	-3.8
27L	T1	544	541	577	6.2	6.7
27L	T2	573	485	463	-19.3	-4.7
27L	T3	634	622	661	4.3	6.3
27L	T4	519	531	544	4.8	2.5
27L	T5	751	765	815	8.5	6.6
27L	Cargo	743	719	656	-11.7	-8.7
27R	T1	455	460	519	14.0	12.8
27R	T2	526	565	568	7.9	0.5
27R	T3	702	713	747	6.4	4.8
27R	T4	512	516	513	0.1	-0.6
27R	T5	786	826	852	8.4	3.2
27R	Cargo	785	718	678	-13.6	-5.5

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

Table 5 Aircraft hold times: comparison of 2015 with 2013 and 2014

Runway	Terminal	Hold (s)[1]			Change from (%)	
		2013	2014	2015	2013[a]	2014[b]
09L	T1	722	480	113	-84.4	-76.5
09L	T2	819	458	589	-28.1	28.6
09L	T3	817	655	546	-33.2	-16.7
09L	T4	1109	638	806	-27.3	26.4
09L	T5	765	559	670	-12.5	19.7
09L	Cargo	830	473	674	-18.8	42.5
09R	T1	605	628	631	4.3	0.4
09R	T2	642	646	642	0.0	-0.6
09R	T3	668	687	697	4.3	1.5
09R	T4	666	660	676	1.6	2.5
09R	T5	689	695	690	0.1	-0.9
09R	Cargo	531	577	517	-2.6	-10.4
27L	T1	569	589	595	4.6	1.0
27L	T2	593	578	554	-6.5	-4.0
27L	T3	609	627	621	2.0	-0.9
27L	T4	558	554	553	-0.9	-0.2
27L	T5	584	604	591	1.2	-2.1
27L	Cargo	484	559	551	13.9	-1.4
27R	T1	532	541	539	1.2	-0.4
27R	T2	555	527	537	-3.2	2.0
27R	T3	587	575	579	-1.3	0.8
27R	T4	801	802	828	3.4	3.3
27R	T5	560	561	560	0.0	-0.1
27R	Cargo	807	746	748	-7.3	0.3

[1] includes time for line-up and pilot reaction
[a] Change % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2015 value – 2014 value) / (2014 value)

Table 6 Weighted average[1] taxi and hold times

Mode	2013	2014	2015	Change from (%)	
				2013[a]	2014[b]
Taxi-In	444	448	437	-1.7	-2.6
Taxi-Out	650	640	661	1.7	3.3
Hold[2]	611	611	611	0.0	0.0

[1] derived from movements in 2015
[a] Change % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Change % = 100 * (2015 value – 2014 value) / (2014 value)
[2] includes time for line-up and pilot reaction

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[viii]) 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[ix], 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 NOx emissions, may be realised dependant on aircraft type and operator technique[2].

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,

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

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 2015 about 21% 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

Although reduced-engine taxiing was not recorded for arrivals, anecdotal evidence suggests its use on arrival is much more common than for departures. We have therefore extended the methodology to cover the arrivals corresponding to the reduce engine departures of the turnarounds (~21% 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 and previous annual updates inventory reports. The 2015 values have been compared with equivalent reported values for 2013 and 2014. The calculated total aircraft NO_x emission (up to 1000 m altitude) for 2015 is 4.9% higher than the equivalent value for 2013, for a 3.6% increase in the number of passengers, but 1.0% lower than the equivalent value for 2014, for a 2.2% increase in the number of passengers.

Table 7 Breakdown of aircraft NO_x emissions by mode: comparison of 2015 with 2013 and 2014

Mode	Annual NO_x emissions (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Ground-level					
Landing roll	41.04	43.91	44.42	8.2	1.2
Taxi-in	153.51	163.60	163.51	6.5	-0.1
Taxi-out	237.53	251.18	259.11	9.1	3.2
Hold	225.63	235.80	234.50	3.9	-0.6
Take-off roll	681.80	741.75	726.78	6.6	-2.0
APU	182.05	185.24	190.02	4.4	2.6
Engine testing[1]	2.80	2.80	2.80	0.0	0.0
Total ground-level	**1524.36**	**1624.28**	**1621.14**	**6.3**	**-0.2**
Elevated					
Approach	594.64	628.51	623.51	4.9	-0.8
Initial climb	773.17	838.77	825.12	6.7	-1.6
Climb-out	1393.60	1452.24	1427.51	2.4	-1.7
Total elevated	**2761.41**	**2919.52**	**2876.14**	**4.2**	**-1.5**
Total	**4285.76**	**4543.80**	**4497.28**	**4.9**	**-1.0**

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

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 is 1.3% higher than in 2013, but 3.1% lower than in 2014, and the NO_x per movement is 4.5% higher than in 2013, but 1.3% lower than in 2014.

Table 8 LTO NO_x emissions per passenger and per movement: comparison of 2015 with 2013 and 2014

	2013	2014	2015	Change from (%)	
				2013[a]	2014[b]
LTO NO_x (tonnes per year)	4285.76	4543.80	4497.28	4.9	-1.0
Passengers[1] (mppa)	72.33	73.37	74.95	3.6	2.2
LTO NO_x (g per passenger[1])	59.25	61.93	60.00	1.3	-3.1
Movements[2] (1000s)	471.94	472.80	474.09	0.5	0.3
LTO NO_x (kg per movement[2])	9.08	9.61	9.49	4.5	-1.3

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

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 2015 is 6.3% higher than the equivalent value for 2013, for a 0.5% increase in the total number of movements, but 0.2% lower than for 2014, for a 0.3% increase in the total number of movements. Compared with 2013, the fractional range for the individual ground-level modes (excluding engine testing) shown in Table 7 vary from +3.9% (for Hold) to +9.1% (for Taxi-out). Compared with 2014, the range is from -2.0% (for Take-off roll) to +3.2% (for Taxi-out). This variability is not surprising, given that the changes in the fleet will affect emission rates differently at different 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 2015 with the equivalent distribution in 2013 and 2014. 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 each year (25.2% in 2013, 24.8% in 2014 and 25.0% in 2015). However, the larger aircraft types, B747, B777 and A380, together contribute approximately half of the emissions in each period (50.8% in 2013, 52.4 in 2014 and 52.3% in 2015), 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 2015 with those for 2013 and 2014. There is a 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	2013			2014			2015		
	NO_x (t/year)	%	NO_x (kg/mvt)	NO_x (t/year)	%	NO_x (kg/mvt)	NO_x (t/year)	%	NO_x (kg/mvt)
Small	1.67	0.1	0.55	2.13	0.1	0.62	2.26	0.2	0.64
Medium	373.61	27.9	1.25	386.98	26.9	1.31	390.37	27.3	1.32
A318/319	113.60	8.5	1.17	112.86	7.9	1.20	101.59	7.1	1.20
A320	143.70	10.7	1.17	169.11	11.8	1.28	181.23	12.7	1.28
A321	79.74	6.0	1.63	73.89	5.1	1.75	74.76	5.2	1.75
B737	24.10	1.8	1.12	20.43	1.4	1.08	20.51	1.4	1.12
Others	12.48	0.9	1.36	10.69	0.7	1.61	12.29	0.9	1.50
Heavy	882.31	65.9	5.49	943.53	65.7	5.75	892.11	62.5	5.55
A330	70.54	5.3	3.90	71.28	5.0	4.03	71.58	5.0	4.01
B747	211.78	15.8	6.54	224.83	15.7	7.62	193.64	13.6	7.55
B767	108.99	8.1	3.27	103.96	7.2	3.25	88.07	6.2	3.11
B777	387.14	28.9	6.39	424.30	29.5	6.65	409.96	28.7	6.55
Other	103.86	7.8	6.33	119.17	8.3	5.62	128.87	9.0	4.88
A380	81.93	6.1	9.17	103.60	7.2	9.58	143.57	10.1	9.68
Total	1339.51	100.0	2.84	1436.24	100.0	3.04	1428.32	100.0	3.01

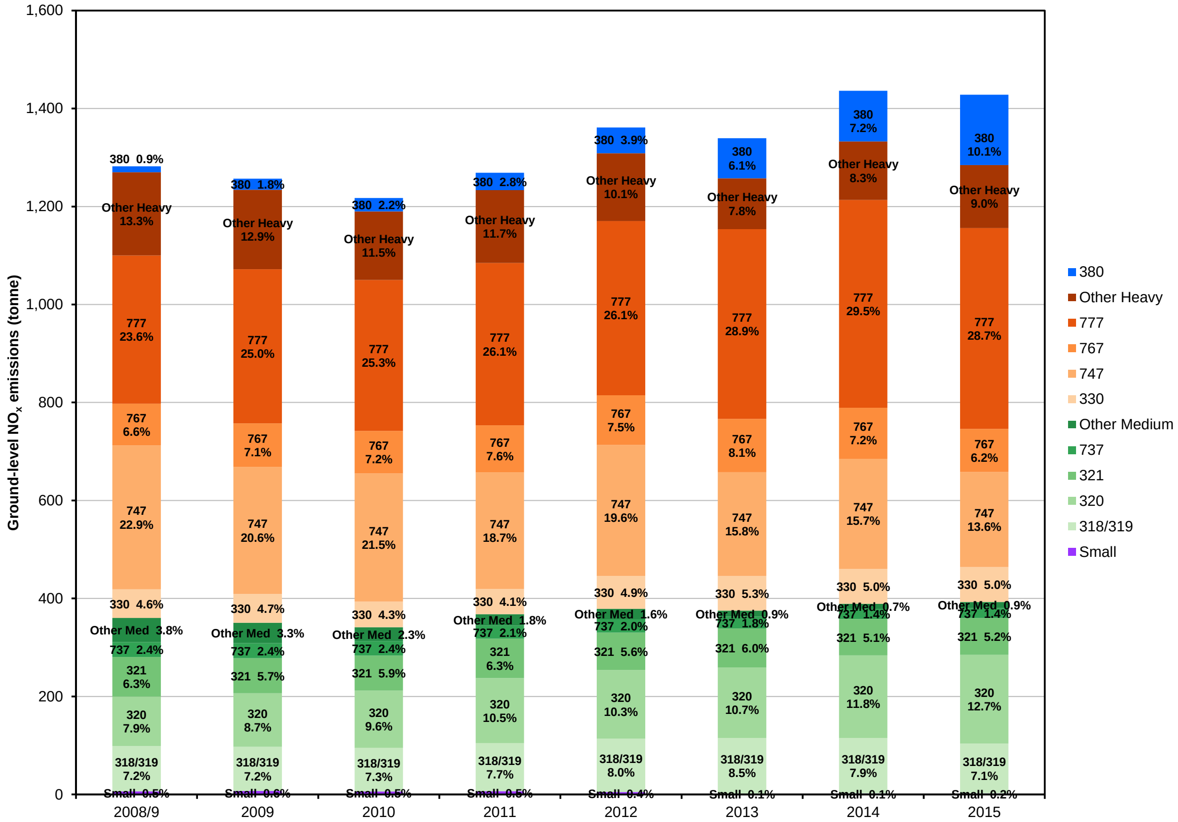
[1] Ground–level emissions from main engines only (omitting APU and engine testing).

Overall, the fleet-averaged value of ground-level aircraft NO_x emissions per movement, excluding APUs and engine testing, has risen by 6.1% between the 2013 inventory and the 2015 inventory, from 2.84 kg per movement in 2013 to 3.01 kg per movement in 2015. However, it has fallen slightly (0.8%) from 3.04 kg per movement in the 2014 inventory.

Including APUs and engine testing, the increase from the 2013 inventory is 5.9%, from 3.23 kg per movement in 2013 to 3.42 kg per movement in 2015. Conversely, the decrease from the 2014 inventory is 0.5% (from 3.44 kg per movement).

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 2015



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

4.1.1 Alternative operating times

4.1.1.1 APUs

Table 10 presents NO_x emissions as calculated using the 'alternative' 2013 APU times, comparing them with the emissions calculated for 2013 and 2014 (calculated using the 'alternative' 2013 APU times). This table is the 'alternative' equivalent of Table 7. Table 10 shows that calculated aircraft emissions for the whole LTO cycle (including elevated) were 5.4% higher in 2015 than in 2013, but 0.6% lower than in 2014. APU emissions were 16.3% higher than in 2013, and 13.2% higher than in 2014, and ground-level aircraft emissions were 7.8% higher than in 2013, and 1.0% higher than in 2014.

For comparison using the 2015 times in Table 2, the whole LTO cycle emissions were 4.9% higher in 2015 than in 2013, but 1.0% lower than in 2014. APU emissions were 4.4% higher than in 2013, and 2.6% higher than in 2014, and ground-level aircraft emissions were 6.3% higher than in 2013, but 0.2% lower than in 2014.

Table 10 Aircraft NO_x emissions using 'alternative' APU times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 APU times)

Mode	NO_x emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
APU	182.05	187.00	211.63	16.3	13.2
Ground-level	1524.36	1626.04	1642.75	7.8	1.0
Total aircraft LTO	4285.76	4545.56	4518.89	5.4	-0.6

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

Table 11 compares the two methodologies, showing emissions calculated for the 2015 inventory using the 'alternative' 2013 APU times (refer to Table 10) and using the 2014 and 2015 APU times (refer to Table 7). Note that all other emission sources are unchanged between the three calculations presented in Table 11. The APU emissions calculated using the 2015 times are 10.2% lower than those calculated using the 'alternative' 2013 times. This is a reflection of the differences in the running times as given in Table 2; the lower APU running times for wide-bodied aircraft more than compensate for the higher running times for narrow-bodied aircraft and the A380.

Table 11 Aircraft NO_x emissions: comparison of emissions calculated using 2015 APU times with those calculated using 2013 and 2014 APU times

Mode	NO_x emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
APU	211.63	214.75	190.02	-10.2	-11.5
Ground-level	1642.75	1645.87	1621.14	-1.3	-1.5
Total aircraft LTO	4518.89	4522.01	4497.28	-0.5	-0.5

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.1.1.2 Taxi and hold

Table 12 presents NO_x emissions as calculated using the 'alternative' 2013 taxi and hold times, comparing them with the emissions calculated for 2013 and 2014 (calculated using the 'alternative' 2013 taxi and hold times). This table is the 'alternative' equivalent of Table 7. Table 12 shows that calculated aircraft emissions for the whole LTO cycle (including elevated) were 4.4% higher in 2015 than in 2013, but 1.0% lower than in 2014. Ground-level aircraft emissions were 4.9% higher than in 2013, but 0.1% lower than in 2014.

For comparison using the 2015 times in Table 3, Table 4 and Table 5, the whole LTO cycle emissions were 4.9% higher in 2015 than in 2013, but 1.0% lower than in 2014. Ground-level aircraft emissions were 6.3% higher than in 2013, but 0.2% lower than in 2014.

Table 12 Aircraft NO_x emissions using 'alternative' taxi and hold times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 taxi and hold times)

Mode	NO_x emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Taxi-in	153.51	159.61	161.92	5.5	1.4
Taxi-out	237.53	242.53	244.33	2.9	0.7
Hold	225.63	225.52	229.41	1.7	1.7
Ground-level	1524.36	1601.36	1599.68	4.9	-0.1
Total aircraft LTO	4285.76	4520.88	4475.82	4.4	-1.0

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

Table 13 compares the two methodologies, showing emissions calculated for 2015 using the 'alternative' 2013 taxi and hold times (refer to Table 12) and using the 2015 taxi and hold times (refer to Table 7). Overall, emissions from taxi-in, taxi-out and hold calculated using the 2015 times are higher than those calculated using the 'alternative' 2013 times (by 1.0%, 6.1% and 2.2% respectively). With the exception of taxi-in, these differences are greater than what would be expected from the differences in overall average taxi and hold times (refer to Table 6), but could be explained by the considerable variation in the differences between runways and terminals pairings seen in Table 3, Table 4 and Table 5.

Table 13 Aircraft NO_x emissions: comparison of emissions calculated using 2015 taxi and hold times with those calculated using 2013 and 2014 taxi and hold times

Mode	NO_x emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
Taxi-in	161.92	163.57	163.51	1.0	0.0
Taxi-out	244.33	244.19	259.11	6.1	6.1
Hold	229.41	229.41	234.50	2.2	2.2
Ground-level	1599.68	1601.19	1621.14	1.3	1.2
Total aircraft LTO	4475.82	4477.33	4497.28	0.5	0.4

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.1.1.3 Combined

Table 14 presents NO_x emissions as calculated using the 'alternative' 2013 operating times, comparing them with the emissions calculated for 2013 and 2014 (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 14 shows that calculated aircraft emissions for the whole LTO cycle (including elevated) were 4.9% higher in 2015 than in 2013, but 0.6% lower than in 2014. Ground-level aircraft emissions were 6.4% higher than in 2013, and 1.1% higher than in 2014.

For comparison using the 2015 times, the whole LTO cycle emissions were 4.9% higher in 2015 than in 2013, but 1.0% lower than in 2014. Ground-level aircraft emissions were 6.3% higher than in 2013, but 0.2% lower than in 2014.

Table 14 Aircraft NO_x emissions using 'alternative' operating times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 operating times)

Mode	NO_x emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Taxi-in	153.51	159.61	161.92	5.5	1.4
Taxi-out	237.53	242.53	244.33	2.9	0.7
Hold	225.63	225.52	229.41	1.7	1.7
APU	182.05	187.00	211.63	16.3	13.2
Ground-level	1524.36	1603.12	1621.29	6.4	1.1
Total aircraft LTO	4285.76	4522.64	4497.43	4.9	-0.6

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

Table 15 compares the two methodologies, showing emissions calculated 2015 using the 'alternative' 2013 operating times (refer to Table 14) and using the 2014 and 2015 operating times (refer to Table 7).

Table 15 Aircraft NO_x emissions: comparison of emissions calculated using 2015 operating times with those calculated using 2013 and 2014 operating times

Mode	NO_x emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
Taxi-in	161.92	163.57	163.51	1.0	0.0
Taxi-out	244.33	244.19	259.11	6.1	6.1
Hold	229.41	229.41	234.50	2.2	2.2
APU	211.63	214.75	190.02	-10.2	-11.5
Ground-level	1621.29	1625.92	1621.14	0.0	-0.3
Total aircraft LTO	4497.43	4502.06	4497.28	0.0	-0.1

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.1.2 Reduced-engine taxi

Table 16 presents NO_x emissions taking account of reduced-engine taxi. It compares emissions that account for reduced-engine taxi on both departure and arrival and emissions that account for reduced-engine taxi-out only with emissions calculated assuming conventional taxi.

Table 16 Breakdown of aircraft NO_x emissions by mode - 2015: comparison of reduced-engine taxi with conventional taxi

Mode	Annual NO_x emissions (tonnes)			Change (%)	
	Conventional	RET-o[1]	RET[2]	RET-o[3]	RET[4]
Taxi-in	163.51	163.51	158.27	0.0	-3.2
Taxi-out	259.11	247.95	247.95	-4.3	-4.3
APU	190.02	198.08	201.85	4.2	6.2
Ground-level	1621.14	1618.04	1616.57	-0.2	-0.3
Total aircraft LTO	4497.28	4494.18	4492.71	-0.1	-0.1

[1] Reduced-engine taxi-out only
[2] Reduced-engine taxi-in and taxi-out
[3] Change % = 100 * (RET-o value – Conventional value) / (Conventional value)
[4] Change % = 100 * (RET value – Conventional value) / (Conventional value)

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

Table 17 shows aircraft PM_{10} emissions broken down by mode (phase of the LTO cycle), using the same categories as in the 2008/9 and previous annual updates inventory reports. Table 18 shows the equivalent comparison for $PM_{2.5}$. The 2015 values have been compared with equivalent values for from the 2013 and 2014 inventories. The calculated total aircraft PM_{10} ($PM_{2.5}$) emissions (up to 1000 m) for the 2015 are 2.8% (3.9%) lower than the equivalent value for 2013, for a 0.5% increase in the number of movements, and 0.3% (0.6%) lower than the equivalent value for 2014, for a 0.3% 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 17 Breakdown of aircraft PM_{10} emissions by mode: comparison of 2015 with 2013 and 2014

Mode	Annual PM_{10} emissions (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Ground-level					
Landing roll	0.55	0.53	0.53	-3.1	0.9
Taxi-in	3.18	3.12	3.16	-0.8	1.0
Taxi-out	4.90	4.75	4.93	0.7	3.9
Hold	4.62	4.47	4.46	-3.5	-0.3
Take-off roll	3.34	3.07	2.99	-10.2	-2.6
Brake wear	9.25	9.45	9.58	3.6	1.4
Tyre wear	6.10	6.27	6.38	4.6	1.7
APU	3.52	3.47	3.15	-10.4	-9.1
Engine testing[1]	0.06	0.06	0.06	0.0	0.0
Total ground-level	**35.51**	**35.19**	**35.24**	**-0.7**	**0.1**
Elevated					
Approach	5.69	5.50	5.50	-3.3	0.0
Initial climb	3.27	3.01	2.95	-9.7	-1.9
Climb-out	6.50	5.99	5.86	-9.8	-2.1
Total elevated	**15.46**	**14.50**	**14.32**	**-7.4**	**-1.3**
Total	**50.97**	**49.69**	**49.56**	**-2.8**	**-0.3**

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

Table 18 Breakdown of aircraft $PM_{2.5}$ emissions by mode: comparison of 2015 with 2013 and 2014

Mode	Annual $PM_{2.5}$ emissions (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Ground-level					
Landing roll	0.55	0.53	0.53	-3.1	0.9
Taxi-in	3.18	3.12	3.16	-0.8	1.0
Taxi-out	4.90	4.75	4.93	0.7	3.9
Hold	4.62	4.47	4.46	-3.5	-0.3
Take-off roll	3.34	3.07	2.99	-10.2	-2.6
Brake wear	3.68	3.76	3.81	3.6	1.4
Tyre wear	4.27	4.39	4.47	4.6	1.7
APU	3.52	3.47	3.15	-10.4	-9.1
Engine testing[1]	0.06	0.06	0.06	0.0	0.0
Total ground-level	**28.11**	**27.62**	**27.56**	**-1.9**	**-0.2**
Elevated					
Approach	5.69	5.50	5.50	-3.3	0.0
Initial climb	3.27	3.01	2.95	-9.7	-1.9
Climb-out	6.50	5.99	5.86	-9.8	-2.1
Total elevated	**15.46**	**14.50**	**14.32**	**-7.4**	**-1.3**
Total	**43.57**	**42.12**	**41.88**	**-3.9**	**-0.6**

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

Table 19 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 6.2% lower than in 2013, and 2.4% lower than in 2014, and the PM_{10} per movement is 3.2% lower than in 2013, and 0.5% lower than in 2014. The $PM_{2.5}$ per passenger is 7.2% lower than in 2013, and 2.7% lower than in 2014, and the $PM_{2.5}$ per movement is 4.3% lower than in 2013, and 0.8% lower than in 2014.

Table 19 LTO PM emissions per passenger and per movement: comparison of 2015 with 2013 and 2014

	2013	2014	2015	Change from (%)	
				2013[a]	2014[b]
LTO PM_{10} (tonnes per year)	50.97	49.69	49.56	-2.8	-0.3
LTO $PM_{2.5}$ (tonnes per year)	43.57	42.12	41.88	-3.9	-0.6
Passengers[1] (mppa)	72.33	73.37	74.95	3.6	2.2
LTO PM_{10} (g per passenger[1])	0.70	0.68	0.66	-6.2	-2.4
LTO $PM_{2.5}$ (g per passenger[1])	0.60	0.57	0.56	-7.2	-2.7
Movements[2] (1000s)	471.94	472.80	474.09	0.5	0.3
LTO PM_{10} (kg per movement[2])	0.11	0.11	0.10	-3.2	-0.5
LTO $PM_{2.5}$ (kg per movement[2])	0.09	0.09	0.09	-4.3	-0.8

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

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 APU emissions and engine testing emissions) for 2015 is 0.7% (1.9% for $PM_{2.5}$) lower than the equivalent value for 2013, for a 0.5% increase in the total number of movements. Ground-level aircraft PM emissions are barely changed from 2014 (0.1% higher for PM_{10} and 0.2% lower for $PM_{2.5}$, for a 0.3% increase in the total number of movements).

For the main engine exhaust emissions, the difference from 2013 ranges from -10.2% (Take-off roll) to +0.7% (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 45.3% of the ground-level PM_{10} emissions in 2015 (30.0% for $PM_{2.5}$). The increase in this combined contribution from 2013 to 2015 is 4.0% for PM_{10} and 4.2% for $PM_{2.5}$. The increase from 2014 to 2015 is 1.5% for PM_{10} and 1.6% for $PM_{2.5}$.

Table 20 gives a breakdown of ground-level aircraft exhaust PM emissions (omitting APUs, engine testing, brake wear and tyre wear) by aircraft type, comparing the distribution in 2015 with the equivalent distribution in 2013 and 2014. 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 each year (44.2% in 2013, 44.6% in 2014 and 45.3% in 2015). The larger aircraft types, B747, B777 and A380, together contribute over third of the emissions in each year (38.3% in 2013, 36.9% in 2014 and 36.6 in 2015), despite accounting for less than a quarter of the total movements.

Table 20 also gives ground-level emissions per movement (excluding APU, engine testing and brake and tyre wear emissions) for each aircraft type, comparing values for 2015 with those for 2013 and 2014. 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 2-3 times higher than for the single-aisle jets.

Table 20 Breakdown of ground-level aircraft PM[1] emissions[2] by aircraft type

Aircraft Type	2013			2014			2015		
	PM (t/year)	%	PM (g/mvt)	PM (t/year)	%	PM (g/mvt)	PM (t/year)	%	PM (g/mvt)
Small	0.06	0.4	20.5	0.09	0.5	25.0	0.08	0.5	21.9
Medium	7.84	47.3	26.2	7.51	47.1	25.5	7.71	48.0	26.2
A318/319	2.81	16.9	28.9	2.65	16.6	28.1	2.43	15.1	28.9
A320	3.14	18.9	25.6	3.27	20.5	24.7	3.59	22.3	25.4
A321	1.38	8.3	28.3	1.20	7.5	28.3	1.27	7.9	29.6
B737	0.34	2.1	15.9	0.29	1.8	15.3	0.29	1.8	15.7
Others	0.17	1.0	18.8	0.11	0.7	16.4	0.13	0.8	16.3
Heavy	8.10	48.8	50.4	7.66	48.1	46.7	7.28	45.3	45.3
A330	0.56	3.4	31.0	0.61	3.8	34.3	0.59	3.7	33.3
B747	2.83	17.0	87.3	2.21	13.8	74.8	1.90	11.8	74.0
B767	0.94	5.7	28.3	1.04	6.5	32.6	0.99	6.1	34.8
B777	2.94	17.8	48.6	3.00	18.8	47.0	2.98	18.5	47.6
Other	0.82	5.0	50.1	0.81	5.1	38.3	0.83	5.2	31.4
A380	0.58	3.5	65.1	0.68	4.3	63.3	1.00	6.2	67.7
Total	16.59	100.0	35.1	15.95	100.0	33.7	16.08	100.0	33.9

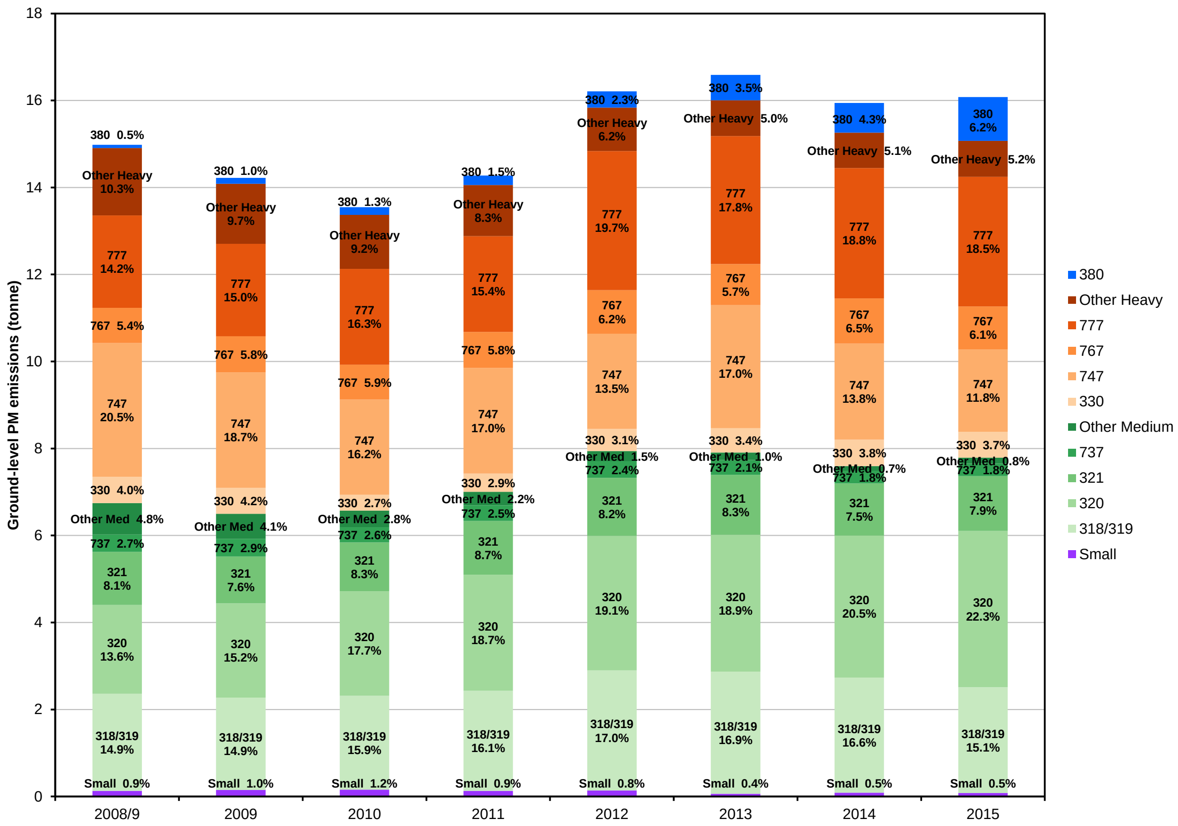
[1] For exhaust emissions, PM_{10} and $PM_{2.5}$ have been taken to be the same.
[2] Ground–level emissions from main engines only (omitting APU, engine testing, brake wear and tyre wear)

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 3.5% between the 2013 inventory and the 2015 inventory, from 35.1 grams per movement in 2013 to 33.9 grams per movement in 2015. However, it has increased slightly (0.6%) from 33.7 grams per movement the 2014 inventory.

Including APUs, engine testing, brake wear and tyre wear, the decrease in ground-level aircraft PM_{10} emissions per movement from the 2013 inventory is 1.2% (2.4% for $PM_{2.5}$), from 75.2 grams of PM_{10} (59.6 grams of $PM_{2.5}$) per movement in 2013 to 74.3 grams of PM_{10} (58.1 grams of $PM_{2.5}$) per movement in 2015. The decrease from the 2014 inventory is 0.1% (0.5% for $PM_{2.5}$), from 74.4 grams of PM_{10} (58.4 grams of $PM_{2.5}$) per movement).

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 2015



[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

4.2.1.1 APUs

Respectively, Table 21 and Table 22 present PM_{10} and $PM_{2.5}$ emissions as calculated using the 'alternative' 2013 APU times, comparing them with the emissions calculated for 2013 and 2014 (calculated using the 'alternative' 2013 APU times). These tables are the 'alternative' equivalents of Table 17 and Table 18. Table 21 and Table 22 show that calculated aircraft emissions of PM_{10} ($PM_{2.5}$) for the whole LTO cycle were 2.1% (3.1%) lower in 2015 than in 2013, but 0.3% (0.1%) higher in 2015 than in 2014. APU emissions were 1.3% (1.3%) lower than in 2013, and 0.4% (0.4%) lower than in 2014, and ground-level aircraft emissions were 0.2% higher (0.8% lower) than in 2013, and 1.0% (0.9%) higher than in 2014.

For comparison using the 2015 times in Table 2, the whole LTO cycle emissions were 2.8% (3.9%) lower in 2015 than in 2013, and 0.3% (0.6%) lower than in 2014. APU emissions were 10.4% (10.4%) lower than in 2013 and 9.1% (9.1%) lower than in 2014 and ground-level aircraft emissions were 0.7% (1.9%) lower than in 2013, and 0.1% higher (0.2% lower) than in 2014.

Table 21 Aircraft PM_{10} emissions using 'alternative' APU times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 APU times)

Mode	PM_{10} emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
APU	3.52	3.49	3.47	-1.3	-0.4
Ground-level	35.51	35.21	35.57	0.2	1.0
Total aircraft LTO	50.97	49.71	49.88	-2.1	0.3

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

Table 22 Aircraft $PM_{2.5}$ emissions using 'alternative' APU times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 APU times)

Mode	$PM_{2.5}$ emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
APU	3.52	3.49	3.47	-1.3	-0.4
Ground-level	28.11	27.64	27.88	-0.8	0.9
Total aircraft LTO	43.57	42.14	42.20	-3.1	0.1

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

Table 23 and Table 24 compare the two methodologies, showing emissions calculated for the 2015 inventory using the 'alternative' 2013 APU times (refer to Table 21 and Table 22) and using the 2014 and 2015 APU times (refer to Table 17 and Table 18). The APU emissions calculated using the 2015 times are 9.2% lower than those calculated using the 'alternative' 2013 times, for both size fractions. This is a reflection of the differences in the running times as given in Table 2; the reduction in APU running times for wide-bodied aircraft more than compensate for the increase in running times for narrow-bodied aircraft and the A380.

Table 23 Aircraft PM_{10} emissions: comparison of emissions calculated using 2015 APU times with those calculated using 2013 and 2014 APU times

Mode	PM_{10} emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
APU	3.47	3.47	3.15	-9.2	-9.1
Ground-level	35.57	35.56	35.24	-0.9	-0.9
Total aircraft LTO	49.88	49.88	49.56	-0.6	-0.6

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

Table 24 Aircraft $PM_{2.5}$ emissions: comparison of emissions calculated using 2015 APU times with those calculated using 2013 and 2014 APU times

Mode	$PM_{2.5}$ emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
APU	3.47	3.47	3.15	-9.2	-9.1
Ground-level	27.88	27.88	27.56	-1.2	-1.1
Total aircraft LTO	42.20	42.19	41.88	-0.8	-0.7

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.2.1.2 Taxi and hold

Respectively, Table 25 and Table 26 present PM_{10} and $PM_{2.5}$ emissions as calculated using the 'alternative' 2013 taxi and hold times, comparing them with the emissions calculated for 2013 and 2014 (calculated using the 'alternative' 2013 taxi and hold times). These tables are the 'alternative' equivalents of Table 17 and Table 18. Table 25 and Table 26 show that calculated aircraft emissions of PM_{10} ($PM_{2.5}$) for the whole LTO cycle were 3.2% (4.4%) lower in 2015 than in 2013, and 0.2% (0.5%) lower than in 2014. Ground-level aircraft emissions were 1.4% (2.8%) lower than in 2013, and 0.3% higher (<0.1% lower) than in 2014.

For comparison using the 2015 times in Table 3, Table 4 and Table 5, the whole LTO cycle emissions were 2.8% (3.9%) lower in 2015 than in 2013, and 0.3% (0.6%) lower than in 2014. Ground-level aircraft emissions were 0.7% (1.9%) lower than in 2013, and 0.1% higher (0.2% lower) than in 2014.

Table 25 Aircraft PM_{10} emissions using 'alternative' taxi and hold times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 taxi and hold times)

Mode	PM_{10} emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Taxi-in	3.18	3.10	3.17	-0.3	2.4
Taxi-out	4.90	4.64	4.71	-3.8	1.6
Hold	4.62	4.32	4.42	-4.3	2.4
Ground-level	35.51	34.90	35.00	-1.4	0.3
Total aircraft LTO	50.97	49.40	49.31	-3.2	-0.2

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

Table 26 Aircraft $PM_{2.5}$ emissions using 'alternative' taxi and hold times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 taxi and hold times)

Mode	$PM_{2.5}$ emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Taxi-in	3.18	3.10	3.17	-0.3	2.4
Taxi-out	4.90	4.64	4.71	-3.8	1.6
Hold	4.62	4.32	4.42	-4.3	2.4
Ground-level	28.11	27.33	27.32	-2.8	0.0
Total aircraft LTO	43.57	41.83	41.63	-4.4	-0.5

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

Table 27 and Table 28 compare the two methodologies, showing emissions calculated for 2015 using the 'alternative' 2013 taxi and hold times (as shown in Table 25 and Table 26) and using the 2015 taxi and hold times (refer to Table 17 and Table 18). Emissions from taxi-in calculated using the 2015 times are 0.5% lower (for both size fractions) than those calculated using the 'alternative' 2013 times, whereas taxi-out and hold calculated using the 2015 times are both higher than those calculated using the 'alternative' 2013 times (4.7% and 0.9% respectively, for both size fractions). With the exception of taxi-in, these differences are greater than what would be expected form the differences in overall average taxi and hold times (refer to Table 6), but could be explained by the considerable variation in the differences between runways and terminals pairings seen in Table 3.

Table 27 Aircraft PM_{10} emissions: comparison of emissions calculated using 2015 taxi and hold times with those calculated using 2013 and 2014 taxi and hold times

Mode	PM_{10} emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
Taxi-in	3.17	3.20	3.16	-0.5	-1.5
Taxi-out	4.71	4.70	4.93	4.7	5.0
Hold	4.42	4.42	4.46	0.9	0.9
Ground-level	35.00	35.02	35.24	0.7	0.7
Total aircraft LTO	49.31	49.33	49.56	0.5	0.5

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

Table 28 Aircraft $PM_{2.5}$ emissions: comparison of emissions calculated using 2015 taxi and hold times with those calculated using 2013 and 2014 taxi and hold times

Mode	$PM_{2.5}$ emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
Taxi-in	3.17	3.20	3.16	-0.5	-1.5
Taxi-out	4.71	4.70	4.93	4.7	5.0
Hold	4.42	4.42	4.46	0.9	0.9
Ground-level	27.32	27.33	27.56	0.9	0.8
Total aircraft LTO	41.63	41.65	41.88	0.6	0.5

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.2.1.3 Combined

Respectively, Table 29 and Table 30 present PM_{10} and $PM_{2.5}$ emissions as calculated using the ‘alternative’ 2013 operating times, comparing them with the emissions calculated for 2013 and 2014 (calculated using the ‘alternative’ 2013 operating times). These tables are the ‘alternative’ equivalents of Table 17 and Table 18. Table 29 and Table 30 show that calculated aircraft emissions of PM_{10} ($PM_{2.5}$) for the whole LTO cycle were 2.6% (3.7%) lower in 2015 than in 2013, but 0.4% (0.3%) higher than in 2014. Ground-level aircraft emissions were 0.5% (1.7%) lower than in 2013, but 1.1% (1.1%) higher than in 2014.

For comparison using the 2015 times, the whole LTO cycle emissions were 2.8% (3.9%) lower in 2015 than in 2013, and 0.3% (0.6%) lower than in 2014. Ground-level aircraft emissions were 0.7% (1.9%) lower than in 2013, and 0.1% higher (0.2% lower) than in 2014.

Table 29 Aircraft PM_{10} emissions using ‘alternative’ operating times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 operating times)

Mode	PM_{10} emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Taxi-in	3.18	3.10	3.17	-0.3	2.4
Taxi-out	4.90	4.64	4.71	-3.8	1.6
Hold	4.62	4.32	4.42	-4.3	2.4
APU	3.52	3.49	3.47	-1.3	-0.4
Ground-level	35.51	34.92	35.32	-0.5	1.1
Total aircraft LTO	50.97	49.42	49.64	-2.6	0.4

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

Table 30 Aircraft $PM_{2.5}$ emissions using 'alternative' operating times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 operating times)

Mode	$PM_{2.5}$ emissions per year (tonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Taxi-in	3.18	3.10	3.17	-0.3	2.4
Taxi-out	4.90	4.64	4.71	-3.8	1.6
Hold	4.62	4.32	4.42	-4.3	2.4
APU	3.52	3.49	3.47	-1.3	-0.4
Ground-level	28.11	27.35	27.64	-1.7	1.1
Total aircraft LTO	43.57	41.84	41.95	-3.7	0.3

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

Table 31 and Table 32 compare the two methodologies, showing emissions calculated for 2015 using the 'alternative' 2013 operating times (refer to Table 29 and Table 30) and using the 2015 operating times (refer to Table 17 and Table 18).

Table 31 Aircraft PM_{10} emissions: comparison of emissions calculated using 2015 operating times with those calculated using 2013 and 2014 operating times

Mode	PM_{10} emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
Taxi-in	3.17	3.20	3.16	-0.5	-1.5
Taxi-out	4.71	4.70	4.93	4.7	5.0
Hold	4.42	4.42	4.46	0.9	0.9
APU	3.47	3.47	3.15	-9.2	-9.1
Ground-level	35.32	35.33	35.24	-0.2	-0.2
Total aircraft LTO	49.64	49.65	49.56	-0.2	-0.2

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

Table 32 Aircraft $PM_{2.5}$ emissions: comparison of emissions calculated using 2015 operating times with those calculated using 2013 and 2014 operating times

Mode	$PM_{2.5}$ emissions per year (tonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
Taxi-in	3.17	3.20	3.16	-0.5	-1.5
Taxi-out	4.71	4.70	4.93	4.7	5.0
Hold	4.42	4.42	4.46	0.9	0.9
APU	3.47	3.47	3.15	-9.2	-9.1
Ground-level	27.64	27.65	27.56	-0.3	-0.3
Total aircraft LTO	41.95	41.97	41.88	-0.2	-0.2

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.2.2 Reduced-engine taxi

Respectively, Table 33 and Table 34 present PM_{10} and $PM_{2.5}$ emissions taking account of reduced-engine taxi. They compare emissions that account for reduced-engine taxi on both departure and arrival and emissions that account for reduced-engine taxi-out only with emissions calculated assuming conventional taxi.

Table 33 Breakdown of aircraft PM_{10} emissions by mode - 2015: comparison of reduced-engine taxi with conventional taxi

Mode	Annual PM_{10} emissions (tonnes)			Change %)	
	Conventional	RET-o[1]	RET[2]	RET-o[3]	RET[4]
Taxi-in	3.16	3.16	3.01	0.0	-4.8
Taxi-out	4.93	4.61	4.61	-6.5	-6.5
APU	3.15	3.33	3.41	5.6	8.3
Ground-level	35.24	35.10	35.03	-0.4	-0.6
Total aircraft LTO	49.56	49.42	49.35	-0.3	-0.4

[1] Reduced-engine taxi-out only
[2] Reduced-engine taxi-in and taxi-out
[3] Change % = 100 * (RET-o value – Conventional value) / (Conventional value)
[4] Change % = 100 * (RET value – Conventional value) / (Conventional value)

Table 34 Breakdown of aircraft $PM_{2.5}$ emissions by mode - 2015: comparison of reduced-engine taxi with conventional taxi

Mode	Annual $PM_{2.5}$ emissions (tonnes)			Change (%)	
	Conventional	RET-o[1]	RET[2]	RET-o[3]	RET[4]
Taxi-in	3.16	3.16	3.01	0.0	-4.8
Taxi-out	4.93	4.61	4.61	-6.5	-6.5
APU	3.15	3.33	3.41	5.6	8.3
Ground-level	27.56	27.42	27.35	-0.5	-0.8
Total aircraft LTO	41.88	41.74	41.67	-0.3	-0.5

[1] Reduced-engine taxi-out only
[2] Reduced-engine taxi-in and taxi-out
[3] Change % = 100 * (RET-o value – Conventional value) / (Conventional value)
[4] Change % = 100 * (RET value – Conventional value) / (Conventional value)

4.3 CO_2

In contrast to NOx 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[3] (3.15 kg/kg). Therefore, the CO_2 emissions are calculated simply by multiplying the calculated fuel burn by that emissions index. Table 35 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 and previous annual updates inventory reports. The 2015 values have been compared with equivalent values for 2013 and 2014. The calculated total aircraft CO_2 emissions (up to 1000m) for 2015 is 1.2% higher than the equivalent value for the 2013, for a 3.6% increase in the number of passengers, and 0.6% higher than the equivalent value for 2014, for a 2.2% increase in the number of passengers.

[3] 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.

Table 35 Breakdown of aircraft CO_2 emissions by mode: comparison of 2015 with 2013 and 2014

Mode	Annual CO_2 emissions (kilotonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Ground-level					
Landing roll	19.77	20.07	20.25	2.4	0.9
Taxi-in	105.45	108.87	109.48	3.8	0.6
Taxi-out	161.15	165.34	171.25	6.3	3.6
Hold	152.63	154.55	154.46	1.2	-0.1
Take-off roll	92.26	92.09	91.89	-0.4	-0.2
APU	63.98	64.41	64.14	0.2	-0.4
Engine testing[1]	1.21	1.21	1.21	0.0	0.0
Total ground-level	**596.46**	**606.53**	**612.69**	**2.7**	**1.0**
Elevated					
Approach	184.96	184.59	184.47	-0.3	-0.1
Initial climb	89.27	88.63	88.72	-0.6	0.1
Climb-out	177.13	174.27	174.13	-1.7	-0.1
Total elevated	**451.36**	**447.49**	**447.32**	**-0.9**	**0.0**
Total	**1047.82**	**1054.02**	**1060.01**	**1.2**	**0.6**

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

Table 36 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 2.4% since 2013, and by 1.6% since 2014. The CO_2 per movement is 0.7% higher than in 2013, and 0.3% higher than in 2014.

Table 36 LTO CO_2 emissions per passenger and per movement: comparison of 2015 with 2013 and 2014

	2013	2014	2015	Change from (%)	
				2013[a]	2014[b]
LTO CO_2 (kilotonnes per year)	1047.82	1054.02	1060.01	1.2	0.6
Passengers[1] (mppa)	72.33	73.37	74.95	3.6	2.2
LTO CO_2 (kg per passenger[1])	14.49	14.37	14.14	-2.4	-1.6
Movements[2] (1000s)	471.94	472.80	474.09	0.5	0.3
LTO CO_2 (tonnes per movement[2])	2.22	2.23	2.24	0.7	0.3

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

Table 37 gives a breakdown of LTO aircraft CO_2 emissions (omitting APUs and engine testing) by aircraft type, comparing the distribution in 2015 with the equivalent distributions in 2013 and 2014. 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 each year (31.1% in 2013 and 31.0% in 2014 and 31.2% in 2015). However, the larger aircraft types, B747, B777 and A380, together contribute almost half of the emissions in each period (45.2% in 2013, 45.9 in 2014 and 45.7% in 2015), despite accounting for less than a quarter of the total movements.

Table 37 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.

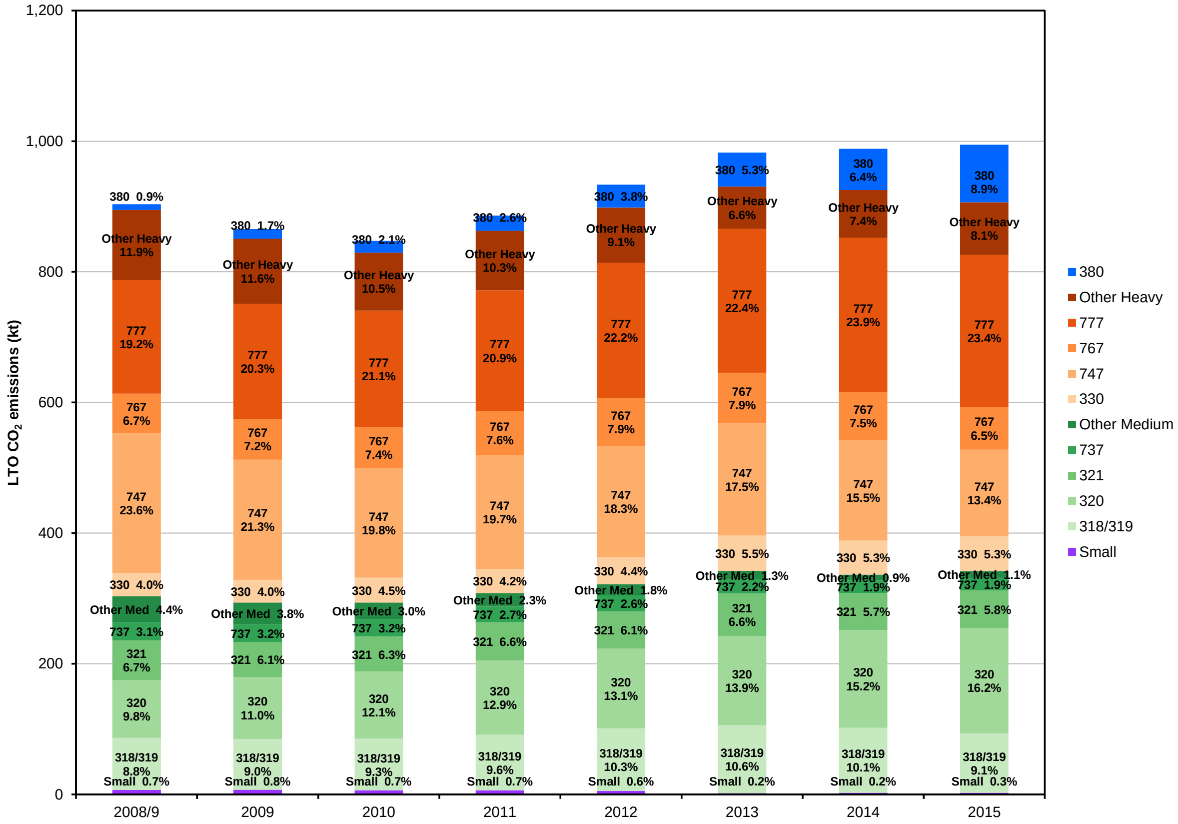
Table 37 Breakdown of LTO aircraft CO_2 emissions[1] by aircraft type

Aircraft Type	2013			2014			2015		
	CO_2 (kt/year)	%	CO_2 (t/mvt)	CO_2 (kt/year)	%	CO_2 (t/mvt)	CO_2 (kt/year)	%	CO_2 (t/mvt)
Small	2.01	0.2	0.66	2.44	0.2	0.71	2.52	0.3	0.71
Medium	340.17	34.6	1.14	334.10	33.8	1.13	339.56	34.1	1.15
A318/319	103.80	10.6	1.07	99.54	10.1	1.06	90.69	9.1	1.08
A320	136.54	13.9	1.11	149.77	15.2	1.13	161.29	16.2	1.14
A321	65.27	6.6	1.34	56.58	5.7	1.34	57.88	5.8	1.35
B737	21.86	2.2	1.02	19.20	1.9	1.02	19.15	1.9	1.04
Others	12.71	1.3	1.39	9.01	0.9	1.35	10.53	1.1	1.29
Heavy	588.37	59.9	3.66	588.41	59.5	3.58	564.36	56.7	3.51
A330	53.94	5.5	2.98	52.17	5.3	2.95	52.67	5.3	2.95
B747	171.98	17.5	5.31	153.24	15.5	5.19	133.14	13.4	5.19
B767	77.43	7.9	2.32	74.16	7.5	2.32	65.08	6.5	2.30
B777	220.21	22.4	3.64	236.04	23.9	3.70	233.05	23.4	3.72
Other	64.82	6.6	3.95	72.80	7.4	3.44	80.42	8.1	3.05
A380	52.08	5.3	5.83	63.45	6.4	5.87	88.22	8.9	5.95
Total	982.63	100.0	2.08	988.40	100.0	2.09	994.66	100.0	2.10

[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 2015



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

4.3.1 Alternative operating times

4.3.1.1 APUs

Table 38 presents CO_2 emissions as calculated using the 'alternative' 2013 APU times, comparing them with the emissions calculated for 2013 and 2014 (calculated using the 'alternative' 2013 APU times). This table is the 'alternative' equivalent of Table 35. Table 38 shows that calculated aircraft emissions for the whole LTO cycle (including elevated) were 1.9% higher in 2015 than in 2013, and 1.2% higher than in 2014. APU emissions were 11.7% higher than in 2013, and 9.6% higher than in 2014, and ground-level aircraft emissions were 3.9% higher than in 2013, and 2.1% higher than in 2014.

For comparison using the 2015 times in Table 2, the whole LTO cycle emissions were 1.2% higher in 2015 than in 2013, and 0.6% higher than in 2014. APU emissions were 0.2% higher than in 2013, but 0.4% lower than in 2014, and ground-level aircraft emissions were 2.7% higher than in 2013, and 1.0% higher than in 2014.

Table 38 Aircraft CO_2 emissions using 'alternative' APU times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 APU times)

Mode	CO_2 emissions per year (kilotonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
APU	63.98	65.20	71.44	11.7	9.6
Ground-level	596.46	607.32	619.99	3.9	2.1
Total aircraft LTO	1047.82	1054.81	1067.31	1.9	1.2

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

Table 39 compares the two methodologies, showing emissions calculated for the 2015 inventory using the 'alternative' 2013 APU times (refer to Table 38) and using the 2015 APU times (refer to Table 35). The APU emissions calculated using the 2015 times are 10.2% lower than those calculated using the 'alternative' 2013 times. This is a reflection of the differences in the running times as given in Table 2; the reduction in APU running times for wide-bodied aircraft more than compensate for the increase in running times for narrow-bodied aircraft and the A380.

Table 39 Aircraft CO_2 emissions: comparison of emissions calculated using 2015 APU times with those calculated using 2013 and 2014 APU times

Mode	CO_2 emissions per year (kilotonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
APU	71.44	71.98	64.14	-10.2	-10.9
Ground-level	619.99	620.53	612.69	-1.2	-1.3
Total aircraft LTO	1067.31	1067.85	1060.01	-0.7	-0.7

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.3.1.2 Taxi and hold

Table 40 presents CO_2 emissions as calculated using the 'alternative' 2013 taxi and hold times, comparing them with the emissions calculated for 2013 and 2014 (calculated using the 'alternative' 2013 taxi and hold times). This table is the 'alternative' equivalent of Table 35. Table 40 shows that calculated aircraft emissions for the whole LTO cycle (including elevated) in 2015 were virtually unchanged from 2013, but 0.8% higher than in 2014. Ground-level aircraft emissions were 0.7% higher in 2015 than in 2013, and 1.3% higher than in 2014.

For comparison using the 2015 times in Table 3, Table 4 and Table 5, the whole LTO cycle emissions were 1.2% higher in 2015 than in 2013, and 0.6% higher than in 2014. Ground-level aircraft emissions were 2.7% higher than in 2013, and 1.0% higher than in 2014.

Table 40 Aircraft CO_2 emissions using 'alternative' taxi and hold times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 taxi and hold times)

Mode	CO_2 emissions per year (kilotonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Taxi-in	105.45	106.43	108.79	3.2	2.2
Taxi-out	161.15	159.90	162.20	0.7	1.4
Hold	152.63	148.67	152.28	-0.2	2.4
Ground-level	596.46	592.77	600.77	0.7	1.3
Total aircraft LTO	1047.82	1040.26	1048.08	0.0	0.8

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

Table 41 compares the two methodologies, showing emissions calculated for 2015 using the 'alternative' 2013 taxi and hold times (refer to Table 40) and using the 2015 taxi and hold times (refer to Table 35). Overall, emissions from taxi-in, taxi-out and hold calculated using the 2015 times are higher than those calculated using the 'alternative' 2013 times (0.6%, 5.6% and 1.4% respectively). With the exception of taxi-in, these differences are greater than what would be expected form the differences in overall average taxi and hold times (refer to Table 6), but could be explained by the considerable variation in the differences between runways and terminals pairings seen in Table 3, Table 4 and Table 5.

Table 41 Aircraft CO_2 emissions: comparison of emissions calculated using 2015 taxi and hold times with those calculated using 2013 and 2014 taxi and hold times

Mode	CO_2 emissions per year (kilotonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
Taxi-in	108.79	109.85	109.48	0.6	-0.3
Taxi-out	162.20	161.83	171.25	5.6	5.8
Hold	152.28	152.28	154.46	1.4	1.4
Ground-level	600.77	601.46	612.69	2.0	1.9
Total aircraft LTO	1048.08	1048.78	1060.01	1.1	1.1

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.3.1.3 Combined

Table 42 presents CO_2 emissions as calculated using the 'alternative' 2013 operating times, comparing them with the emissions calculated for 2013 and 2014 (calculated using the 'alternative' 2013 operating times). This table is the 'alternative' equivalent of Table 35. Table 42 shows that calculated aircraft emissions for the whole LTO cycle (including elevated) in 2015 were virtually unchanged from 2013, but 0.8% higher than in 2014. Ground-level aircraft emissions were 0.7% higher than in 2013, and 1.3% higher than in 2014.

For comparison using the 2015 times, the whole LTO cycle emissions were 1.2% higher in 2015 than in 2013, and 0.6% higher than in 2014. Ground-level aircraft emissions were 2.7% higher than in 2013, and 1.0% higher than in 2014.

Table 42 Aircraft CO_2 emissions using 'alternative' operating times: comparison of 2015 with 2013 and 2014 (all calculated using 2013 operating times)

Mode	CO_2 emissions per year (kilotonnes)			Change from (%)	
	2013	2014	2015	2013[a]	2014[b]
Taxi-in	105.45	106.43	108.79	3.2	2.2
Taxi-out	161.15	159.90	162.20	0.7	1.4
Hold	152.63	148.67	152.28	-0.2	2.4
APU	63.98	65.20	71.44	11.7	9.6
Ground-level	596.46	592.77	600.77	0.7	1.3
Total aircraft LTO	1047.82	1040.26	1048.08	0.0	0.8

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

Table 43 compares the two methodologies, showing emissions calculated for 2015 using the 'alternative' 2013 operating times (refer to Table 42) and using the 2014 and 2015 operating times (refer to Table 35).

Table 43 Aircraft CO_2 emissions: comparison of emissions calculated using 2015 operating times with those calculated using 2013 and 2014 operating times

Mode	CO_2 emissions per year (kilotonnes)			Difference (%)	
	2013 times	2014 times	2015 times	2013[a]	2014[b]
Taxi-in	108.79	109.85	109.48	0.6	-0.3
Taxi-out	162.20	161.83	171.25	5.6	5.8
Hold	152.28	152.28	154.46	1.4	1.4
APU	71.44	71.98	64.14	-10.2	-10.9
Ground-level	600.77	601.46	612.69	2.0	1.9
Total aircraft LTO	1048.08	1048.78	1060.01	1.1	1.1

[a] Difference % = 100 * (2015 value – 2013 value) / (2013 value)
[b] Difference % = 100 * (2015 value – 2014 value) / (2014 value)

4.3.2 Reduced-engine taxi

Table 44 presents CO_2 emissions taking account of reduced-engine taxi. It compares emissions that account for reduced-engine taxi on both departure and arrival and emissions that account for reduced-engine taxi-out only with emissions calculated assuming conventional taxi.

Table 44 Breakdown of aircraft CO_2 emissions by mode: comparison of 2015 with 2013 and 2014

Mode	Annual CO_2 emissions (kilotonnes)			Change (%)	
	Conventional	RET-o[1]	RET[2]	RET-o[3]	RET[4]
Taxi-in	109.48	109.48	106.03	0.0	-3.1
Taxi-out	171.25	163.89	163.89	-4.3	-4.3
APU	64.14	66.53	67.65	3.7	5.5
Ground-level	**612.69**	**607.72**	**605.39**	**-0.8**	**-1.2**
Total aircraft LTO	**1060.01**	**1055.03**	**1052.71**	**-0.5**	**-0.7**

[1] Reduced-engine taxi-out only
[2] Reduced-engine taxi-in and taxi-out
[3] Change % = 100 * (RET-o value – Conventional value) / (Conventional value)
[4] 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 2015 calendar year, based on detailed flight records held by Heathrow Airport. This updates the aircraft component of the published 2013 and 2014 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 2015.

Table 45 shows some summary information about total emissions from the LTO (including APUs, engine testing and brake and tyre wear), while Table 46 presents the same information for ground-level emissions only. Figure 9 to Figure 12 show some trends over the years from 2008/9 to 2015. Note that in these graphs, the vertical scales are chosen to exaggerate the trends, which are typically on the order of one percent per year.

The number of movements in 2015 was 0.5% higher than in 2013 and 0.3% higher than in 2014, whereas the number of passengers was 3.6% higher than in 2013 and 2.2% higher than in 2014. Figure 1 demonstrates that there is no discernible trend in the number of movements over the last ten years. There is little room for growth because 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 1.0% per year (2.7% per year over the last 5 years), and the number of passengers per movement is increasing steadily (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 4.9% higher for 2015 than for 2013, but 1.0% lower than for 2014. For PM_{10} ($PM_{2.5}$), the 2015 value for total LTO emissions is 2.8% (3.9%) lower than for 2013, and 0.3% (0.6%) lower than for 2014. 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 6.3% higher for 2015 than for 2013, but 0.2% lower than for 2014. The calculated value of ground-level aircraft PM_{10} ($PM_{2.5}$) the emissions is 0.7% (1.9%) lower than for 2013, but barely changed from 2014 (0.1% higher for PM_{10} and 0.2% lower for $PM_{2.5}$). Ground-level emissions since 2008/9 are plotted in Figure 9, which suggests that there is no appreciable change in total emissions over the years. However, there is variability for year-to-year. There is a noticeable drop in the reported NO_x in the 2013 inventory. Approximately half of which is due to meteorological effects (2013 was on average colder than any year since 2010); about one third is attributable to the problems with engine assignment identified in section 2.3 and the remainder is the result of other changes (e.g. aircraft fleet/engine mix and taxi times). Note that the values for 2012 and 2013 are as reported and have not been revised in line with Heathrow's AWUR database as was done for Figure 4.

Figure 10 shows the ground-level NO_x emissions per movement and per passenger. NO_x emissions per movement in 2015 were only fractionally higher than in 2008/9, but the fall in emissions per passenger is clear at an average of 1.9% per year. The general expectation for the long-term trend is that passenger numbers increase more quickly than movements (aircraft becoming larger), and NO_x emissions increase faster than movements (larger, longer range aircraft) but slower than passengers (improved engine technology). In other words, NO_x per passenger is expected to fall long-term but NO_x per movement is likely to rise. The inventory data is broadly consistent with this hypothesis, but extrapolating from this period to the longer term is made difficult by the recent economic slump.

Figure 11 and Figure 12 show the ground-level emissions per movement and per passenger, for PM_{10} and $PM_{2.5}$ respectively. Emissions per movement fall slightly over the period, averaging 0.2% per year for PM_{10} and 0.5% for $PM_{2.5}$, and emissions per passenger fall appreciably, averaging about 2.1% per year for PM_{10} and 2.4% for $PM_{2.5}$. These are stronger falls than for NO_x, despite the relative lack of regulatory pressure. This is probably due to the removal of older aircraft with very 'smoky' engines from the fleet mix.

Table 45 Summary of total LTO emissions

	2013	2014	2015	Change (%)		Alternative	
				2013[a]	2014[b]	APU	Taxi/Hold
NO_x (tonnes per year)	4285.76	4543.80	4497.28	4.9	-1.0	4518.89	4475.82
NO_x (g per passenger[1])	59.25	61.93	60.00	1.3	-3.1	60.29	59.71
NO_x (kg per movement[2])	9.08	9.61	9.49	4.5	-1.3	9.53	9.44
PM_{10} (tonnes per year)	50.97	49.69	49.56	-2.8	-0.3	49.88	49.31
PM_{10} (g per passenger[1])	0.70	0.68	0.66	-6.2	-2.4	0.67	0.66
PM_{10} (kg per movement[2])	0.11	0.11	0.10	-3.2	-0.5	0.11	0.10
$PM_{2.5}$ (tonnes per year)	43.57	42.12	41.88	-3.9	-0.6	42.20	41.63
$PM_{2.5}$ (g per passenger[1])	0.60	0.57	0.56	-7.2	-2.7	0.56	0.56
$PM_{2.5}$ (kg per movement[2])	0.09	0.09	0.09	-4.3	-0.8	0.09	0.09
CO_2 (kilotonnes per year)	1047.82	1054.02	1060.01	1.2	0.6	1067.31	1060.01
CO_2 (kg per passenger[1])	14.49	14.37	14.14	-2.4	-1.6	14.24	292.39
CO_2 (tonnes per movement[2])	2.22	2.23	2.24	0.7	0.3	2.25	2325.68

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

Table 46 Summary of ground-level emissions

	2013	2014	2015	Change (%)		Alternative	
				2013[a]	2014[b]	APU	Taxi/Hold
NO_x (tonnes per year)	1524.36	1624.28	1621.14	6.3	-0.2	1642.75	1599.68
NO_x (g) per passenger[1])	21.07	22.14	21.63	2.6	-2.3	21.92	21.34
NO_x (kg) per movement[2])	3.23	3.44	3.42	5.9	-0.5	3.47	3.37
PM_{10} (tonnes per year)	35.51	35.19	35.24	-0.7	0.1	35.57	35.00
PM_{10} (g per passenger[1])	0.49	0.48	0.47	-4.2	-2.0	0.47	0.47
PM_{10} (kg per movement[2])	0.08	0.07	0.07	-1.2	-0.1	0.08	0.07
$PM_{2.5}$ (tonnes per year)	28.11	27.62	27.56	-1.9	-0.2	27.88	27.32
$PM_{2.5}$ (g per passenger[1])	0.39	0.38	0.37	-5.4	-2.3	0.37	0.36
$PM_{2.5}$ (kg per movement[2])	0.06	0.06	0.06	-2.4	-0.5	0.06	0.06

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

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

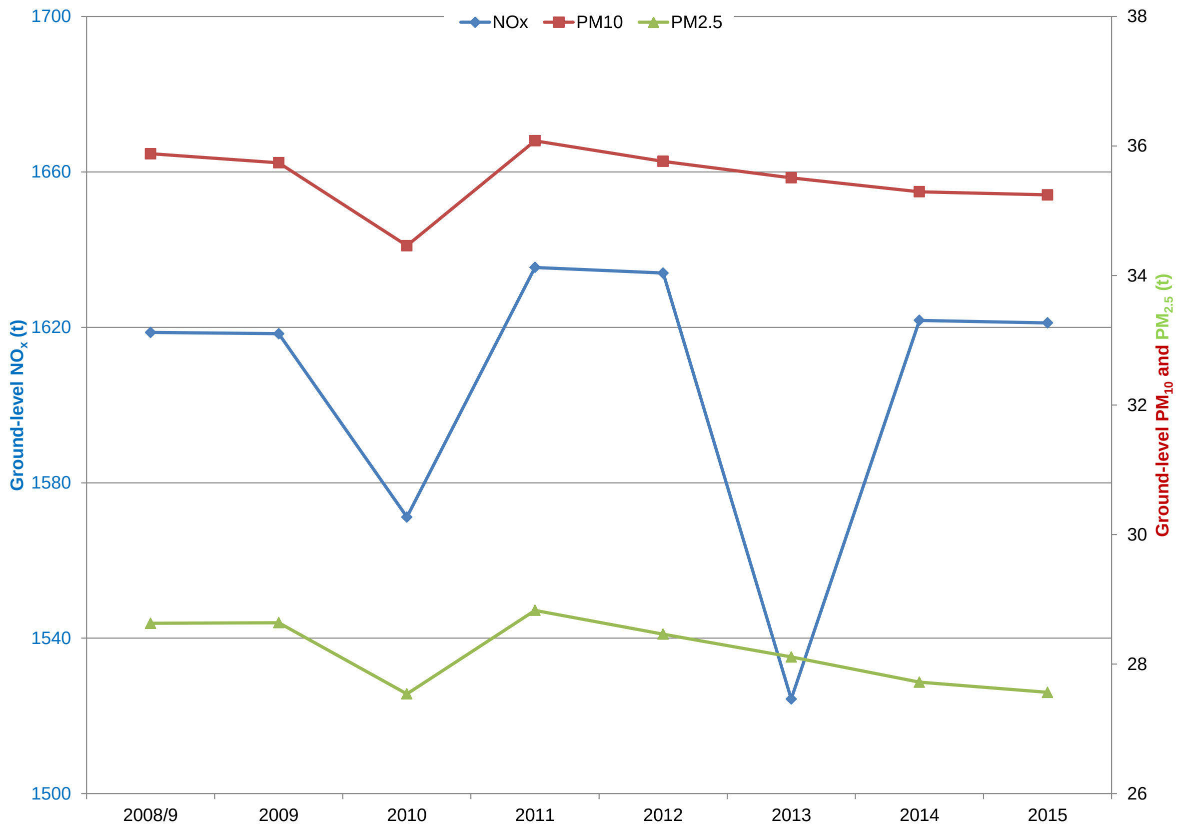


Figure 10 Ground-level NO_x emissions per movement and per passenger

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

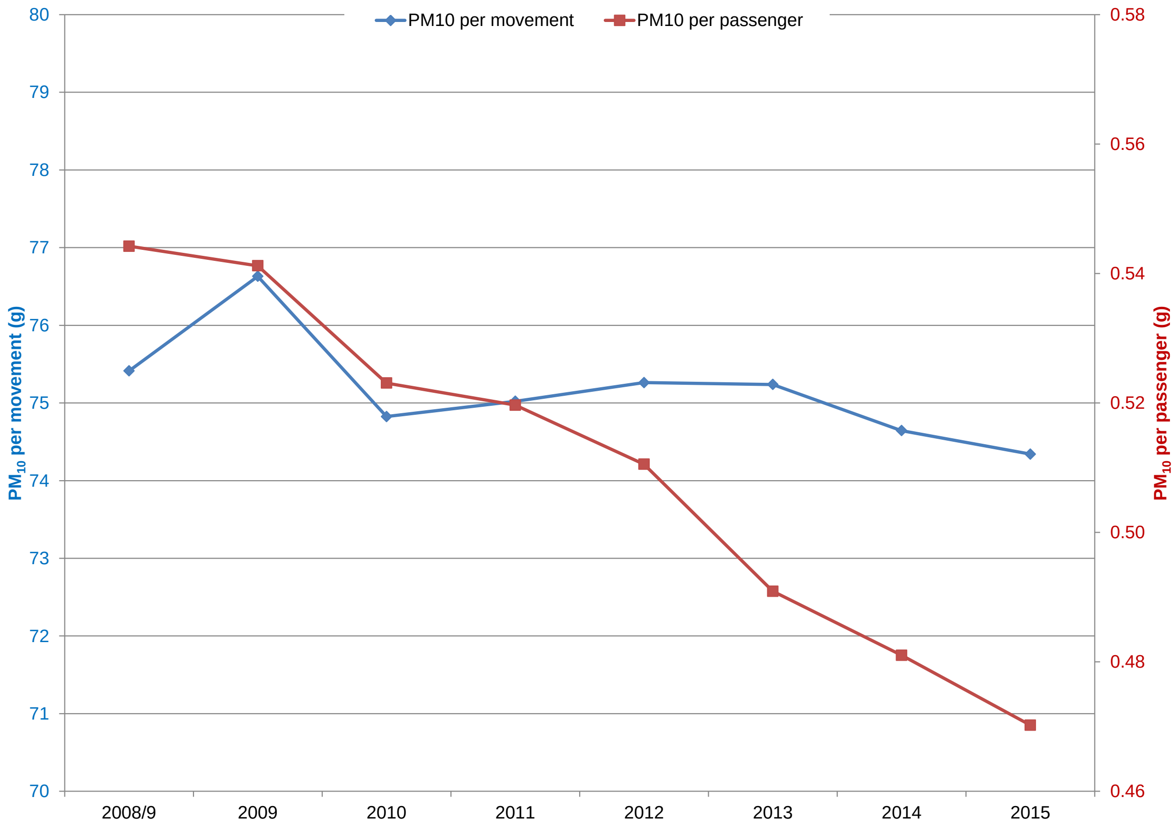
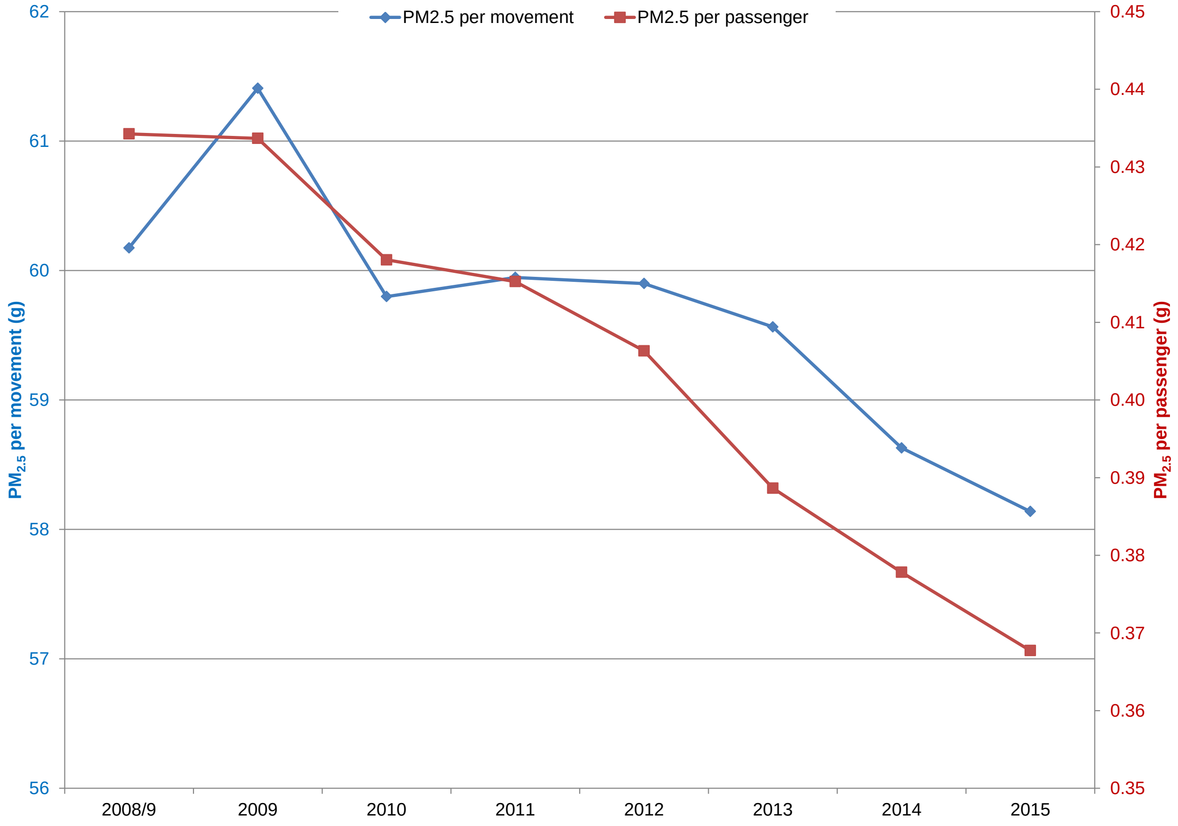


Figure 12 Ground-level $PM_{2.5}$ emissions per movement and per passenger



5.1 Reduced-engine taxi

Reduced-engine taxing at currently recorded use levels (~21% on taxi-out) offer only modest savings over conventional taxing. Savings from reduced-engine taxiing in 2015 were almost completely offset by increased emissions from APUs. The net effect is that with reduced-engine taxi ground-level NOx, PM10 and PM2.5 are 0.3%, 0.6% and 0.8% lower than with conventional taxi, respectively.

We recommend that Heathrow should continue to record the use of reduced-engine taxiing for both 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.

6 References

[i] Underwood B Y, Walker C T and Peirce M J (2010) Heathrow Airport emission inventory 2008/9. AEAT/ENV/R/2906.
[ii] Underwood B Y, Walker C T and Peirce M J (2010) Air quality modelling for Heathrow Airport 2008/9: methodology. AEAT/ENV/R/2915.
[iii] Underwood B Y, Walker C T and Peirce M J (2010) Heathrow Airport air quality modelling for 2008/9: results and model evaluation. AEAT/ENV/R/2948.
[iv] Peace H, Walker C T and Peirce M J (2015) Heathrow Airport 2013 Air Quality Assessment. Ricardo-AEA/R/3438.
[v] Walker C T, Peirce M J and Peace H (2015) Heathrow Airport 2013 Air Quality Assessment: Model Evaluation. Ricardo-AEA/R/3439.
[vi] Walker C T (2015) Heathrow Airport 2014 Emission Inventory. Ricardo-AEA/ED60533.
[vii] Underwood B Y (2010) Heathrow 2008/9 air quality. ED45973/N/002.
[viii] Brooke A S, Caves R E and Jenkinson L R (1995) Methodology for assessing fuel use and emissions from aircraft ground operations. TT 95 R 05. Department of Aeronautical and Automotive Engineering and Transport Studies, the University of Technology, Loughborough
[ix] QinetiQ (2006) Personal communication

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