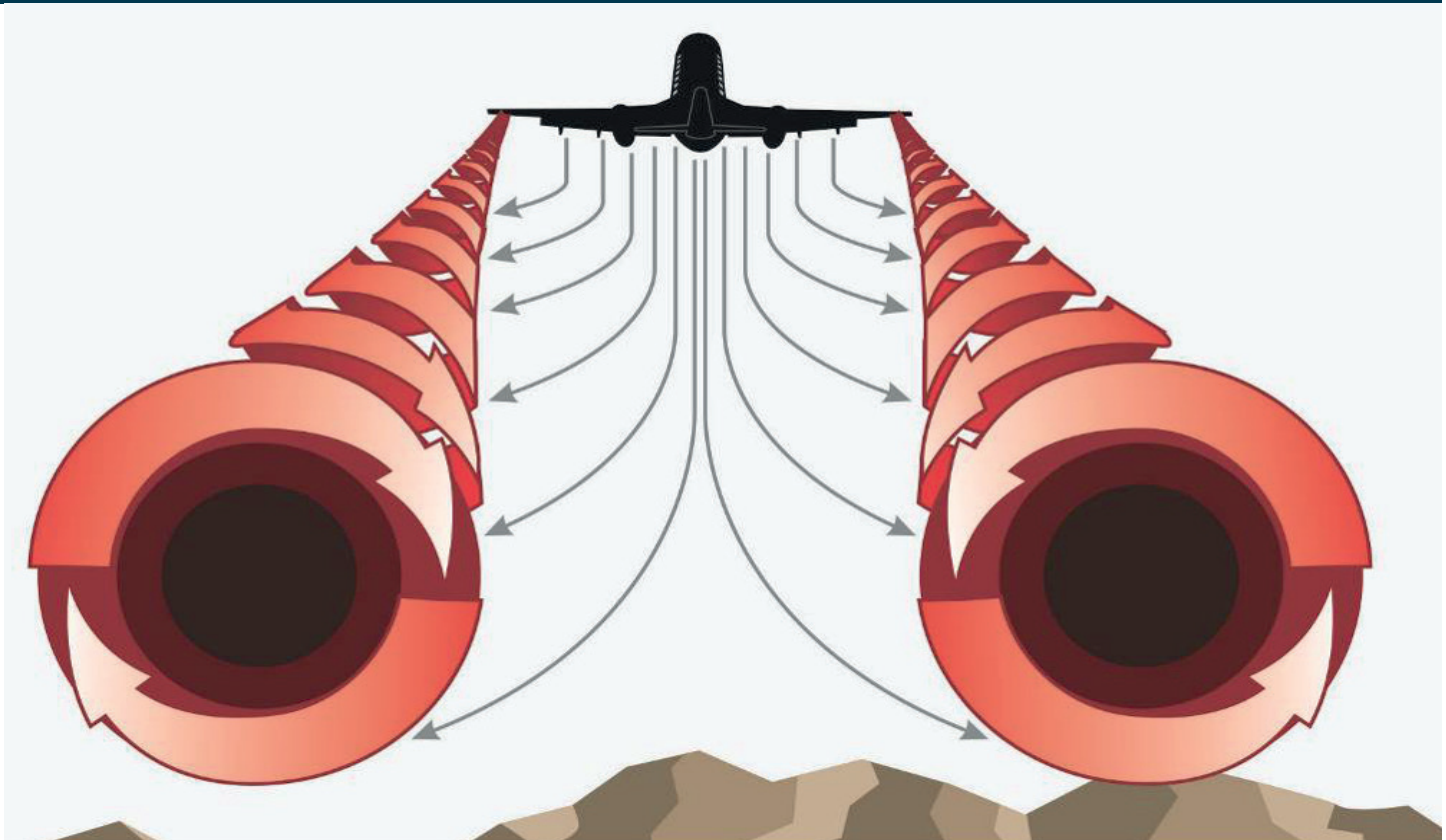




Australian Government
Australian Transport Safety Bureau

Analysis of wake turbulence occurrences at Sydney Airport 2012–2016

A Bayesian analysis



Investigation

ATSB Transport Safety Report

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Postal address: PO Box 967, Civic Square ACT 2608
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Telephone: 1800 020 616, from overseas +61 2 6257 4150 (24 hours)
Accident and incident notification: 1800 011 034 (24 hours)
Facsimile: 02 6247 3117, from overseas +61 2 6247 3117
Email: atsbinfo@atsb.gov.au
Internet: www.atsb.gov.au

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Addendum

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Safety summary

What is wake turbulence

For fixed-wing aircraft, wake turbulence is the combined effect of jet blast or propeller wash with wake vortices. Wake vortices are the primary contributor to wake turbulence. The initial strength of the vortices is primarily dependent upon the generating aircraft's speed, weight and wingspan. These vortices decay with time and largely become non-hazardous—depending on atmospheric conditions—within several minutes.

The wake vortices can affect following aircraft in a similar way to flying through weather-related turbulence. More specifically, aircraft encountering wake turbulence may experience an induced roll, which can increase safety risk, especially during phases of flight close to ground such as arrivals and departures. The risk of an injury resulting from a wake turbulence encounter is higher for cabin crew than passengers, who are generally secured in their seats earlier during arrivals.

To minimise the risk to safety associated with wake turbulence, air traffic control separates aircraft arriving or departing from an airport using wake turbulence separation standards. These are time and/or distance-based measures that limit the separation of leading and following aircraft and are designed to reduce the likelihood and severity of wake turbulence occurrences. These standards are not applicable to parallel runways which are separated by more than 760 m. As a result, they do not apply during parallel runway operations at Sydney Kingsford Smith International Airport (Sydney Airport), where the parallel runways are separated by around 1,000 m.

The analyses in this investigation only includes encounters with wake turbulence, primarily reported by aircrew, that have been classified as an occurrence.¹ Generally, they were reported to have resulted in a missed approach or go-around, control issues for the aircraft, a warning activation, and/or an injury.

Why the ATSB conducted this research

In 2016, through routine monitoring of safety occurrence data, the ATSB identified a potential safety issue regarding the high proportion of wake turbulence occurrences at Sydney Airport.

To identify the contributing factors to this higher rate of occurrences at Sydney, and the level of safety risk of wake turbulence occurrences at the airport, the ATSB initiated an Aviation Research investigation under the *Transport Safety Investigation Act 2003*.

What the ATSB found

In Australia, between 2012 and 2016, 179 wake turbulence occurrences were reported to the ATSB, with 78 of these occurring at Sydney Airport. In addition to its high proportion of wake turbulence occurrences, seven of the eight minor injuries reported as being a result of a wake turbulence occurrences were at Sydney. Further, when compared with the combined data from other major Australian airports (Adelaide, Brisbane, Melbourne and Perth), an aircraft was more likely to have a missed approach or go-around, a ground proximity alert, or have control issues following a wake turbulence encounter at Sydney Airport.

¹ Occurrences (accidents, serious incidents or incidents) are defined, as a minimum, as an event associated with the operation of an aircraft which affects or could affect the safety of operation (International Civil Aviation Organization, Annex 13, *Aircraft accident and incident investigation*), and meets the definition of a 'Transport Safety Matter' (Transport Safety Investigations Act 2003, Section 23).

Sydney Airport is the only major Australian airport currently with parallel runways. The distance between these runways is such that they are treated as individual runways and do not require the application of the wake turbulence separation standard for aircraft operating to a single runway.

The investigation found that at Sydney Airport, when the time between arriving aircraft (including those operating on parallel runways) is less than one per minute, the likelihood of encountering wake turbulence increased substantially, with Runway 34 Right (the shorter of the parallel runways) the most likely to be affected.

Despite the distance between the parallel runways at Sydney Airport exceeding the regulatory standard (for aircraft separation to treat the parallel runways the same as a single runway), evidence indicates that wake turbulence generated by aircraft arriving on one runway can affect aircraft arriving on the parallel runway, especially under certain wind conditions. Aircraft arriving on Runway 34 Left were found to be the most likely cause for more than half of the Runway 34 Right arrival wake turbulence occurrences. A leading Airbus A380 (a super heavy aircraft) probably generated more than one-third of these occurrences.

The rate of reported wake turbulence occurrences by arriving aircraft following an Airbus A380 was more than double that of any other aircraft type arriving at Sydney. All A380 wake turbulence occurrences took place outside peak arrival periods (one or more aircraft arrivals per minute). Medium weight aircraft, such as a Bombardier DHC-8 or Boeing 737, were more likely to report an encounter with wake turbulence than larger aircraft. No light aircraft reported encountering wake turbulence at the airport.

There were no reported wake turbulence occurrences at Sydney Airport between 2012 and 2016 that occurred during a reported loss of separation (breach of the wake turbulence separation standard). In contrast to wake turbulence occurrences, the rate of other turbulence occurrences at Sydney Airport is consistent with other major Australian airports.

The investigation concluded that there was a disproportionate rate and level of consequence of reported wake turbulence occurrences for aircraft arriving at Sydney Airport compared to other major Australian airports in the years 2012 to 2016. Given the parallel runway configuration, wake turbulence occurrences at Sydney Airport were found to be associated with:

- arrival densities of one or more aircraft per minute (including parallel runway arrivals), especially on flights that arrived on Runway 34 Right
- wind direction from the west or north-west for aircraft arriving on Runway 34 Right, especially when coinciding with a heavy or super heavy aircraft arriving on Runway 34 Left
- arrivals following an Airbus A380 compared to other aircraft.

More than half of the wake turbulence occurrences during arrival at Sydney Airport were associated with one or more of the above three factors. Removing all of these factors would halve the occurrence rate and make it more comparable to other major airports, however, the rate at Sydney Airport would likely still be higher than other major Australian airports. This suggests other factors beyond the scope of this investigation are also influencing wake turbulence at Sydney.

What's been done as a result

Airservices Australia will publish an Aeronautical Information Circular (AIC) aimed at operators who operate into Sydney Airport. The AIC will advise industry of the injuries associated with wake turbulence for Runway 34 Right as identified in the ATSB Report. The AIC will also recommend that cabin crew should be seated and secured in the earlier part of the approach.

However, the ATSB did not consider that the proposed safety action would adequately reduce the risk associated with the safety issue. As such, the ATSB has issued a safety recommendation that Airservices introduce measures to reduce the frequency of wake turbulence occurrence at Sydney Airport.

Airservices has since informed the ATSB that the following measures will also be implemented:

- provide wake turbulence caution to aircraft on approach to 34R that will operate within the wake turbulence distance of a Heavy or Super heavy aircraft making an approach to runway 34L
- increasing separation distances for arrivals from 4 NM to 5 NM on runways 16L/R and 34L/R
- applying the single-runway wake turbulence standard to the parallel runways when the leading aircraft is a super heavy like an A380 and the following aircraft is light (under 25,000 kg).

The ATSB agrees that these have the potential to reduce the wake turbulence risk but encourages Airservices to consider conducting their own quantitative analyses to explore other options that could further reduce the risk of wake turbulence for aircraft arriving into Sydney Airport.

Safety message

When departing or arriving at Sydney Airport, aircrews need be alert to the increased likelihood of encountering wake turbulence especially during periods of high movement density or during parallel runway operations, when operating on Runway 34 Right with wind coming from the west or north-west, and/or following an Airbus A380.

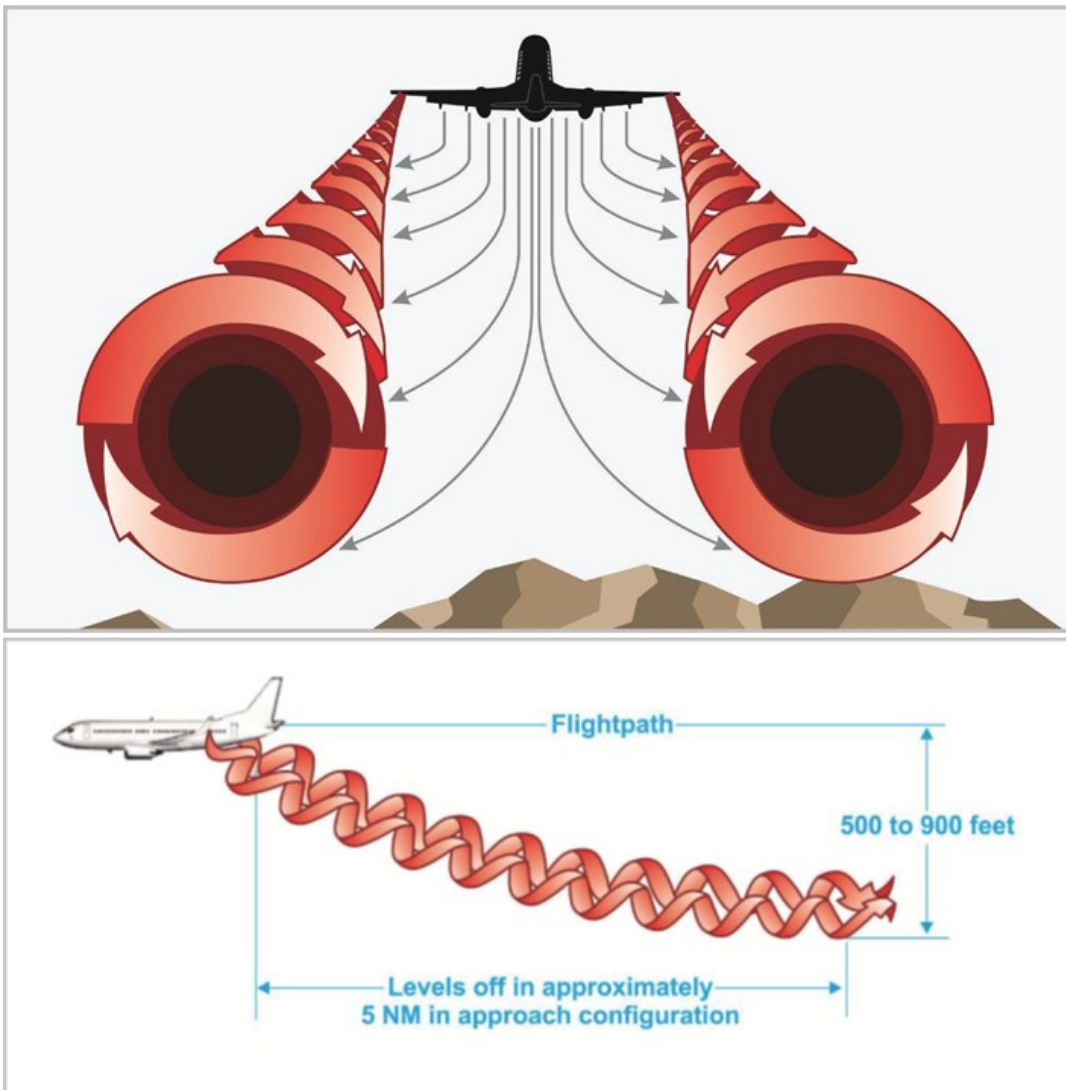
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Wake turbulence

Wake turbulence is the combined effect of jet blast or propeller wash with wake vortices (fixed-wing aircraft) or rotor wash (rotary-wing aircraft). This report is limited to wake turbulence generated by fixed-wing aircraft. Wake vortices are the primary contributor to wake turbulence from fixed-wing aircraft. As an aircraft generates aerodynamic lift, vorticity is generated and shed by the aircraft's wings, flaps, tail and body. Within a few wingspans downstream, this vorticity rolls up into a pair of counter-rotating vortices (Figure 1). These may affect following aircraft. The initial strength of the vortices is primarily dependent upon the generating aircraft's speed, weight, wingspan, and to a lesser extent, flight configuration and design. Vortices decay with time and largely become non-hazardous—depending on atmospheric conditions—within several minutes.²

Figure 1: General propagation of wake vortices



Source: FAA ([Advisory Circular: Aircraft Wake Turbulence, AC No: 90-23G](#)).

² Proctor F. H. et al., *Three-Phased Wake Vortex Decay*, American Institute of Aeronautics and Astronautics, 2010.

The vortices generally descend at an initial rate of around 300 to 500 feet per minute for the first 30 seconds.^{3,4} The descent rate usually decreases and eventually levels-off at around 500 to 900 feet below the flight path (Figure 1). Commonly, the vortices have a lateral velocity of around five knots away from the wingtips.

Extra movement of the vortices can be caused by crosswinds allowing them to remain within the flight path longer, or in higher winds, to cause the vortices to drift from the flight path before sufficiently decaying to a non-hazardous state.

Minimum separation time standards (Table 1) between leading and following aircraft are used by air traffic control to reduce the risk to following aircraft from the effects of wake turbulence. Other standards are also used for other aircraft/runway configurations—aircraft operating in opposite directions, displaced landing thresholds, and intermediate departures.⁵

Wake turbulence separation standards are time and/or distance-based measures that limit the separation of leading and following aircraft and are designed to reduce the likelihood and severity of wake turbulence occurrences. However, it is acknowledged that wake turbulence separation standards will not completely eliminate the hazards associated with wake turbulence vortices.

All aircraft are categorised into four wake turbulence weight categories:

- SUPER HEAVY
 - Airbus A380 and Antonov AN225
- HEAVY⁶ – Aircraft (excluding the A380 and AN225) with an MTOW⁷ of 136,000 kg or more
 - Boeing 747, Boeing 767, Airbus A330, Boeing 777 and Airbus A340
- MEDIUM – Aircraft with an MTOW greater than 7,000 kg and less than 136,000 kg
 - Boeing 737, Airbus A320, Bombardier DHC-8, SAAB 340, and Fokker F27 and F28
- LIGHT – Aircraft with an MTOW of 7,000 kg or less.
 - Piper PA28, Cessna 172, Cessna 182, Piper PA31 and Cessna 210.

³ Airservices Australia, *Wake Turbulence Hazards and Characteristics*. <http://www.airservicesaustralia.com/wp-content/uploads/wake.pdf>.

⁴ *Pilot and Air Traffic Controller Guide to Wake Turbulence*. Federal Aviation Administration. https://www.faa.gov/training_testing/training/media/wake/04SEC2.PDF

⁵ *Manual of Standards Part 172—Air Traffic Services Version 1.7*. Flight standards Branch, Standards Division, Civil Aviation Safety Authority.

⁶ Includes Boeing 757 and CH-47 aircraft, despite having MTOW's less than 136,000 kg.

⁷ Maximum take-off weight.

Table 1: Time and distance-based wake turbulence separation minima for full length or crossing runway operations, or crossing flight paths. Valid for following aircraft operating within 760 m laterally of the leading aircraft’s flight path—distance between parallel runways at Sydney Airport is around 1,000 m

Aircraft Categories		Separation Minima - Time		Separation Minima - Distance	
Leading aircraft	Following aircraft	Departure* (minutes)	Arrival (minutes)	Departures* (nautical miles)	Arrival (nautical miles)
SUPER	HEAVY	2	3	6	6
	MEDIUM	3	3	7	7
	LIGHT	3	4	8	8
HEAVY	HEAVY	Distance only	Distance only	4	4
	MEDIUM	2	2	5	5
	LIGHT	2	3	6	6
MEDIUM fixed-wing aircraft with MTOW of 25,000 kg or more, and all MEDIUM helicopters	LIGHT	2	3	5	5

* Refers full length (or crossing) runway operation

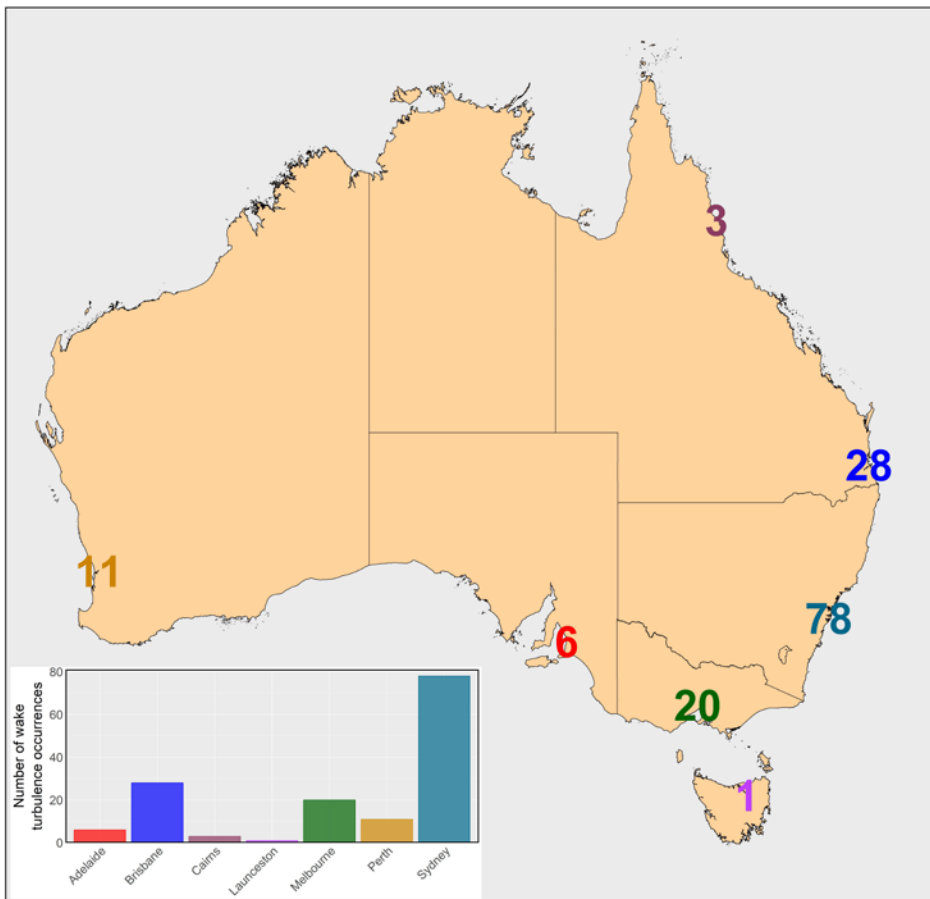
Wake turbulence occurrences at major Australian airports

Why investigate wake turbulence occurrences at Sydney Airport

Almost half (44 per cent) of all wake turbulence occurrences in Australia, reported to the ATSB between 2012 and 2016, were at Sydney Kingsford Smith International Airport (Sydney Airport). When excluding occurrences that happened en route (not associated with arrival or departure), this represents over half of all wake turbulence occurrences in Australia (Figure 2).

Further analysis found that Sydney Airport has a significantly higher rate of reported wake turbulence occurrences than other major Australian airports. Sydney is the busiest major airport in Australia and the only major airport currently with parallel runways. The mix of super heavy to medium and light aircraft differs across airports, and Sydney has more super heavy aircraft than many other major airports. Although these factors are not explicitly compared across airports in this analysis, their influence on wake turbulence is examined specifically for Sydney Airport in the chapter below.

Figure 2: Number of reported wake turbulence occurrences at Australian Airports (2012–2016)⁸



Map source: [Australian Bureau of Statistics](http://www.abs.gov.au). Data source: ATSB occurrence database

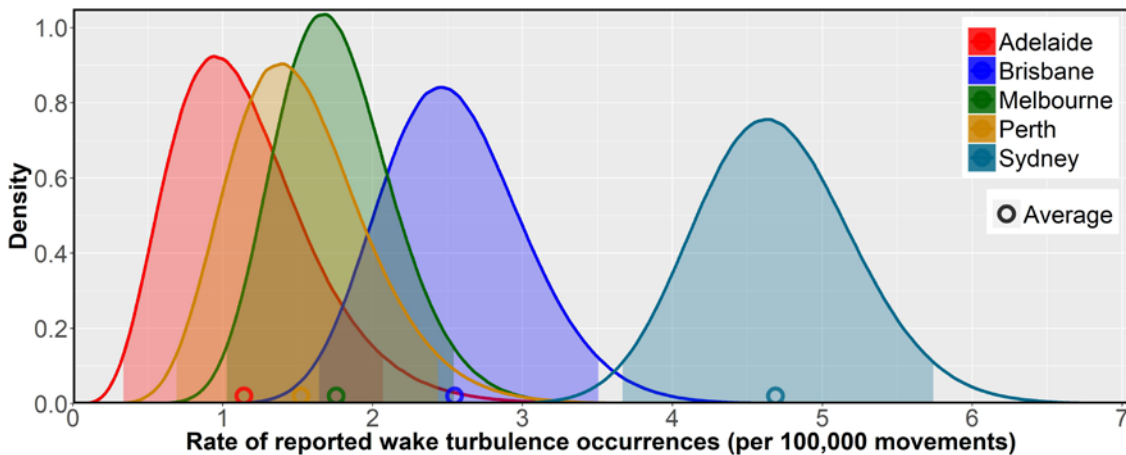
⁸ All plots through this report were created in R using the ggplot2 package (H. Wickham. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, 2009.).

The rate⁹ of reported wake turbulence occurrences at Sydney Airport (2012–2016) was found to be statistically significantly greater than all other major Australian airports.

Figure 3 displays the probability density function of the rate (per 100,000 movements) of reported wake turbulence occurrences at major Australian airports where wake turbulence occurrences were reported. Due to the limited data available, the method adopted for presenting rates in this report also displays the uncertainty in the rate. For example, although Sydney had a rate of 4.8, limited data means there may be some error, but Bayesian statistical methods show we are 95 per cent certain the actual rate at Sydney is between 3.8 and 5.8 wake turbulence occurrences (per 100,000 movements). The shaded areas presented in the figures below indicate the 95 per cent certainty in the estimate of the rate.

Table 3 (Appendix B) summarises this by comparisons between the airports’ rates. This information highlights that the rate at Sydney Airport is significantly greater than the other major airports.

Figure 3: Estimate of the rate of reported wake turbulence occurrences (per 100,000 movements) at major Australian airports with at least one reported wake occurrence (2012–2016)



Data sources: Airservices movements data and ATSB occurrence database. Shaded regions are the 95 per cent highest density intervals.

There is a 99.8 per cent probability that the rate at Sydney Airport is greater than at Brisbane Airport—the second highest Australian airport average¹⁰ rate. The expected number of occurrences per 100,000 movements at Sydney is 0.7 to 3.5 (95% highest density interval (HDI))¹¹ more than Brisbane.

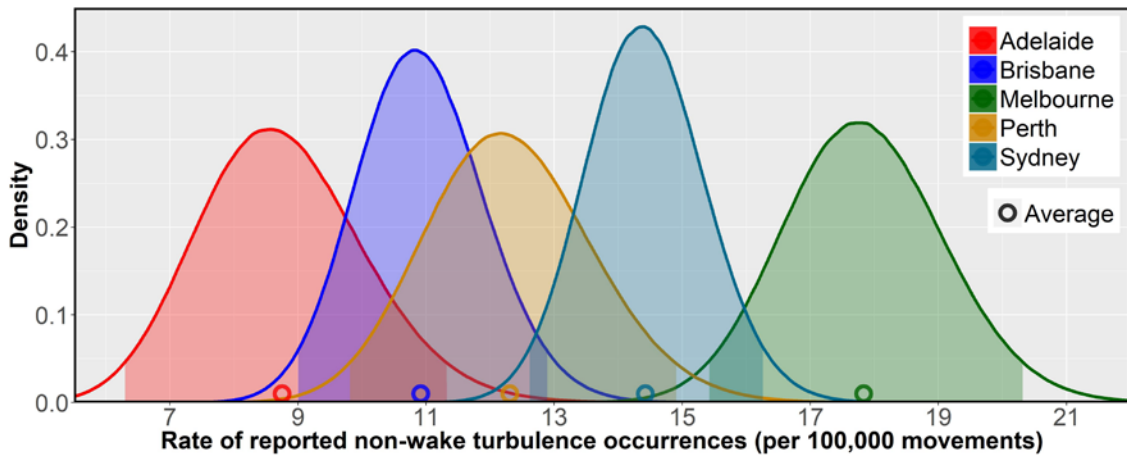
Contrary to wake turbulence occurrences, the rate of other turbulence occurrences at Sydney Airport is consistent with other major Australian airports (Figure 4).

⁹ Throughout this report the rate of reported wake turbulence occurrences is derived from the probability of an occurrence (per movements) using prior beta-binomial models with the Haldane prior. The Haldane prior beta(0,0) is the most appropriate prior for minimising the influence of prior data on the posterior distribution for a beta-binomial model (*Bayesian Methods for Statistical Analysis*, Borek Puza, ANU eView, Acton ACT Australia).

¹⁰ Within this report, the term “average” refers to the arithmetic mean.

¹¹ The Highest Density Interval (HDI) is the shortest interval which a specified proportion—95 per cent—of the data is contained. Alternatively, it can be defined as the interval in which there is a specified probability—95 per cent—that the mode of the data resides.

Figure 4: Estimate of the rate of reported turbulence occurrences—excluding wake turbulence—(per 100,000 movements) at major Australian airports featuring at least one reported wake occurrence (2012–2016)



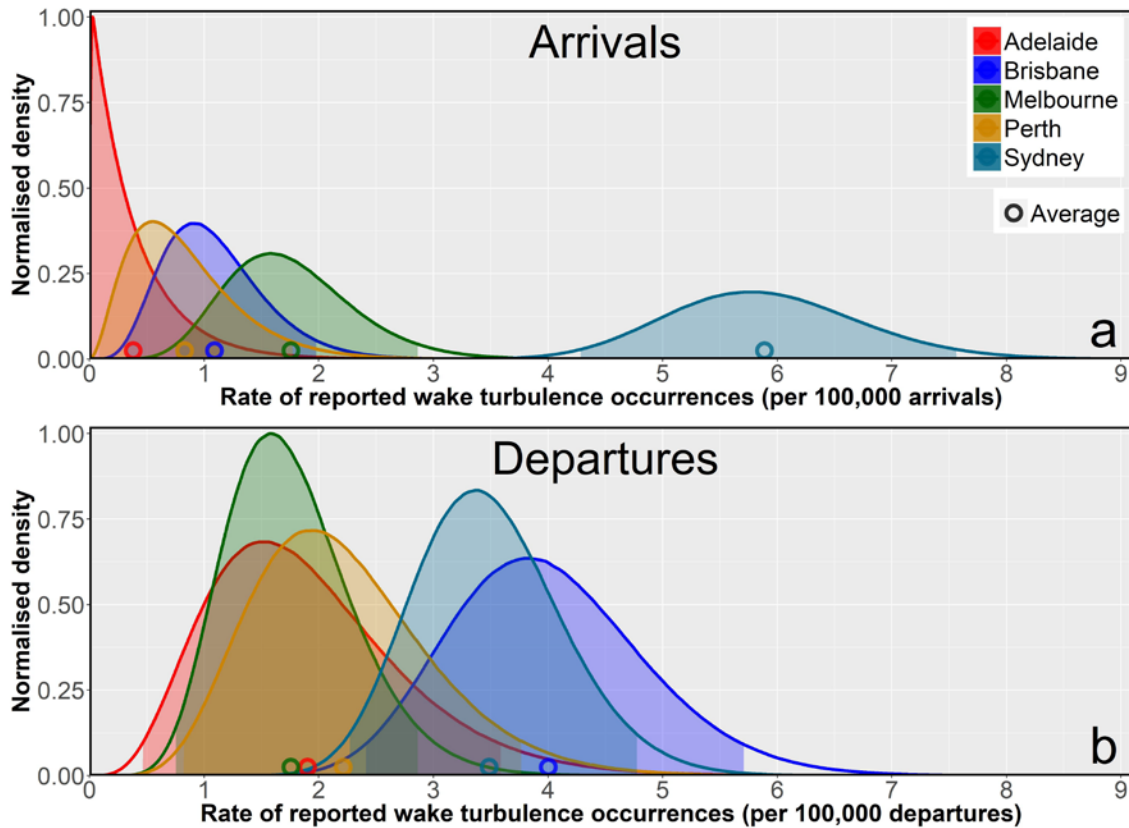
Data sources: Airservices movements data and ATSB occurrence database. The shaded regions are the 95 per cent highest density intervals.

Figure 4 shows that the higher wake turbulence rate at Sydney Airport is probably not a result of misidentifying or misclassifying other turbulence types.

Comparison between the rate of reported wake turbulence occurrences at major Australian airports is displayed separately for arrivals and departures in Figure 5. This shows that the increased rate at Sydney Airport, compared to other major airports, is driven primarily by occurrences that happen on arrival:

- Sydney was the only airport to have more wake turbulence occurrences on arrival than departure (Melbourne had an equal number split between these phases).
- The probability that the wake turbulence occurrence rate for arriving aircraft at Sydney is greater than Melbourne (the airport with the second highest rate) is more than 99.99 per cent. This would result in 1.5 to 6.5 more wake turbulence occurrences per 100,000 arrivals. Further, there is a 98 per cent probability that the rate at Sydney Airport is more than double that of Melbourne.
- The wake turbulence occurrence rate for aircraft departing Sydney Airport was consistent with the other Australian major airports. There is a 68.15 per cent probability that Brisbane Airport's rate was greater than Sydney Airport.

Figure 5: Estimate of the rate of reported wake turbulence occurrences for aircraft arriving per 100,000 arrivals (a) or aircraft departing per 100,000 departures (b) at major Australian airports (2012–2016)



Data sources: Airservices movements data and ATSB occurrence database. Shaded regions are the 95 per cent highest density intervals. For ease of comparison, all density values were normalised with respect to one for the highest value.

The rate of reported wake turbulence occurrences affecting medium aircraft (e.g. a Bombardier DHC-8 or Boeing 737) at Sydney Airport is statistically significantly greater (99.96%) than at any other major Australian airport (Figure 6a).

Considering the rate of wake turbulence occurrences for heavy¹² aircraft (e.g. Boeing 747, 767 or Airbus A330 (Figure 6b)), the probability that the rate at Sydney is greater than other major Australian airports is around 21.4 per cent. The probability of Adelaide Airport having a greater rate was 73.5 per cent. However, this result was strongly influenced by the single occurrence at Adelaide—only one heavy aircraft occurrence from relatively few movements—resulting in a high level of uncertainty.

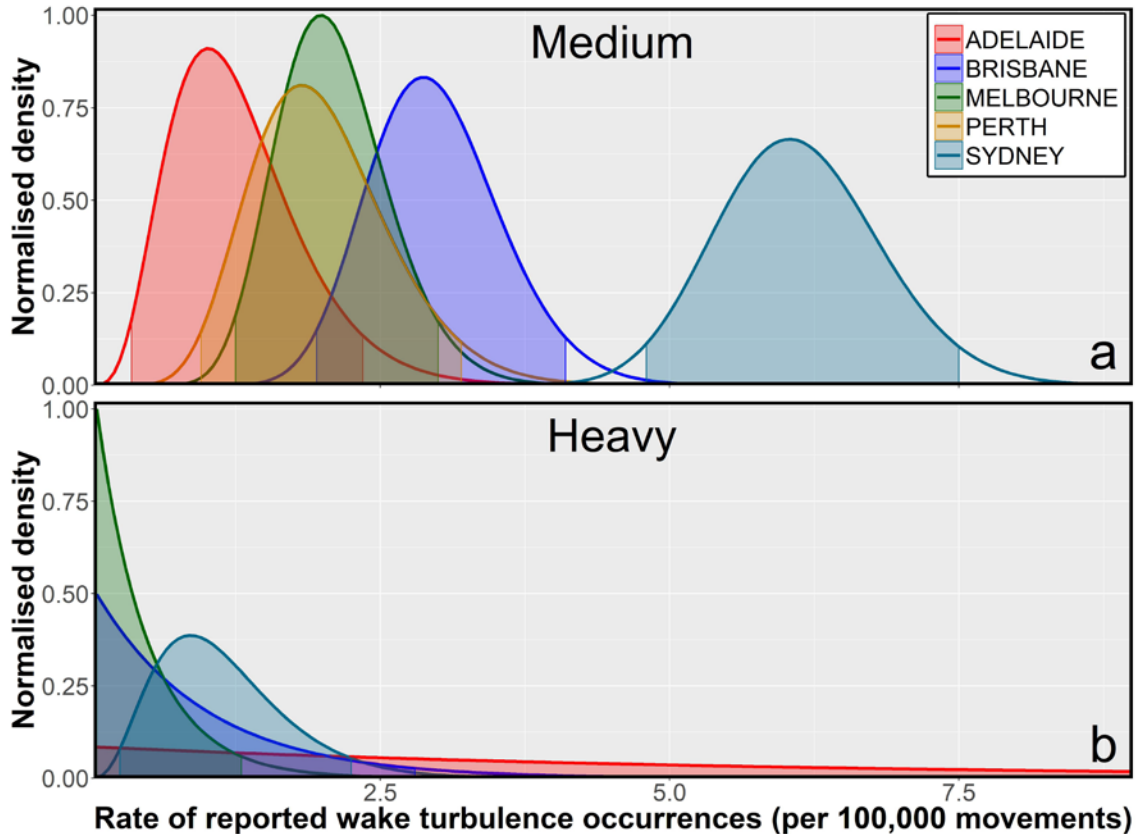
No light aircraft reported encountering wake turbulence at a major Australian airport between 2012 and 2016. Overall, the probability of no light aircraft wake turbulence occurrences over the time period is around 0.4 per cent. A full examination of the reasons for this low number is outside the scope of this investigation, however, some possible causes are:

- there are relatively fewer light aircraft operating at Australian major airports
- light weight aircraft operators are less likely to report encountering wake turbulence than other heavier aircraft operators
- a significant number of light weight aircraft operate outside of peak times when encountering wake turbulence is more likely

¹² The Airservices movements data in this part of the analysis did not separate between 'heavy' and 'super heavy' weight category aircraft. Although 'super heavy' aircraft contributed to the rate of wake turbulence at Sydney Airport disproportionately to other aircraft, the difference was not sufficient as to require more data from Airservices.

- the wake turbulence separation standards are better at countering the effects of wake turbulence for light weight aircraft than for heavier aircraft
- light weight aircraft are more likely to operate on different departure and arrival routes, or runways, than heavier aircraft.

Figure 6: Estimate of the rate of reported wake turbulence occurrences (per 100,000 movements) for medium (a) and heavy (b) weight category aircraft at major Australian airports (2012–2016)



Data sources: Airservices movements data and ATSB occurrence database. Shaded regions are the 95 per cent highest density intervals. For ease of comparison, all density values were normalised with respect to one for the highest value.

Consequences and injuries from wake turbulence occurrences at Australian airports

There are two components that constitute the risk of an occurrence, its likelihood (expected frequency) and the consequence of the occurrence (injuries, aircraft damage, reduction in safety margins etc.). This section explores the consequence of encountering wake turbulence at Sydney Airport compared to the combined data from other major Australian airports.¹³

Six wake turbulence occurrences resulted in minor injuries to eight people at major Australian airports over the study period. Five of these occurrences (seven minor injuries) involved aircraft arriving or departing Sydney Airport.

- During descent to Sydney Airport, two cabin crewmembers sustained minor injuries when the Airbus A320 encounter wake turbulence. The ‘seat belts on’ sign was off at the time of the occurrence (ATSB occurrence 201202518).
- During descent to Melbourne Airport, passing FL 250, one passenger sustained an ankle injury when the Embraer ERJ190 encountered wake turbulence. Paramedics attended to the

¹³ Over the study period (2012–2016), Sydney airport had 78 wake turbulence occurrences and the other major Airports (Adelaide, Brisbane, Melbourne and Perth) had a combined total of 65 wake turbulence occurrences.

passenger before they were transferred to hospital. The ‘seat belts on’ sign was on at the time of the occurrence (ATSB occurrence 201304546).

- During descent to Sydney Airport, a cabin crewmember sustained a minor injury when they hit their head when the Bombardier DHC-8 encountered wake turbulence. The ‘seat belts on’ sign was off at the time of the occurrence (ATSB occurrence 201306227).
- During climb from Sydney Airport, two cabin crewmembers sustained minor injuries when the Boeing 767 encountered wake turbulence. The ‘seat belts on’ sign was off at the time of the occurrence (ATSB occurrence 201307335).
- During descent to Sydney Airport, a cabin crewmember sustained a minor injury when the Embraer ERJ190 encounter wake turbulence (ATSB occurrence 201401357).
- During climb from Sydney Airport, a cabin crewmember sustained a minor injury to their shoulder when the Embraer ERJ190 encountered wake turbulence (ATSB occurrence 201500192).

In addition, during the study period, three other wake turbulence occurrences resulting in injury were reported. These occurred during cruise in Australian airspace and resulted in minor injuries to crewmembers (ATSB occurrences 201403800, 201501720 and 201508236).

Over the study period, there were also 84 wake turbulence occurrences (excluding occurrences with injuries) at major Australian airports where the ATSB classified risk using Event Risk Classification¹⁴ at ‘medium’. Forty-eight of these occurred at Sydney Airport. A small sample are presented below:

- During initial climb from Brisbane Airport, the Boeing 717 encounter wake turbulence resulting in around five oscillations of 20°. The flight crew reported that the aircraft was ‘at the point of being uncontrollable’ (ATSB occurrence 201310391).
- On approach to Sydney Airport, the SAAB 340 experienced an uncommanded nose down pitch and roll to the left resulting in a momentary loss of control following an encounter with wake turbulence (ATSB occurrence 201406800).
- During take-off from Adelaide Airport, the SAAB 340 encountered wake turbulence causing a 40–45° bank, a ground proximity alert and a momentary stall warning (ATSB occurrence 201501172).
- A Boeing 737, on approach at Melbourne Airport, conducted a go-around following an encounter with wake turbulence at low altitude that resulted in the approach becoming unstable. The aircraft returned for an uneventful landing (ATSB occurrence 201505617).
- Passing 1,400 ft on approach to Sydney Airport, the Embraer ERJ190 encountered wake turbulence. The aircraft banked 30° then settled back ‘wings level’. Shortly after, the aircraft rolled abruptly and the autopilot disconnected automatically. A brief stick shaker was experienced followed by the windshear fail, shaker anticipated and angle-of-attack cautions. A go-around was conducted and aircraft returned for an uneventful landing (ATSB occurrence 201507115).

Figure 7 displays the probability of an occurrence (for specific occurrences types) following an encounter with wake turbulence at Sydney Airport, compared to the combined data from other major Australian airports.¹⁵

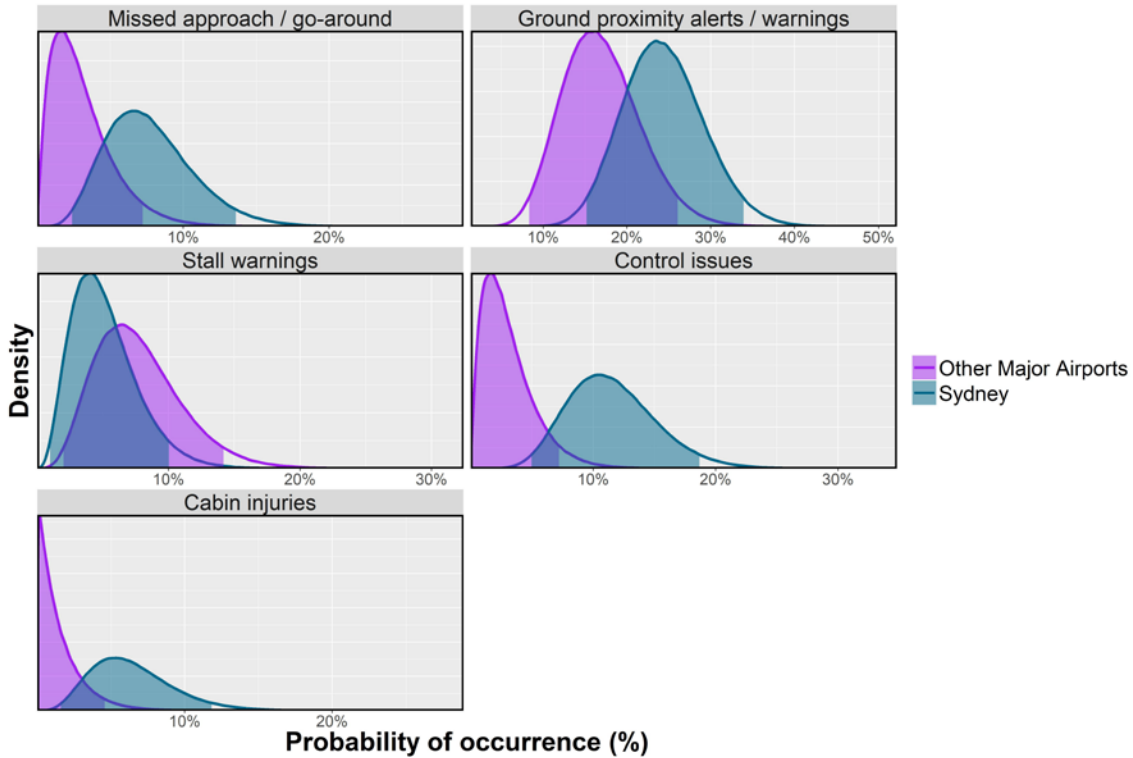
Four of the five occurrence types (control issues, go-around, ground proximity alerts, cabin injuries) were found to be more likely (greater than 86%) to occur at Sydney Airport following an

¹⁴ The Event Risk Classification (ERC) methodology is from the report The ARMS Methodology for Operational Risk Assessment in Aviation Organisations (version 4.1, March 2010). ARMS is an industry working group set up in 2007 in order to develop a new and better methodology for Operational Risk Assessments. The methodology is freely available from <https://skybrary.aero/bookshelf/content/bookDetails.php?bookId=1141>.

¹⁵ The reason for combining other major airports data was to have a comparable set (with Sydney Airport), especially when considering the lack of other occurrence types that followed a wake turbulence encounter.

encounter with wake turbulence. Alternatively, there was around a 75 per cent probability that a ‘stall warning’ is more likely following a wake turbulence encounter from the combined major airports data than at Sydney Airport.

Figure 7: Probability of selected occurrence types following a wake turbulence encounter at Sydney Airport and other major Australian airports (2012–2016)

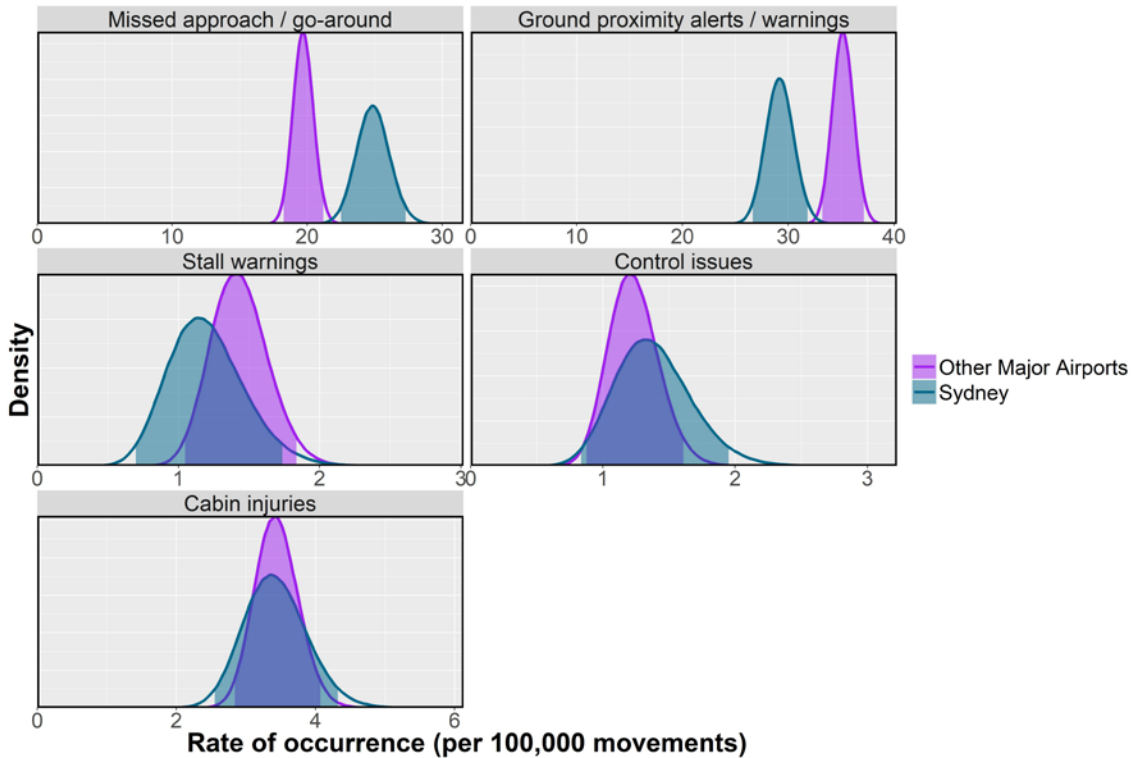


Data sources: ATSB occurrence database. Shaded regions are the 95 per cent highest density intervals.

These results may not present a fair comparison. There may be characteristics of the different airspaces¹⁶ (different aircraft and airspace operators, weather conditions, airport layout etc.) that result in contrasting likelihoods of the examined occurrence types. Figure 8 displays the overall (not just following a wake turbulence encounter) rate of occurrence for the examined occurrence types. These form the ‘base rate’, and normalise the data in Figure 7. For example, the rate of ground proximity alerts or warnings at Sydney Airport is less than the combined rate of the other airports, however; the probability of this occurrence type following a wake turbulence encounter is greater at Sydney.

¹⁶ Sydney Airport and the combined data from the other major airports.

Figure 8: Estimate of the rate for selected occurrence types (per 100,000 movements) at Sydney Airport and other major Australian airports (2012–2016)



Data sources: Airservices movements data and ATSB occurrence database. Shaded regions are the 95 per cent highest density intervals.

The extent (incorporating the data presented in Figure 7 and Figure 8) that a wake turbulence encounter increased the likelihood (from the 'base rate') of each of the selected occurrence types at Sydney Airport compared with the combined data from the other major airports is displayed in Table 2. This gives a measure of the affect a wake turbulence encounter has on the likelihood of a proceeding event (for the examined occurrence types). For example, an aircraft is around two thousand times more likely to have a cabin injury following a wake turbulence encounter than on a 'normal' flight into Sydney Airport.

Table 2: Increase (as a multiplicative factor) in the likelihood of specific occurrence types following an encounter with wake turbulence compared to its ‘base rate’ at Sydney Airport and the combined data from other major Australian airports (2012–2016)

Occurrence Type	Increase in likelihood following wake turbulence encounter		Probability Sydney Airport had a greater increase
	Sydney Airport	Other Major airports	
Missed approach/ go-around	x314 (x96 – x560)	x157 (x4 – x370)	84.6%
Ground proximity alerts/ warnings	x868 (x530 – x1,220)	x486 (x238 – x751)	96.0%
Stall warnings	x5,331 (x795 – x12,008)	x5,961 (x1,396 – x11,596)	43.9%
Control issues	x13,718 (x4,422 – x27,411)	x2,918 (x51 – x6,435)	99.2%
Cabin injuries	x2,049 (x489 – x3,984)	x451 (x0 – x1,358)	96.1%

Data sources: Airservices movements data and ATSB occurrence database. Bracketed ranges are the 95 per cent highest density intervals.

Table 2 highlights that the consequences of a wake turbulence encounter Sydney Airport are generally greater when compared to the combined data from the other major airports.

The following chapters of this report are an examination of the factors that influence the rate of reported wake turbulence occurrences at Sydney Airport. The same level of analysis was not conducted on occurrence rates at other major Australian airports. Hence, findings and conclusions below provide reasons as to why wake turbulence events are experienced at Sydney Airport and do not provide a detailed assessment of why Sydney Airport has a higher rate than the other major Australian airports.

Factors influencing reported wake turbulence occurrences at Sydney Airport

To investigate factors influencing the probability of a wake turbulence occurrence at Sydney Airport, the ATSB obtained five years (2012-2016) of weather observations from the Bureau of Meteorology and aircraft movement data from Airservices Australia. These data were coupled with data from the ATSB's occurrence database over the same study period.

This resulted in a large set of potential influencing factors, which were then narrowed down to the ten most significant potential influencing factors (Figure 9). These were identified through a mix of domain knowledge augmented with machine learning models¹⁷ (Appendix C displays a selection of machine learning results). The machine learning identified factors that may have been overlooked and was also used to reduce the effects of cognitive biases.

The ten potential influencing factors identified were:

- preceding aircraft's phase of flight (number of aircraft arrivals or departures)
- preceding aircraft's runway (number of aircraft operations on each runway)
- preceding aircraft's model (what were the preceding aircraft)
- aircraft model (the model of the aircraft used in that analysis)
- aircraft's runway (on what runway was the aircraft under analysis operating)
- average wind direction (what was the wind direction at the time of analysis)
- average wind speed (what was the wind speed at the time of analysis)
- arrival density (number of aircraft arriving per minute at the time of analysis)
- departure density (number of aircraft departing per minute at the time of analysis)
- aircraft's phase of flight (was the aircraft under analysis arriving or departing the airport).

Also identified were some of the relationships between the factors that could influence the probability of a wake turbulence occurrence. A combination of Bayesian network structure learning and domain knowledge was used to identify these relationships.

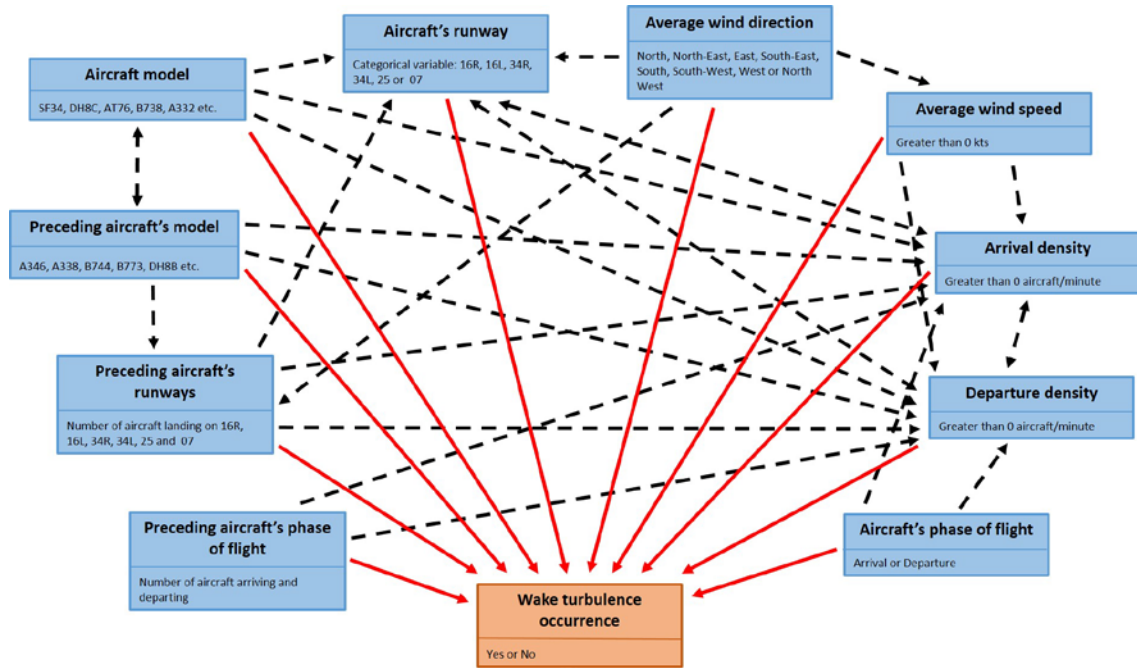
These relationships assist to identify groups of factors that may behave differently when paired than when acting independently. Figure 9 shows red solid arrows to indicate a possible direct causal link with wake turbulence occurrences, while black dashed arrows indicate possible relationships between the various factors that influence wake turbulence. The analyses below explores these factors.

Weather factors other than wind direction (temperature, pressure and humidity), were also investigated. These were found to be minor contributors to the probability of a reported wake turbulence occurrence (Appendix E displays the results for the weather factors). Wind speed (not including other factors) was investigated to a greater detail than temperature, pressure and humidity with the results presented in Appendix F.

Arrival and departure densities were calculated by dividing the number of arrivals or departures in the preceding 10 movements by the time between the first and last arrivals or departures. These calculations included movements on parallel runways and represent a brief record of the density surrounding an aircraft's arrival or departure.

¹⁷ Machine learning models that were tested include: support vector machines (linear and radial based function kernels), random forests, neural networks and gradient-boosted machines. Each was trained hundreds of times on multiple factor sets.

Figure 9: Factors influencing the rate of reported wake turbulence occurrences at Sydney Airport (2012-2016)



Red solid arrows indicate possible causal links; black dashed arrows indicate relationships between factors.

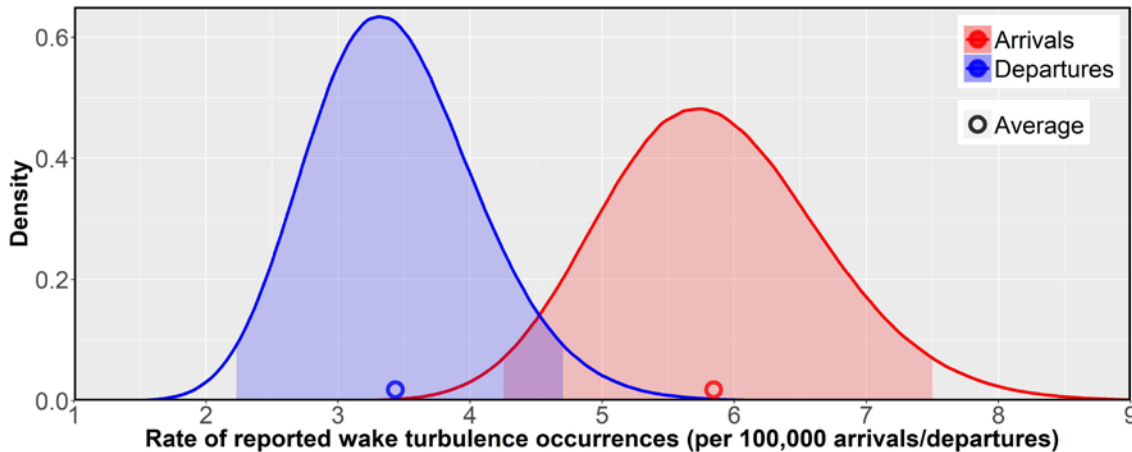
Aircraft's phase of flight

The comparison between the rate of reported wake turbulence occurrences for an aircraft's phase of flight—arriving (descent, approach or landing phases of flight) or departing (take-off, initial climb or climb phases of flight)—at Sydney airport is in Figure 10.

It was found that there is a 98.99 per cent probability that the rate of reported wake turbulence occurrences is greater for arriving than departing aircraft at Sydney Airport. The rate of a reported wake turbulence occurrence is 1.0 to 2.6 times greater for arriving than departing aircraft (resulting in 0.4 to 4.5 more occurrences per 100,000 arrivals/departures (95% HDI)). Across the various phases of flight, the ratio of occurrences were approximately:

- forty-four per cent during approach
- twenty-two per cent during climb
- sixteen per cent during descent
- thirteen per cent during initial climb
- five per cent during take-off or landing.

Figure 10: Estimate of the rate (per 100,000 arrivals/departures) of reported wake turbulence occurrences for aircraft arriving or departing Sydney Airport (2012–2016)



Data sources: Airservices movements data and ATSB occurrence database. Shaded regions are the 95 per cent highest density intervals.

Aircraft arrival/departure density¹⁸

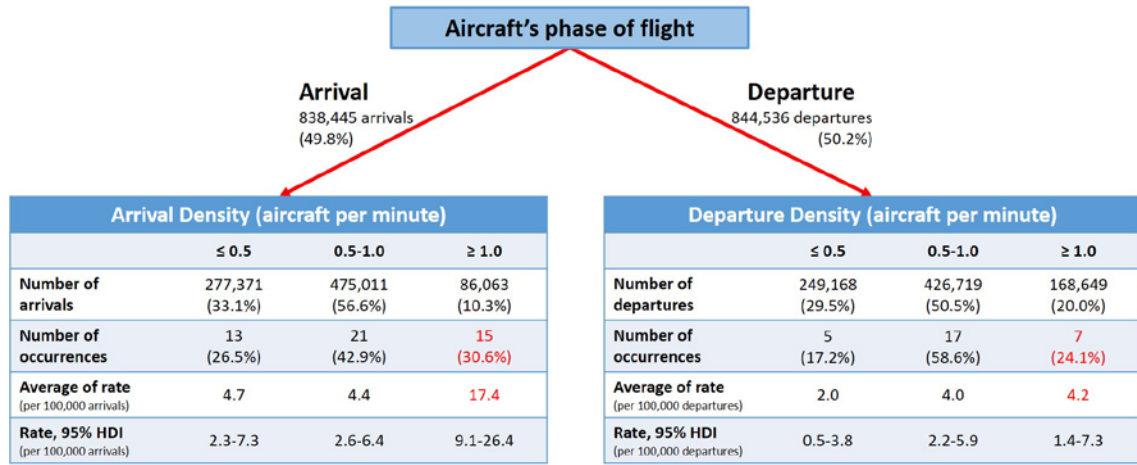
The comparison of the rate of reported wake turbulence occurrences for aircraft arriving or departing (including on parallel runways) and the aircraft arrival/departure density is in Figure 11. The rate of reported wake turbulence occurrences increases significantly with the airport’s arrival or departure density. For arrivals, there is a 99.9 per cent probability that arrival densities of one or more aircraft per minute result in a higher rate of wake turbulence occurrences than lower arrival densities. The rate of wake turbulence occurrence is 1.8 to 6.5 times greater when the arrival density is one aircraft per minute or greater. This results in 4.4 to 22.0 more occurrences per 100,000 movements (95% HDI).

Nineteen per cent of all wake turbulence occurrences result from 5.1 per cent of all arrivals when the density is greater than or equal to one aircraft per minute.

For departures, densities of one or more aircraft per minute resulted in 2.3 less to 4.3 more occurrences per 100,000 movements (95% HDI). The probability is 67.9 per cent that the rate of a wake turbulence occurrence is greater when the departure density is one or more aircraft per minute. Alternatively, departure densities greater than, or equal to, 0.5 aircraft per minute result in an increase of 0.4 to 4.4 more occurrences per 100,000 movements (95% HDI).

¹⁸ Arrival and departure densities were calculated by dividing the number of arrivals or departures, in the preceding 10 movements, by the time between the first and last arrivals or departures. These calculations included movements on parallel runways.

Figure 11: Estimate of the rate of reported wake turbulence occurrences (per 100,000 arrivals/departures) for a given aircraft’s phase of flight and arrival/departure density at Sydney Airport (2012–2016) ¹⁹



Data sources: Airservices movements data and ATSB occurrence database

Runway

Sydney Airport has two parallel runways (34 Left/16 Right, 34 Right/16 Left) and one crossing runway (07/25), as seen in Figure 12.

¹⁹ The range of the three density categories (≤0.5, 0.5 to 1.0 and ≥1.0) was determined by varying the size of each split and calculating the weighted total (arrival and departure) information gain. The set of ranges with the greatest information gain was chosen.

Figure 12: Sydney Airport Runway map

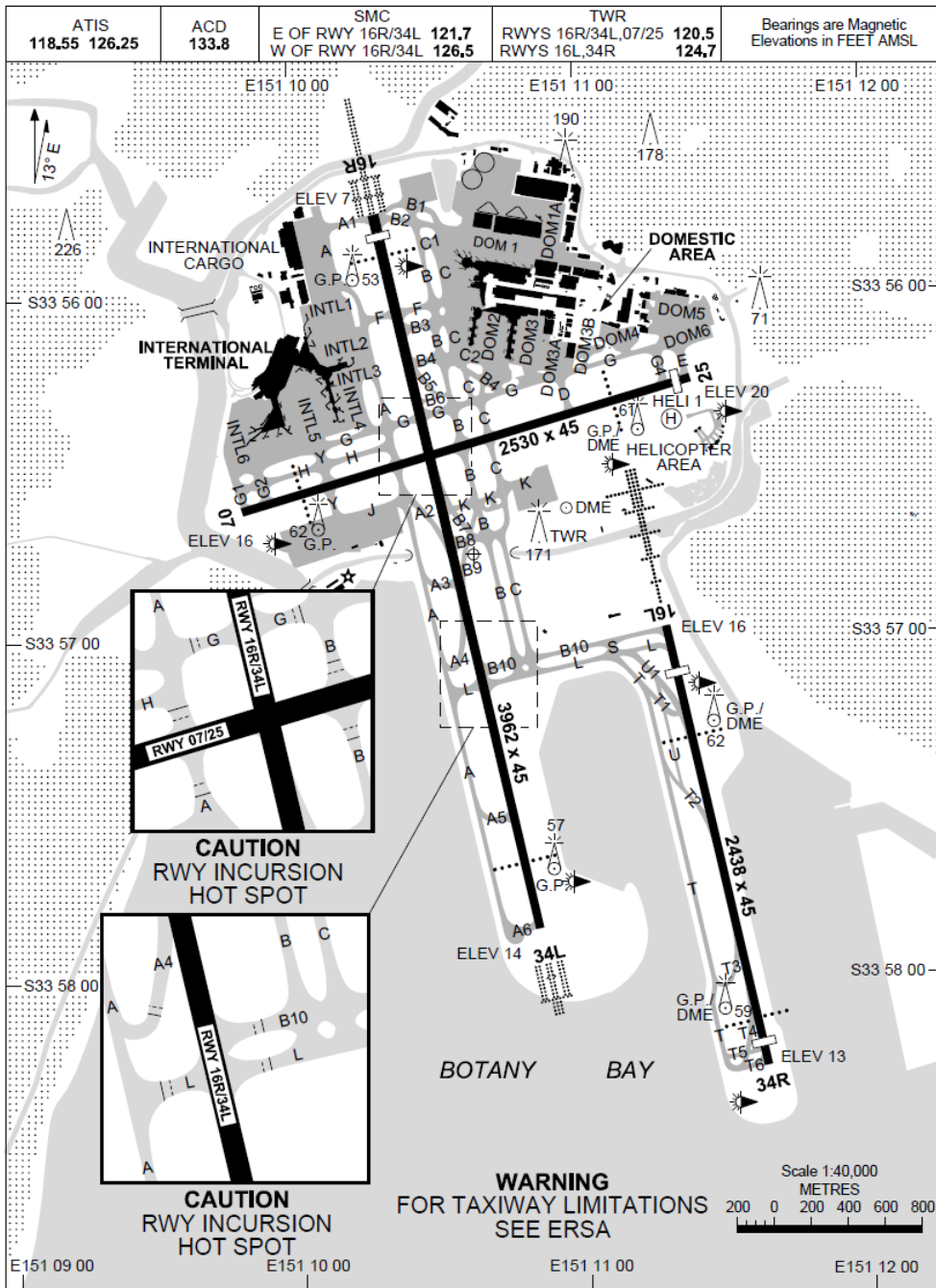


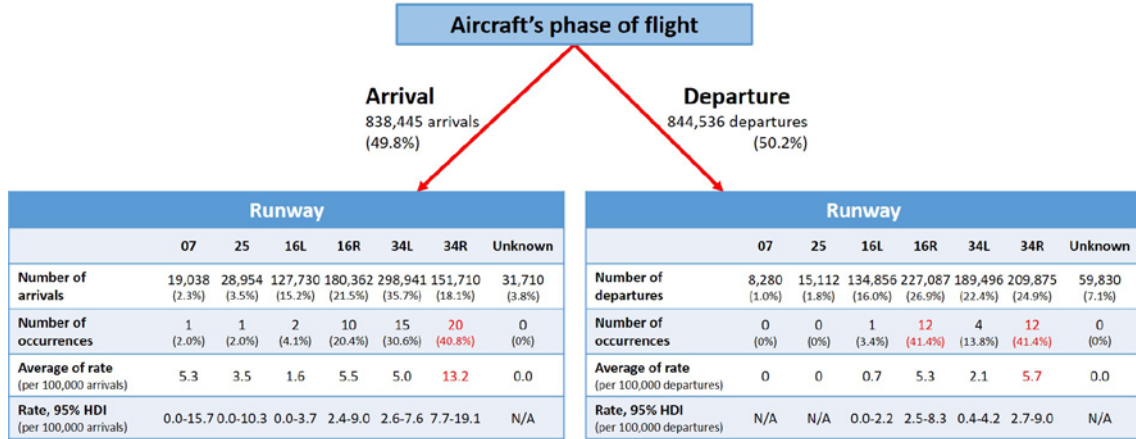
Image source: Airservices Australia (www.airservicesaustralia.com/aip/current/dap/SSYAD01-150_24MAY2018.pdf)

Comparison of the rate of reported wake turbulence occurrences for given runways at Sydney Airport is displayed in Figure 13.

Over 40 per cent of wake turbulence occurrences—on arrival or departure—involve the affected aircraft operating on Runway 34 Right.

There is at least a 90 per cent probability that the rate of reported wake turbulence occurrences is greater for arrivals on Runway 34 Right than any other runway.

Figure 13: Estimate of the rate of reported wake turbulence occurrences (per 100,000 arrivals/departures) for a given aircraft’s phase of flight and runway



Data sources: Airservices movements data and ATSB occurrence database.

Runway and arrival/departure density

Comparison of the rate of reported wake turbulence occurrences for given runways and arrival/departure densities is in Figure 14.

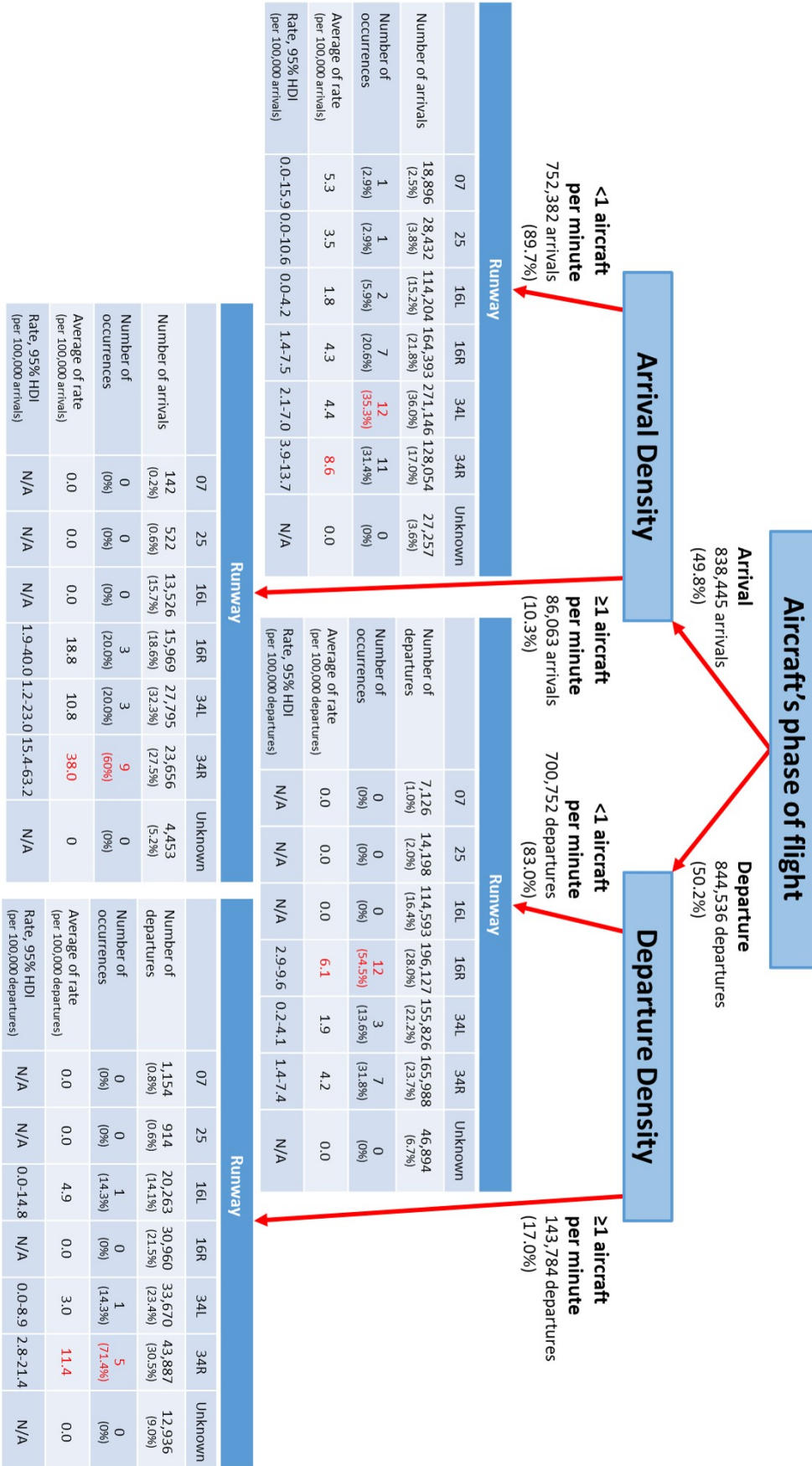
For aircraft arriving on Runway 34 Right, when the arrival density is one or more aircraft per minute, the average rate is more than double that of any other runway/arrival or departure density combinations at Sydney Airport. Around 12 per cent of all reported occurrences resulted from less than 1.4 per cent of all movements at Sydney Airport.

Runway 34 Right has a significantly higher average rate of occurrences in three out of the four scenarios presented in Figure 14.

The probability of a wake turbulence occurrence on Runway 34 Right is 1.2 to 3.9 (95% HDI) more likely than on Runway 34 Left, resulting in 1.5 to 8.5 more occurrences per 100,000 movements. Runways 34 Right and Left had around the same number of light and medium aircraft movements (335,683 vs 319,327) between 2012 and 2016. However, the ratio of light/medium to heavy/super heavy aircraft movements on Runway 34 Right was around 13-to-one, whereas for Runway 34 Left this is around two-to-one. Given lighter aircraft are more likely to be affected by wake turbulence created by larger aircraft, Runway 34 Left would be expected to have more occurrences. This is evidence of the possibility of wake turbulence created by aircraft operating on Runway 34 Left affecting aircraft on Runway 34 Right.

Runway 16 Right had around 12 per cent more light/medium movements than Runway 16 Left and a light/medium to heavy/super heavy ratio of around two-to-one. Whereas the ratio for Runway 16 Left was around 18-to-one. Further, the probability of a wake turbulence occurrence for aircraft using Runway 16 Right is 0.7 to 2.4 (95% HDI) times more likely than on Runway 34 Left. This is weak evidence to support a hypothesis of wake turbulence created on Runway 16 Left affecting aircraft on Runway 16 Right. Like Runway 34 Right, aircraft arriving or departing Runway 16 Right fly under the flight path of aircraft operating on the parallel runway.

Figure 14: Estimate of the rate of reported wake turbulence occurrences (per 100,000 arrivals/departures) for a given aircraft’s runway and arrival/departure density



Data sources: Airservices movements data and ATSB occurrence database.

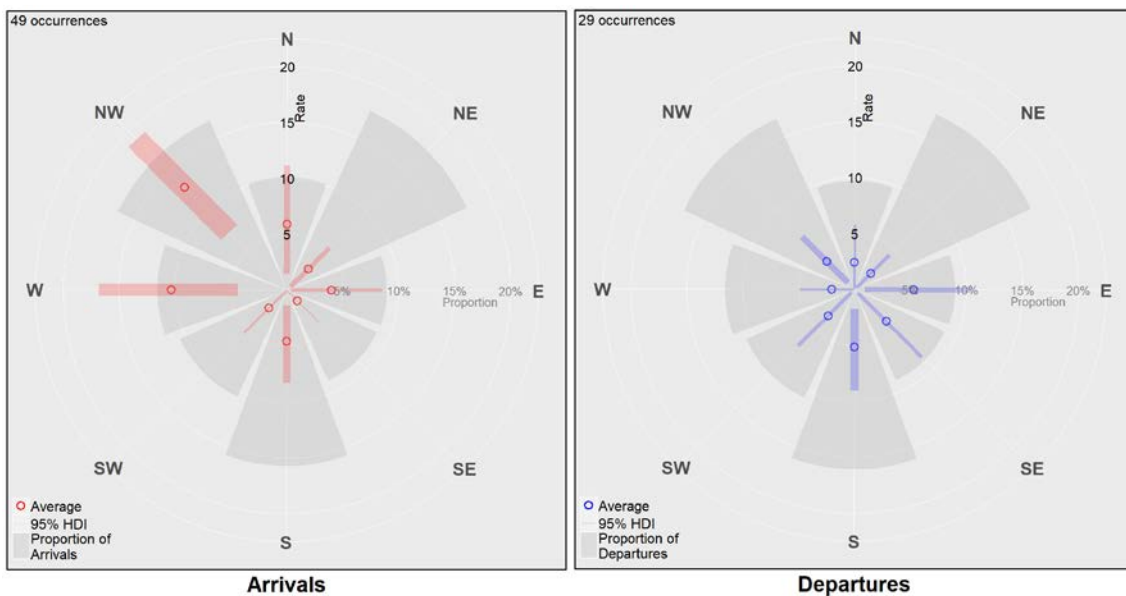
Wind direction effects on wake turbulence

Comparison of the rate of reported wake turbulence occurrences for given wind direction and aircraft orientation at Sydney Airport is in Figure 15.

For arriving aircraft, the average rate of reported wake turbulence occurrences is greatest when the wind is coming from the north-west followed by the rate of occurrences when the wind is from the west. The probability that either of these directions has the highest rate is greater than 95 per cent.

For departing aircraft, the average of the rate of wake occurrences is greatest when the wind is blowing from the east, south-east or south. The probability that any of these directions has the highest rate is greater than 77 per cent.

Figure 15: Estimate of the rate of reported wake turbulence occurrences per 100,000 arrivals (red) and departures (blue) for a given wind direction and aircraft’s phase of flight at Sydney Airport (2012–2016)



Data sources: Bureau of Meteorology weather observations, Airservices movements data and ATSB occurrence database. Red/blue bars are the 95% HDI of the rate and the width of the bars display the number of occurrence—thinnest bars indicate one occurrence and the thickest 20 occurrences. Grey segments are the proportion of flights arriving/departing when the wind is coming from that direction.

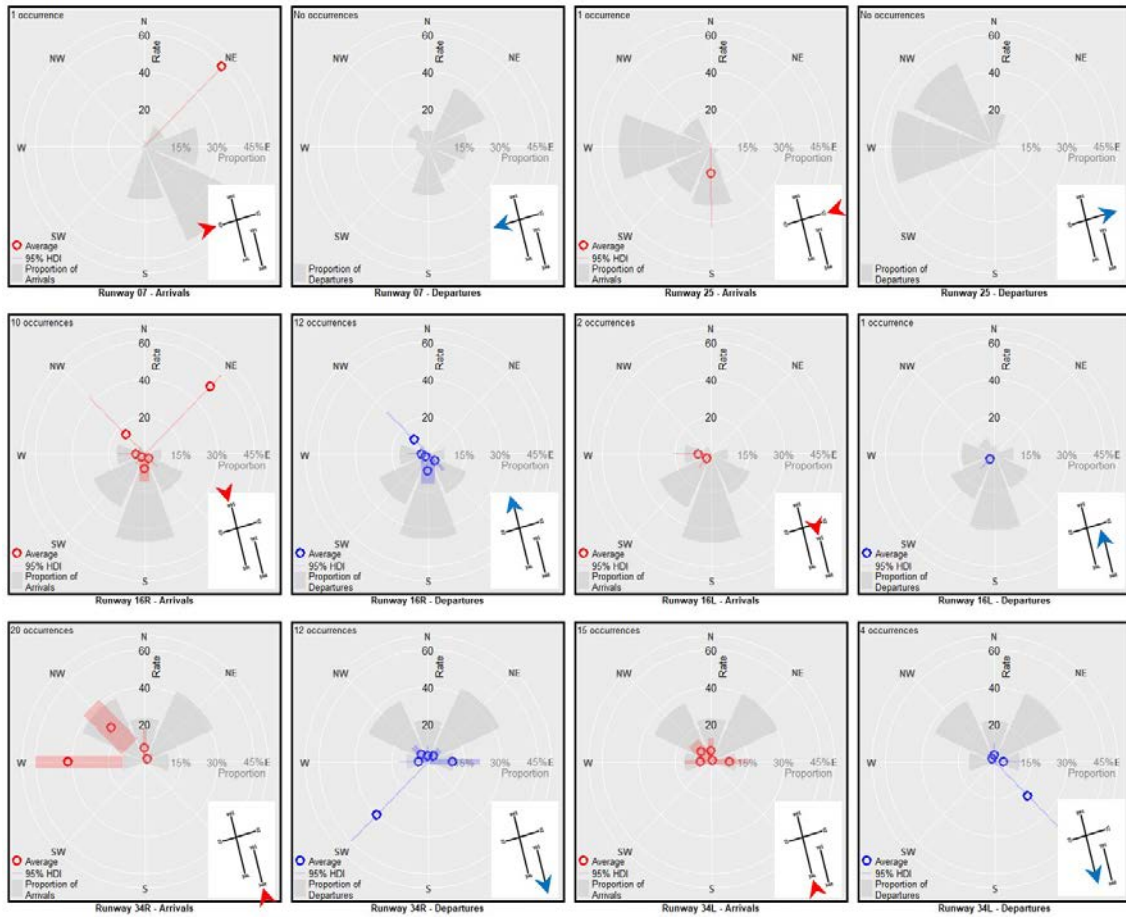
Wind direction and runway effects on wake turbulence

Comparison of the rate of reported wake turbulence occurrences for any given wind direction, runway and/or aircraft orientation at Sydney Airport is in Figure 16.

Excluding wind directions with only one reported occurrence (thinnest red/blue bars on Figure 16), the rate of wake turbulence occurrences on Runway 34 Right, when the wind is blowing from the west or north-west (the direction of Runway 34 Left) is significantly greater than for other wind direction and runway combinations. The occurrence rate increases by a factor of 4.1 to 12.6 (95% HDI), or 12.7 to 40.6 more occurrence per 100,000 arrivals, compared to other runway and wind direction combinations—including Runway 34 Right when the wind is not coming from the west or north-west.

This data supports the hypothesis that wake turbulence produced by aircraft arriving on Runway 34 Left can affect aircraft arriving on Runway 34 Right.

Figure 16: Estimate of the rate of reported wake turbulence occurrences per 100,000 arrivals (red) and departures (blue) by wind direction, aircraft’s orientation and runway at Sydney Airport (2012–2016)



Data sources: Bureau of Meteorology weather observations, Airservices movements data and ATSB occurrence database. Red/blue bars are the 95% HDI of the rate and the width of the line displays the number of occurrences for that given wind direction—the thinnest bars indicate one occurrence and the thickest 11 occurrences. Grey segments are the proportion of flights arriving/departing when the wind is coming from that direction.

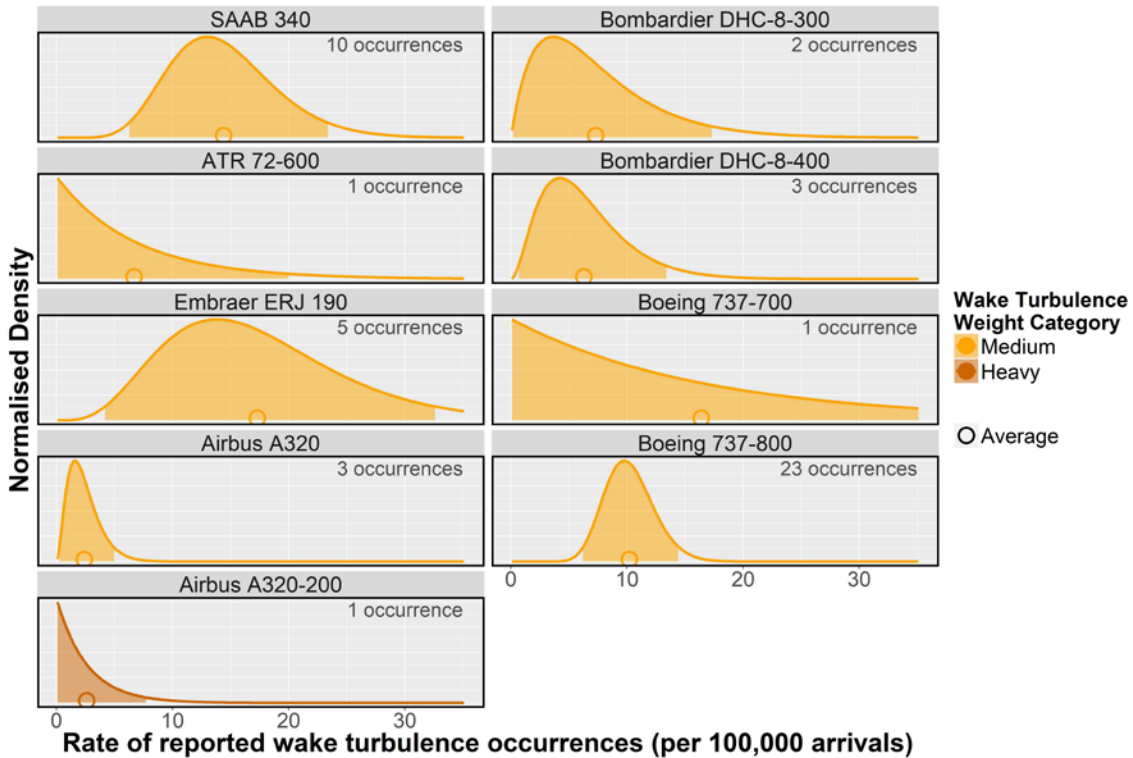
Wake turbulence-affected aircraft models

Comparison of the aircraft models most likely to report a wake turbulence occurrence at Sydney Airport is in Figure 17 for arriving aircraft and Figure 18 for departing aircraft.

No light aircraft reported encountering wake turbulence at Sydney Airport in the five-year study period. Light aircraft made up 5.9 per cent of all movements at the airport. The likelihood that there would be zero light aircraft wake turbulence occurrences is less than one per cent—assuming equal probability of wake turbulence occurrences for all aircraft weight categories. This assumption is probably an underestimation as heavier aircraft can be expected to be less susceptible to wake turbulence. This could indicate that light aircraft operators are less likely to report encountering wake turbulence occurrences, or that the separation standard between light and other weight category aircraft is sufficient to avoid an occurrence.

Medium aircraft (73 per cent of all movements at Sydney Airport) made up almost 95 per cent of the reported wake turbulence occurrences. Heavy aircraft made up the remaining five per cent despite making up almost 19 per cent of all movements. No super heavy aircraft reported encountering wake turbulence. Presuming operators and aircrews of these weight categories have similar reporting rates, this is a good indicator that heavier aircraft are less susceptible to wake turbulence and/or the wake turbulence separation standards involving heavy aircraft are sufficient to avoid most occurrences.

Figure 17: Estimate of the rate of reported wake turbulence occurrences (per 100,000 arrivals) for affected aircraft models arriving at Sydney Airport (2012–2016)

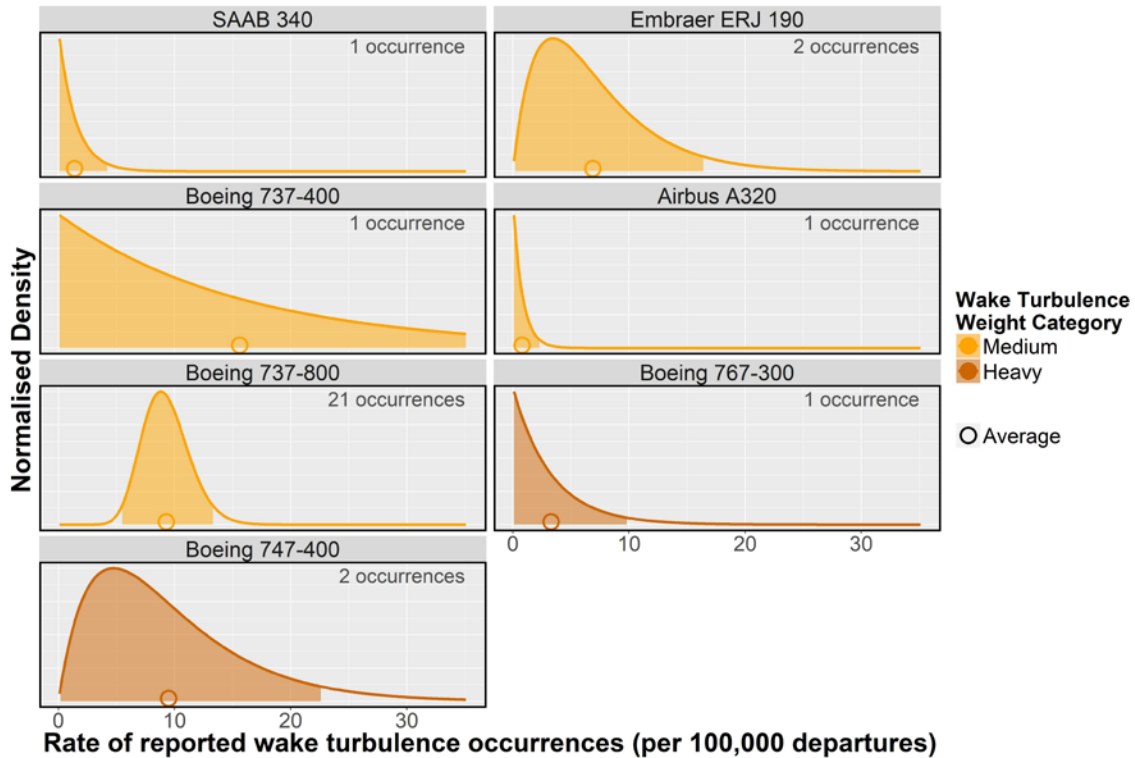


Data sources: Airservices movements data and ATSB occurrence database. Plots are ordered by the aircraft's MTOW. For ease of comparison, all density values were normalised with respect to one for the highest value.

Despite making up around 27 per cent of all movements at Sydney Airport, over half (56 per cent) of all reported wake turbulence occurrences were experienced by Boeing 737-800 aircraft. Assuming equal probabilities for all aircraft models, there is less than a one per cent probability that this aircraft would have so many occurrences compared to other models. This could possibly indicate that 737-800s are more susceptible than most other aircraft to wake turbulence and/or that their operators and aircrews are more likely to report encountering wake turbulence. When only considering wake turbulence occurrences on departure (Figure 16), 737-800s make up an even greater proportion of wake turbulence reports.

Embraer 190s were also overrepresented with a probability under one per cent of having so many occurrences, when compared to other aircraft. SAAB 340s made up the bulk of the remaining occurrences with a slightly higher probability of around 2.3 per cent—the majority on arrival.

Figure 18: Estimate of the rate of reported wake turbulence occurrences (per 100,000 departures) for affected aircraft models departing at Sydney Airport (2012–2016)



Data sources: Airservices movements data and ATSB occurrence database. Plots are ordered by the aircraft's MTOW. For ease of comparison, all density values were normalised with respect to one for the highest value.

Probable wake turbulence-generating aircraft models

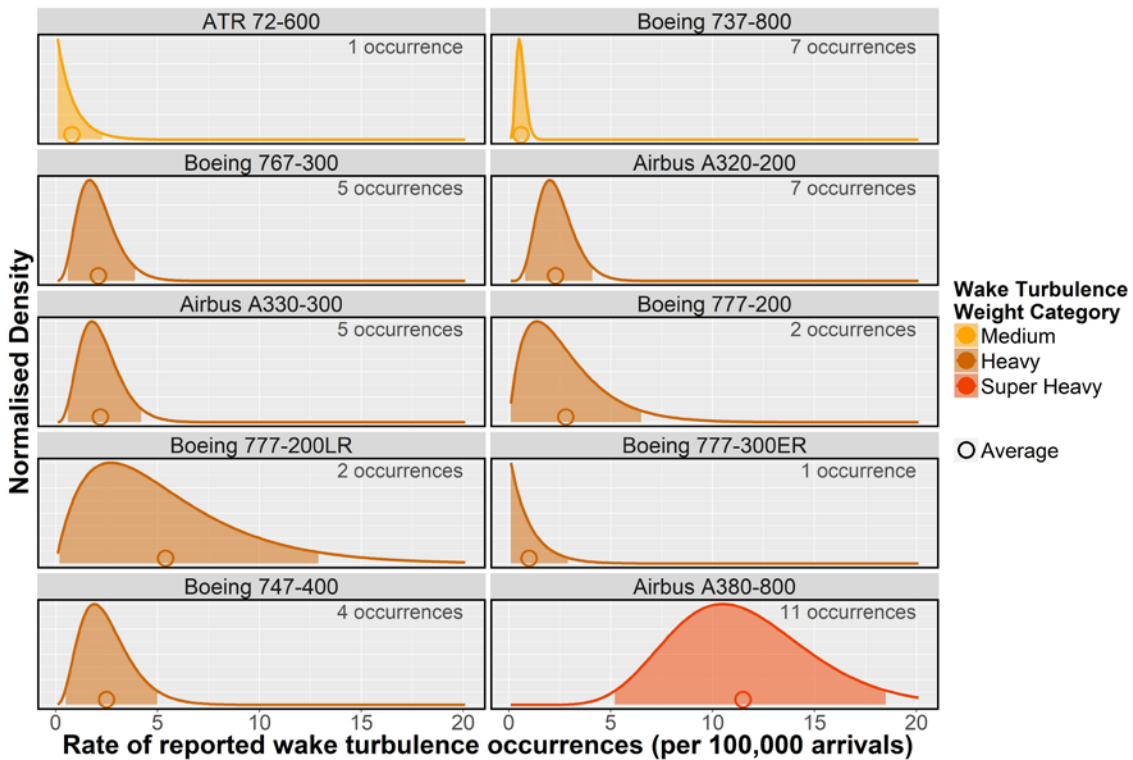
Often the report of wake turbulence does not identify the wake generating aircraft or the aircraft is misidentified. To minimise the impact of these errors on this investigation, an algorithm incorporating reporter information and Airservices data was developed to determine the most probable aircraft of the 10 previous movements prior to a wake turbulence occurrence (Appendix G).

The algorithm only identified a most probable wake generating aircraft for 77 of the 78 occurrences. The discrepancy is possibly caused by limitations of the algorithm (that excludes wake generating aircraft of a lesser weight category than the affected aircraft, wake turbulence generated by reverse heading or crossing aircraft, and separation time limitations) or errors in the reported data (other forms of turbulence misreported as wake turbulence).

For arrivals (Figure 19), there is a greater than 85 per cent probability that the reported rate of wake turbulence occurrences generated by an Airbus A380-800 was more than any other aircraft arriving at Sydney Airport between 2012 and 2016. This probability increases to over 98 per cent when excluding the Boeing 777-200LR from the comparison set.

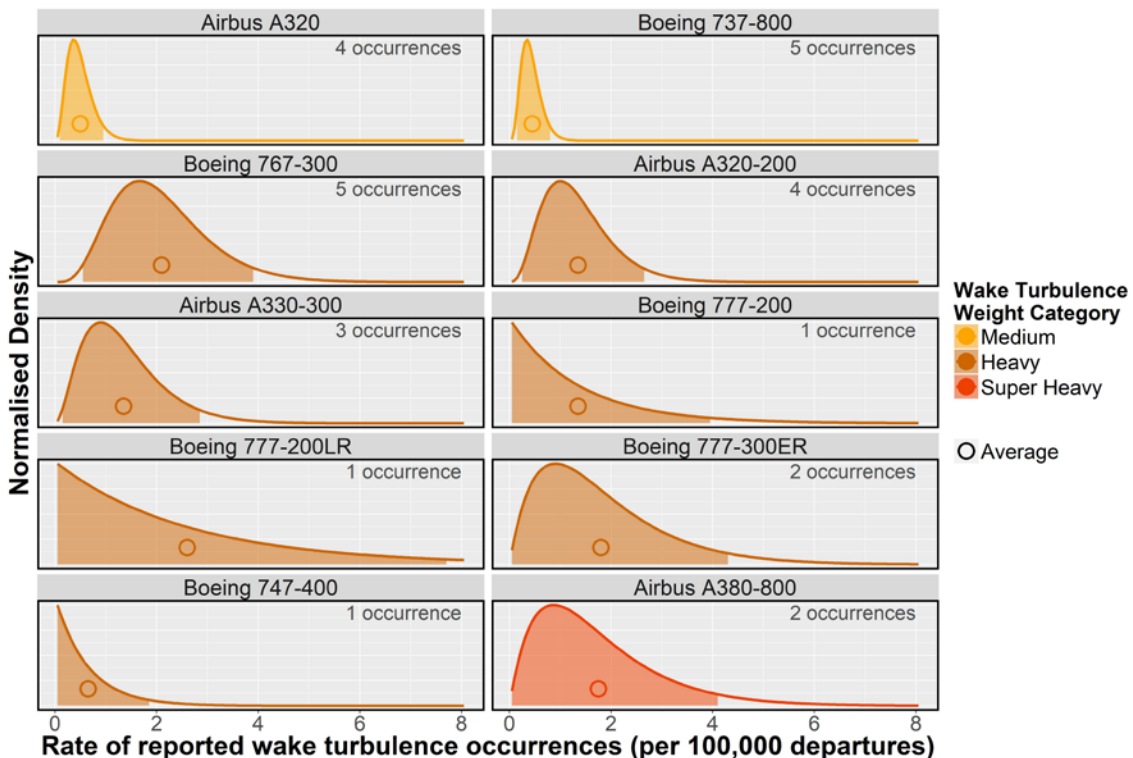
For departures (Figure 20), no single aircraft was identified as significantly increasing the rate of wake turbulence occurrences.

Figure 19: Estimate of the rate of reported wake turbulence occurrences (per 100,000 arrivals) for arrivals at Sydney Airport (2012–2016) by probable generating aircraft model



Data sources: Aircservices movements data and ATSB occurrence database. Only the top 10 aircraft with the greatest average rates are displayed. Plots are ordered by the aircraft's Maximum take-off weight. For ease of comparison, all density values were normalised with respect to one for the highest value.

Figure 20: Estimate of the rate of reported wake turbulence occurrences (per 100,000 departures) for departures at Sydney Airport (2012–2016) by probable generating aircraft model



Data Sources: Aircservices movements data and ATSB occurrence database. Only the top 10 aircraft with the greatest average rates are displayed. Plots are ordered by the aircraft's maximum take-off weight. For ease of comparison, all density values were normalised with respect to one for the highest value.

The results were similar to those above when only considering aircraft models that were in the previous 10 movements prior to a reported wake turbulence occurrence (Appendix H)—not those identified by the algorithm outlined in Appendix G. The A380 is 95 per cent more likely to have been present before a wake turbulence occurrence than most other aircraft models. However, the Airbus A340-600 and Boeing 777-300 are around 90 per cent less likely, and the Boeing 777-200LR and Boeing 787-800 are around 80 per cent less likely to have been present in the 10 prior aircraft movements before a wake turbulence occurrence than the A380. This is further evidence suggesting the probability of an aircraft on arrival at Sydney Airport encountering wake turbulence increases significantly following an A380—generally greater than a factor of two. However, this effect is not observed for aircraft departing Sydney Airport.

There were no reported wake turbulence occurrences when the arrival density was one or more aircraft per minute and the most probable wake turbulence generating aircraft was an A380, or the A380 was among the 10 preceding arrivals. The increase in the rate following an A380 is not correlated with an increase in the arrival density.

Considering only occurrences where the wake turbulence generating aircraft and the affected aircraft were operating on parallel runways, the A380-800 was identified as the most probable aircraft in five of the 12 occurrences. There was a 73 per cent probability that the rate of reported occurrences was greater when an A380 arrived in the previous 10 movements than the rate of any other wake-generating aircraft.

Operating runway for the aircraft most likely generating wake turbulence involved in occurrences

Figure 21 displays the operating runway for the aircraft most likely generating the wake turbulence involved in occurrences and the runway the affected aircraft were operating to.

The highest average rate (per 100,000 arrivals) was for aircraft arriving at Sydney Airport on Runway 34 Right where the wake turbulence was generated by an aircraft arriving on Runway 34 Left. The likelihood of encountering wake turbulence is probably greatest for aircraft operating on Runway 34 Right where the effect was produced by an aircraft operating on Runway 34 Left.

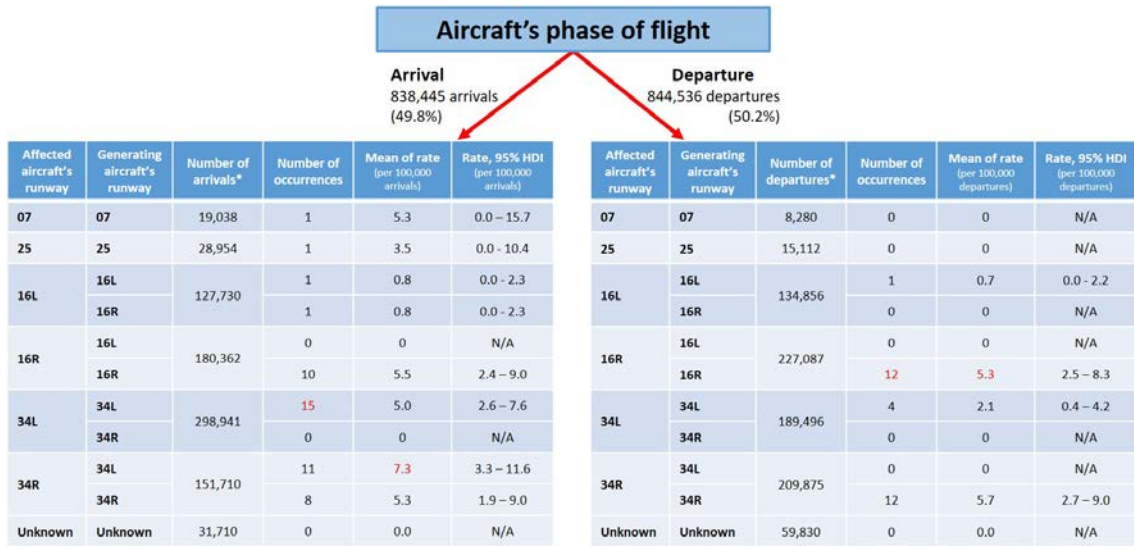
For aircraft operating on Runway 34 Right, there is a 76 per cent probability that the rate of reported wake turbulence is higher when generated from an aircraft on Runway 34 Left than Runway 34 Right. For four of these occurrences, an A380 was the most probable wake turbulence-generating aircraft model. Therefore, there is a 65 per cent probability that the A380's rate is higher than any other wake-generating aircraft operating on Runway 34 Left and affecting aircraft operating on Runway 34 Right over the study period.

Following the A380, the Airbus A330-200, the A330-300 and the Boeing 737-800 were twice identified as the most probable aircraft operating on Runway 34 Left to have generated wake turbulence that affected an aircraft on arrival on Runway 34 Right. In addition, the Boeing 777-200LR and 777-300ER were identified as the most probable for one occurrence each.

Further, the most commonly affected aircraft types (arriving on Runway 34 Right and probably affected by wake turbulence generated by an aircraft arriving on runway 34 left), were Boeing 737-800 and SAAB 340 with three occurrences each. All of the occurrences happened while the affected aircraft was in the approach phase with all but one occurring below 2,000 ft.

For departures, there were no identified occurrences where the wake turbulence was generated from an aircraft operating on a parallel runway.

Figure 21: Estimate of the rate of reported wake turbulence occurrences (per 100,000 arrivals/departures) at Sydney Airport (2012–2016) for given runway where the affected aircraft was operating against the runway where the probable wake-generating aircraft was operating



* The number of arrivals/departures on the runway where the aircraft that reported the wake turbulence occurrence was operating.

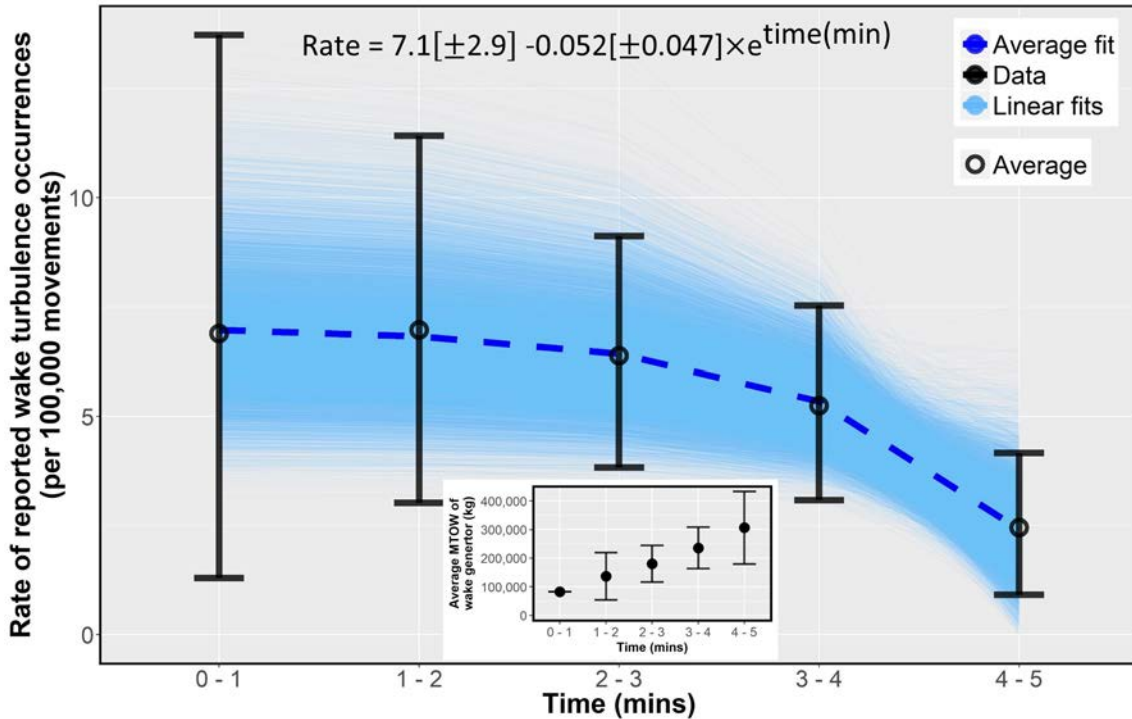
Data sources: Airservices movements data and ATSB occurrence database.

Separation time

As the separation time between most probable wake turbulence generating aircraft and the affected aircraft increases, the rate of reported wake turbulence decreases (Figure 22).²⁰ This is expected as the vortices' strength decays with time. (Note that distances between aircraft is unknown. The below analysis of time-based separation is also the closest proxy available for distance.)

²⁰ The method used to fit the model to the data is similar to that presented in Appendix F.

Figure 22: Estimate of the rate of reported wake turbulence occurrences (per 100,000 movements) at Sydney Airport (2012–2016) as a function of aircraft separation time, excluding probable parallel runway occurrences



Data sources: Airservices movements data and ATSB occurrence database. Error bars are the 95% HDI of the rate. Dotted black line is the average of the 10,000 linear fits (light blue lines)—where the rates were random sampled from the distribution at each separation time category. Insert displays the relationship between average wake generating aircraft's MTOW and the separation time.

From zero to around three minutes, separation time has little effect on the rate of wake turbulence occurrences; this is likely an artefact of the wake turbulence separation standard (Table 1). Aircraft that fall within higher wake turbulence weight categories (based on their MTOWs) have greater separation time standards. This is illustrated in the insert in Figure 22, as the separation time increases the average MTOW of the most probable wake generating aircraft increases.

The greater the initial strength of the generated vortices (dependent on the aircraft's MTOW) the longer the effect is likely to persist before decaying to a non-hazardous state for following aircraft. This can also be inferred from the data, as the greater MTOW aircraft have a greater effect on the rate of wake turbulence occurrences as the separation time increases.

As these data are consistent with expected results, they perform a weak test of the most probable wake generating aircraft algorithm (Appendix G), and adding more validity to the findings based on the algorithm.

Safety analysis

The analyses in this investigation only includes encounters with wake turbulence, primarily reported by aircrew, that have been classified as an occurrence (incident or serious incident), because they were reported as resulting in control issues, a missed approach or go-around, a warning activation for the aircraft, and/or an injury resulted from the encounter. (Events where the air traffic control wake turbulence separation standard was not met were not part of the analyses unless control issues and/injury also resulted. There were no wake turbulence occurrences at Sydney Airport between 2012 and 2016 during a reported loss of the separation standard.)

Almost half of all wake turbulence occurrences reported to the ATSB between 2012 and 2016 were at Sydney Kingsford Smith International Airport (Sydney Airport). This resulted in an average rate (per movement) that was almost double that of the Australian airport with the second highest average rate (Brisbane Airport). However, this was primarily due to wake turbulence occurrences involving aircraft arriving at Sydney Airport. For aircraft departing Sydney Airport, the rate of wake turbulence occurrences was similar to other major airports.

There were seven minor injuries (from five occurrences) associated with an aircraft encountering wake turbulence at Sydney Airport. In comparison, all the other major Australian airports combined resulted in only one minor injury over the study period.

Sydney Airport is the only major Australian airport currently with parallel runways. The distance between these runways is greater than the maximum distance required for the application of the same wake turbulence separation standard as for aircraft operating on a single runway. The primary factors identified as contributing to Sydney Airport's increased rate of reported wake turbulence occurrences were:

- **Arrival densities of one or more aircraft per minute** (including parallel runway arrivals)²¹. While only accounting for 5.1 per cent of all movements, arrival densities of one or more aircraft per minute accounted for around 20 per cent of all reported wake turbulence occurrences at Sydney Airport. This effect was more pronounced for the 1.4 per cent of all flights that arrived on Runway 34 Right when the arrival density was one or more aircraft per minute but made up around 11.5 per cent of all occurrences.
- **Wind direction from the west or north-west**. When the wind direction was coming from the west or north-west, the rate of wake turbulence occurrences almost certainly increased for aircraft arriving on Runway 34 Right. The major contributor to this is probably wake turbulence produced by heavy or super heavy aircraft arriving on Runway 34 Left.
- **On arrival, following an Airbus A380**. The rate of encountering wake turbulence at Sydney Airport increases significantly following an Airbus A380 when compared to other aircraft.

The ATSB conducted further analyses to determine the effect of each of the above factors, both in isolation and together. Removing all three factors together significantly reduced the rate of occurrences for arriving aircraft at Sydney (by half). However, the rate at Sydney Airport would likely still be higher than the other airports without all three factors. Removing any of the factors in isolation, while reducing the rate at Sydney, the rate remained significantly greater than other major airports.

Therefore, although the above three factors together account for over a half of the occurrences for arriving aircraft at Sydney, this suggests other factors beyond the scope of this investigation are also influencing wake turbulence at Sydney.

It has been clearly established that Sydney Airport has a disproportionately high rate of wake turbulence occurrences compared to other Australian major airports. In addition, the ATSB

²¹ As explained on page 11, arrival densities were calculated by dividing the number of arrivals, in the preceding 10 movements, by the time between the first and last arrivals.

considers that the risk posed to aircraft arriving at Sydney Airport is higher when taking into account the probabilities documented in this report and the potential consequences. Those potential consequences include either a slight reduction in safety margins or functional capabilities due to aircraft control issues, a missed approach or go-around, or several minor injuries, for aircraft with more than 100 occupants.

In addition to its high proportion of wake turbulence occurrences, seven of the eight minor injuries reported as result of a wake turbulence occurrences were at Sydney. Further, when compared with the combined data from other major Australian airports (Adelaide, Brisbane, Melbourne and Perth), an aircraft was more likely to have a missed approach or go-around, a ground proximity alert, or control issues following a wake turbulence encounter at Sydney Airport.

The risk of an injury resulting from a wake turbulence encounter at Sydney Airport is higher for cabin crew than passengers who are generally secured in their seats earlier on arrival. This is also incorporated into the consequence of injury within the risk assessment, due to the working environment. It is generally accepted that flight crew (including cabin crew) will be exposed to a higher risk than passengers.

The modelled scenarios excluded aircraft in the cruise phase of flight.

Findings

From the available information, the following findings are made regarding the analysis of reported wake turbulence occurrences at Sydney Airport between 2012 and 2016. These findings are not to be read as apportioning blame or liability to any particular organisation or individual.

Safety issues, or system problems, are highlighted in bold to emphasise their importance.

A safety issue is an event or condition that increases safety risk and (a) can reasonably be regarded as having the potential to adversely affect the safety of future operations, and (b) is a characteristic of an organisation or a system, rather than a characteristic of a specific individual, or characteristic of an operating environment at a specific point in time.

- **Given the parallel runway configuration, there was a disproportionate rate of reported wake turbulence occurrences for aircraft arriving at Sydney Airport compared to other major Australian airports in the years 2012 to 2016. Wake turbulence occurrences at Sydney Airport were found to be primarily associated with three factors:**
 - **arrival densities of one or more aircraft per minute (including parallel runway arrivals), especially on flights that arrived on Runway 34 Right**
 - **wind direction from the west or north-west for aircraft arriving on Runway 34 Right, especially when coinciding with a heavy or super heavy aircraft arriving on Runway 34 Left**
 - **arrivals following an Airbus A380 compared to other aircraft. [Safety issue]**

Safety issues and actions

The safety issues identified during this investigation are listed in the Findings and Safety issues and actions sections of this report. The Australian Transport Safety Bureau (ATSB) expects that all safety issues identified by the investigation should be addressed by the relevant organisation(s). In addressing those issues, the ATSB prefers to encourage relevant organisation(s) to proactively initiate safety action, rather than to issue formal safety recommendations or safety advisory notices.

Depending on the level of risk of the safety issue, the extent of corrective action taken by the relevant organisation, or the desirability of directing a broad safety message to the [aviation, marine, rail - as applicable] industry, the ATSB may issue safety recommendations or safety advisory notices as part of the final report.

The initial public version of these safety issues and actions are repeated separately on the ATSB website to facilitate monitoring by interested parties. Where relevant the safety issues and actions will be updated on the ATSB website as information comes to hand.

Wake turbulence occurrences at Sydney Airport

Number:	AR-2017-011-SI-01
Issue owner:	Airservices Australia
Operation affected:	Aviation: Air transport
Who it affects:	Aircraft arriving at Sydney Airport

Safety issue description:

Given the parallel runway configuration, there was a disproportionate rate of reported wake turbulence occurrences for aircraft arriving at Sydney Airport compared to other major Australian airports in the years 2012 to 2016. Wake turbulence occurrences at Sydney Airport were found to be primarily associated with three factors:

- arrival densities of one or more aircraft per minute (including parallel runway arrivals), especially on flights that arrived on Runway 34 Right
- wind direction from the west or north-west for aircraft arriving on Runway 34 Right, especially when coinciding with a heavy or super heavy aircraft arriving on Runway 34 Left
- arrivals following an Airbus A380 compared to other aircraft.

Response to safety issue by Airservices Australia

Received 19 November 2018

Airservices will publish an Aeronautical Information Circular (AIC) aimed at operators who operate into Sydney Airport. The AIC will advise industry of the injuries associated with wake turbulence for runway 34R as identified in the ATSB Report. The AIC will also recommend that cabin crew should be seated and secured in the earlier part of the approach.

Received 18 December 2019

...We consider that the action is proportionate to the likelihood and consequence of the risk when it is considered in the broader picture of Sydney operations. Consideration of other options, such as an attempt to increase the spacing on Runway 34R when an A380 lands on Runway 34L, would result in increased complexity for controllers and increased delays for industry. The operations are based on the runways being treated as independent operations and any requirement to change this interaction is likely to introduce other risk into the system...

...As the service provider, Airservices complies with the current wake turbulence separation ruleset as prescribed in CASR Part 172. Airservices Manual of Air Traffic Services (MATS) continues to meet all

current regulatory requirements on wake turbulence separation. CASA have not raised any concerns over our application of wake turbulence standards at Sydney during recent surveillance events. If there is ongoing concern with the safety outcomes being achieved by the current ruleset, we request the ATSB consider readdressing the safety issue to the Civil Aviation Safety Authority (CASA)...

ATSB comment in response

The ATSB appreciates Airservices' response to the identified safety issue regarding wake turbulence occurrences at Sydney Airport and acknowledges the proposed action to reduce the number of injuries associated with these occurrences. However, the ATSB does not consider that the proposed safety action adequately reduces the risk associated with the safety issue, primarily concerning the frequency of wake turbulence occurrence on arrival at Sydney Airport. The proposed safety action attempts to address only one aspect of the consequence (injury), and does not address temporary loss of control scenarios that can result from wake turbulence. Further, as wake turbulence related injuries on arrival to Sydney Airport during the study period all occurred during the descent phase of flight, the introduction of measures to have cabin crew seated in the earlier part of approach may have limited impact on preventing future injuries.

ATSB safety recommendation to Airservices Australia

Action number: AR-2017-011-SR-011

Action status: Released

The Australian Transport Safety Bureau recommends that Airservices Australia introduce measures to reduce the frequency of wake turbulence occurrence at Sydney Airport. Measures that could reduce the likelihood of these occurrences are primarily associated with:

- arrival densities of one or more aircraft per minute (including parallel runway arrivals), especially on flights that arrived on Runway 34 Right
- wind direction from the west or north west for aircraft arriving on Runway 34 Right, especially when coinciding with a heavy or super heavy aircraft arriving on Runway 34 Left
- arrivals following an Airbus A380 compared to other aircraft.

Response from Airservices Australia

Following the advanced release of the safety recommendation, Airservices Australia informed the ATSB of the following:

On 6 December 2018, Airservices issued a Temporary Local Instruction for Sydney requiring that the distance between successive arrivals on runway 16L and 16R [and runway 34L and 34R] increase from 4 NM to 5 NM. This instruction will be permanently incorporated into Sydney Operational Procedures (via Letter of Agreement 3183).

While this instruction was issued to reduce the likelihood of go-around and loss of separation events at Sydney, it significantly reduces the likelihood of wake turbulence events.

In addition, as it recognised that the potential for wake turbulence is more prevalent when the wind is from the north or northwest, to increase pilot awareness and caution, the following action is being taken.

- Air traffic controllers will be required to place a standard caution on the Aeronautical Terminal Information Service (ATIS). This will be documented in Local Instructions.
- A wake turbulence caution will be included in the local En Route Supplement Australia (ERSA).

Temporary Local Instructions and a Notice to Air Men (NOTAM) will be issued on 16 February 2019 as interim measures ahead of publication of the above documents (see below).

The increased distance between arrivals and improved awareness in the piloting community significantly reduces the risk of wake turbulence events at Sydney aerodrome. We will monitor wake turbulence events and pilot feedback, and intervene further if circumstances demand.

Amend Letter of Agreement 3138 as follows: TLI to be issued 16/2/19

10.3 WAKE TURBULENCE

10.3.1 Parallel Approach Limitations

When a super wake turbulence category aircraft is making an approach to a parallel runway provide wake turbulence distance separation to the adjacent runway when the aircraft making an approach to the adjacent runway has a MTOW less than 25 000kg.

10.3.2 RWY 34R Traffic Requirements

When ATIS notification of parallel wake turbulence applies, APP/DIR provide traffic information and a wake turbulence caution to aircraft on approach to 34R that will operate within the wake turbulence distance of a Heavy or Super aircraft making an approach to runway 34L.

Example:

'QFA501, TRAFFIC A380 SUPER RUNWAY LEFT 4 MILES AHEAD CAUTION WAKE TURBULANCE'

Note: This traffic advice can be combined with other traffic information requirements of Independent Visual Approaches when applicable.

This is in accordance with AIP (GEN 3.4-88)

Amend Local Instruction as follows: TLI to be issued 16/2/19

Local Instructions add a note regarding Wake Turbulence for inclusion on the ATIS.

When the wind is unfavourable as stated below. "Caution possible W/T from parallel runway operations".

Amend Local ERSA Entry as follows: NOTAM to be issued 16/2/19 then include in ERSA August publication

"Due to the nature of operations at Sydney during 34// operations with wind from the west to northwest" CAUTION Wake turbulence may exist.

ATSB comment in response

The ATSB agrees that the measures being implemented by Airservices have the potential to reduce the frequency of wake turbulence events at Sydney Airport, in particular:

- increasing separation distances for arrivals from 4 NM to 5 NM on runways 16L/R and 34L/R
- applying the single-runway wake turbulence standard to the parallel runways when the leading aircraft is a super heavy like an A380 and the following aircraft is light (under 25,000 kg).

Furthermore, increasing pilot awareness of the potential for wake turbulence when the wind is from the north or northwest will provide an opportunity for crews to be prepared for wake turbulence in advance of any experience of it. While this could reduce the consequences of a wake turbulence encounter, it is unlikely to affect the likelihood of encountering wake turbulence.

The analysis in this ATSB research investigation showed that over half of the wake turbulence occurrences at Sydney were attributable to one or more of the three factors outlined in the safety issue. Although the actions by Airservices have the potential to reduce some of the influence of some of these, they are somewhat limited. The 5 NM separation will only affect heavy aircraft following another heavy aircraft, and medium aircraft following another medium aircraft, as other aircraft already have at least 5 NM wake turbulence separation standard applied. The application of the wake turbulence separation standard to the parallel runways does address the worst-case combination of a super heavy aircraft leading and an aircraft below 25,000 kg following (which did not result in any wake turbulence events in the study period). However, it will not apply when the following aircraft is a medium above 25,000 kg or heavy aircraft (including most common passenger aircraft operating to Sydney). In addition, even through eliminating the influence of all three, Sydney Airport would likely still have a higher rate of wake turbulence events than other major airports.

As such, the ATSB encourages Airservices to consider conducting their own quantitative analyses to explore other options that could further reduce the risk of wake turbulence for aircraft arriving into Sydney Airport.

Appendices

Appendix A: Estimative language

Throughout this report, estimative language is used. This defines a probability range of an occurrence or outcome given in a statement (Table 3).

Table 3: Estimative language expressions with associated probability of occurrence/outcome

Terminology	Likelihood of the occurrence/outcome	Equivalent terms
Virtually certain	> 99% probability	<i>Extremely likely, almost certain</i>
Highly likely	> 95% probability	<i>Highly probable</i>
Very likely	> 90% probability	<i>Very probably</i>
Likely	> 66% probability	<i>Probable</i>
About as likely as not	33 to 66% probability	<i>More or less likely</i>
Unlikely	< 33% probability	<i>Improbable</i>
Very unlikely	< 10% probability	
Exceptionally unlikely	< 1% probability	<i>Extremely unlikely</i>

Appendix B: Pairwise comparison of the rate of reported wake turbulence occurrences at major Australian airports

Table 4: Pairwise comparison of major Australian airports with at least one reported wake turbulence occurrence (2012–2016). The probability that the rate at Airport 1 is greater than Airport 2 was calculated by comparison of 1 million samples from each airport's beta distribution. The highest density interval (HDI) was calculated from the distribution resulting from subtracting samples of the rate parameter from Airport 2's beta distribution from samples of Airport 1's beta distribution.

Airport 1	Airport 2	Probability Airport 1 rate is greater than Airport 2 rate	95% HDI of difference between Airport 1 and Airport 2 rates (per 100,000 movements) ²²
Sydney	Adelaide	> 99.9%	2.1 to 4.9
Sydney	Brisbane	99.8%	0.7 to 3.5
Sydney	Melbourne	> 99.9%	1.6 to 4.3
Sydney	Perth	> 99.9%	1.8 to 4.5
Brisbane	Adelaide	97.7%	0.1 to 2.7
Brisbane	Melbourne	90.1%	-0.4 to 2.0
Brisbane	Perth	93.8%	-0.3 to 2.3
Melbourne	Adelaide	84.9%	-0.6 to 1.8
Melbourne	Perth	66.2%	-1.0 to 1.4
Perth	Adelaide	73.0%	-0.9 to 1.7

Data sources: Airservices movements data and ATSB occurrence database

²² This was calculated by subtracting the rate parameters derived from 1 million Monte Carlo simulations of the beta distribution for Airport 2 from the rate parameters from a further 1 million simulations of the beta distribution for Airport 1.

Appendix C: Machine learning used to determine relevant factors

All the models were fitted using repeated cross validation (10 fold, 5 repeats)²³ and undersampling/oversampling—accounted for the class imbalance. The data was split into training (3/4 of the samples) and test (1/4 of samples) sets, the models were trained on the training set and tested on the test set. The probability of detection is the proportion of reported wake turbulence occurrence that were correctly identified and the probability of false alarm is the proportion of flights where there was no reported wake turbulence that were incorrectly identified. The ‘Importance’ axis on the variable importance plots is normalised to 100 for the variable ranked as the most important for that model’s fit. The importance can be used to either increase the probability of detection or decrease the probability of false alarm. A higher value could indicate that a factor is a good predictor of no reported wake turbulence occurring.

Due to the large false alarms rates, the machine learning modelling was not intended to predict the wake turbulence occurrences accurately but was instead used to help reduce the size of the possible factors to a smaller set. Constructing a model(s) that could fulfil the requirement for accurate and low error prediction of wake turbulence occurrences would require significantly more data than the 79 occurrences used in this analysis.

Linear support vector machine (Figure 23a)²⁴

Probability of detection: 80%; Probability of false alarm: 31%

Most important factors identified: the runway the affected aircraft was operating on, the number of ‘Super’ weight category aircraft arrivals, the departure density, the wind direction, and the arrival density.

Gradient boosted machine (Figure 23b)²⁵

Probability of detection: 80%; Probability of false alarm: 29%

Most important factors identified: the average wind speed, the arrival and departure densities, the weight class of the affected aircraft, and the number of ‘Super’ weight category aircraft arrivals.

Neural network (Figure 23c)²⁶

Probability of detection: 75%; Probability of false alarm: 24%

Most important factors identified: the arrival density, the affected aircraft’s phase of flight (arriving/departing), the number of ‘Super’ weight category aircraft arrivals, the wind direction, and number of ‘Super’ weight category aircraft departures.

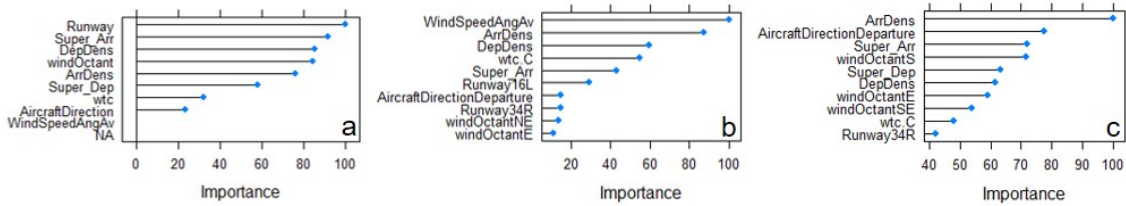
²³ Max Kuhn. Contributions from Jed Wing, Steve Weston, Andre Williams, Chris Keefer, Allan Engelhardt, Tony Cooper, Zachary Mayer, Brenton Kenkel, the R Core Team, Michael Benesty, Reynald Lescarbeau, Andrew Ziem, Luca Scrucca, Yuan Tang, Can Candan and Tyler Hunt. (2016). caret: Classification and Regression Training. R package version 6.0-73. <https://CRAN.R-project.org/package=caret>

²⁴ Alexandros Karatzoglou, Alex Smola, Kurt Hornik, Achim Zeileis (2004). kernlab - An S4 Package for Kernel Methods in R. *Journal of Statistical Software* 11(9), 1-20. URL <http://www.jstatsoft.org/v11/i09/>

²⁵ Greg Ridgeway with contributions from others (2015). gbm: Generalized Boosted Regression Models. R package version 2.1.1. <https://CRAN.R-project.org/package=gbm>

²⁶ Venables, W. N. & Ripley, B. D. (2002) *Modern Applied Statistics* with S. Fourth Edition. Springer, New York. ISBN 0-387-95457-0

Figure 23: Relative importance of each factor used in machine learning models



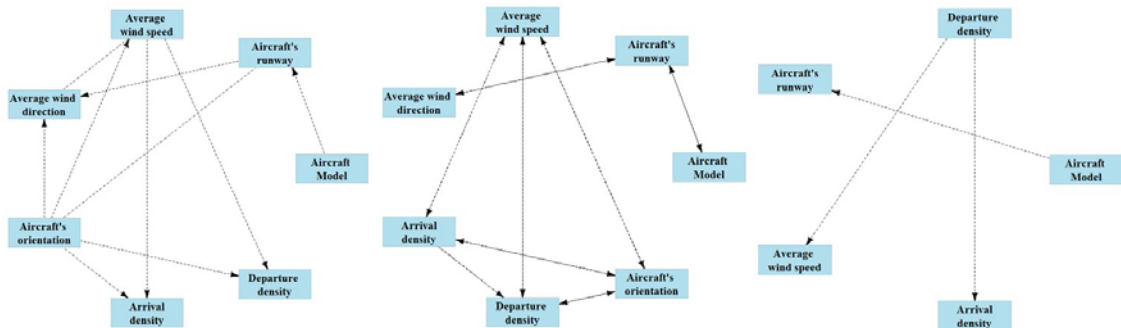
Appendix D: Bayesian network structure learning for relationships between the factors

To assist in the identification of the relationships between relevant factors influencing the probability of a reported wake turbulence occurrence, a Bayesian network structure learning was utilised.²⁷ Multiple network structures were learnt utilising multiple algorithms, below are three examples.

The preceding aircrafts models, runways and orientations were not included in the factors analysed, this was primarily due to the complexity that would have been required. Further, it was determined that they would have the same inter-factor relationships as the affected aircraft’s model, runway and orientation.

Due to the level of uncertainty in determining causal relationships, some of the inter-factor relationship obviously have the wrong causal direction. For example, it is highly unlikely that an aircraft’s orientation has any effect on the average wind speed or direction, consequently, these links (relationships) were reversed.

Figure 24: Bayesian networks displaying causal relationships between factors influencing reported wake turbulence occurrences at Sydney Airport (2012–2016)



Network structure learnt using hill climbing score-based algorithm and bootstrap aggregation (20 bootstrap samples). Causal relationships (links) are chosen when link occurs in at least 70% of the bootstrap results and the direction is more than half of the iterations

Network structure learnt using semi-interleaved Hilton-PC constraint-based algorithm and bootstrap aggregation (20 bootstrap samples). Causal relationships (links) are chosen when link occurs in at least 70% of the bootstrap results, all links are non-causal

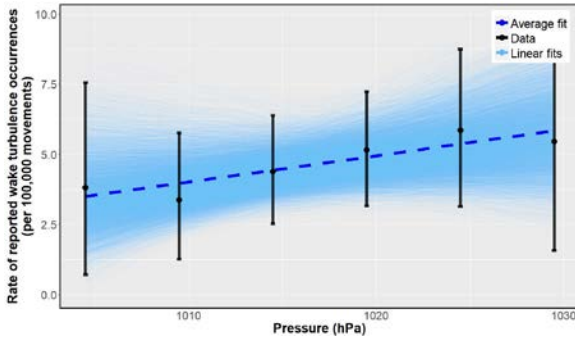
Network structure learnt using max-min hill climbing (MMHC) hybrid algorithm and bootstrap aggregation (20 bootstrap samples). Causal relationships (links) are chosen when link occurs in at least 70% of the bootstrap results and the direction is more than half of the iterations

²⁷ Marco Scutari (2010). Learning Bayesian Networks with the bnlearn R Package. Journal of Statistical Software, 35(3), 1-22. URL <http://www.jstatsoft.org/v35/i03/>.

Appendix E: Weather-related factors

Approximately 13 per cent of the 10,000 linear fits to the data (blue lines) had a negative slope. This ratio was determined to be sufficiently high to eliminate pressure from the set of primary factors contributing to reported wake turbulence occurrence at Sydney Airport (2012–2016).

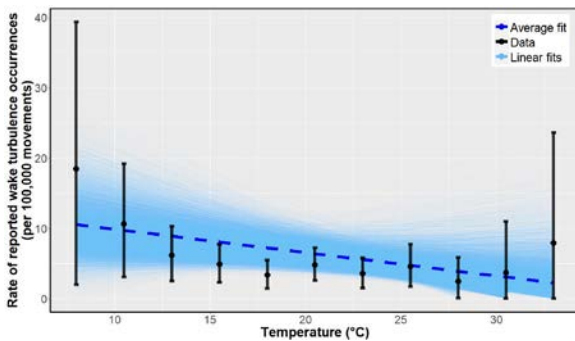
Figure 25: Estimate of the rate of reported wake turbulence occurrences (per 100,000 movements) at Sydney Airport (2012–2016) as a function of mean sea level pressure.



Data sources: Bureau of meteorology weather observations, Aircservices movements data and ATSB occurrence database. Error bars are the 95% HDI.

Approximately eight per cent of the 10,000 linear fits to the data (blue lines) had a positive slope. This ratio was determined to be sufficiently high to eliminate temperature from the set of primary factors contributing to reported wake turbulence occurrence at Sydney Airport (2012–2016).

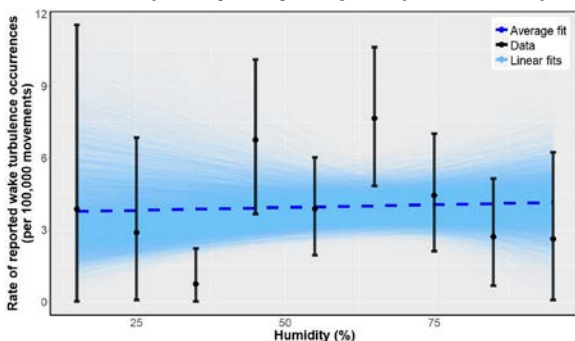
Figure 26: Estimate of the rate of reported wake turbulence occurrences (per 100,000 movements) at Sydney Airport (2012–2016) as a function of temperature.



Data sources: Bureau of meteorology weather observations, Aircservices movements data and ATSB occurrence database. Error bars are the 95% HD.

Approximately 37 per cent of the 10,000 linear fits to the data (blue lines) had a negative slope. This ratio was determined to be sufficiently high to eliminate humidity from the set of primary factors contributing to reported wake turbulence occurrence at Sydney Airport (2012–2016).

Figure 27: Estimate of the rate of reported wake turbulence occurrences (per 100,000 movements) at Sydney Airport (2012–2016) as a function of humidity.



Data sources: Bureau of meteorology weather observations, Aircservices movements data and ATSB occurrence database. Error bars are the 95% HD.

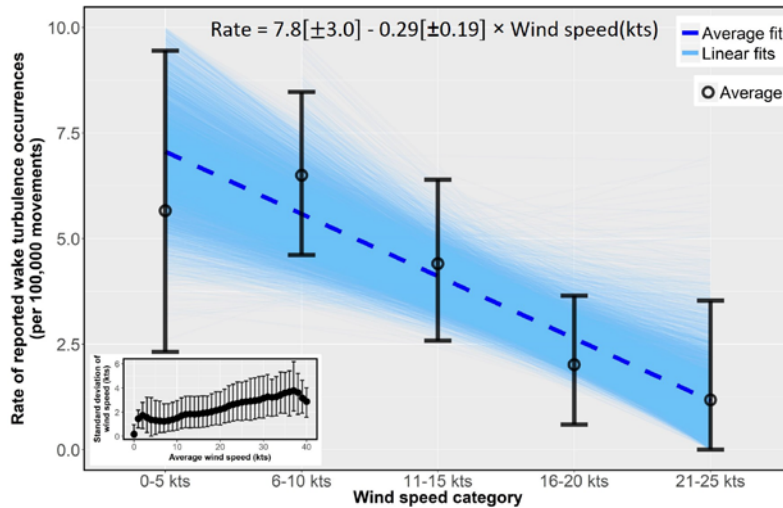
Appendix F: Wind speed effects on wake turbulence

To investigate the relationship between wind speed and the rate of reported wake turbulence occurrences, the average wind speed for the 10 minutes prior to time of the occurrence was divided into five categories (0–5 kts, 6–10 kts, 11–15 kts, 16–20 kts and 21–25 kts).

Linear (straight-line) fits were applied to 10,000 random samples from each of the wind speed category rate distributions (error bars Figure 26).²⁸ From the slope of the average of these fits, it was determined that for each one kt increase in wind speed the number of wake turbulence occurrences per 100,000 movements decreases by around 0.29 at Sydney Airport.

Less than 0.5 per cent of the 10,000 linear fits had a positive slope, strongly indicating that there is a general inverse relationship between wind speed and the rate of reported wake turbulence occurrences at Sydney Airport over the study period.

Figure 28: Comparison of 10-minute average wind speed and estimate of the rate of reported wake turbulence occurrence (per 100,000 movements) at Sydney Airport (2012–2016).



Data sources: Airservices movements data and ATSB occurrence database. Error bars are the 95% HDI of the rate. Dotted black line is the average of the 10,000 linear fits (light blue lines)—where the rates were random sampled from the distribution at each wind speed category. Insert displays the relationship between average wind speed and the standard deviation of the wind speed.

This result is expected since the decay rate—life span—of wingtip vortices (the primary component of wake turbulence) increases with atmospheric instability.²⁹ So an increase in the wind speed would generally be associated with more turbulent atmosphere (see insert³⁰ Figure 28).

Further, the greater the wind speed, the shorter the period that the wake turbulence would be expected to remain within the region of the flight path and affect following aircraft. However, since wingtip vortices generally propagate laterally from the wings at around five kts,³¹ crosswind speeds of around five kts can cause the vortices to remain within the flight path for longer—this possibly explains the decrease in the average rate in the 0–5 kts range.

²⁸ Chi-squared (χ^2) goodness of fit analysis was performed on the mean of the rate data to the average of the model fits with a p-value of 0.965. Hence there is little evidence indicating that the model results and data are independent.

²⁹ Proctor F. H. et al., *Three-Phased Wake Vortex Decay*, American Institute of Aeronautics and Astronautics, 2010

³⁰ The standard deviation of the wind speed was calculated by first separating the 10 previous wind speed measurements (recorded at one minute intervals) into orthogonal components (x and y) using the wind direction (angle). The standard deviation of the 10 measurements for each component (σ_x and σ_y) was calculated and combined into a single value for the total standard deviation ($\sigma = \sqrt{\sigma_x^2 + \sigma_y^2}$)

³¹ Airservices Australia, *Wake Turbulence Hazards and Characteristics*. <http://www.airservicesaustralia.com/wp-content/uploads/wake.pdf>.

Appendix G: Algorithm used to identify aircraft most likely to have generated wake turbulence effect

The formula endeavours to determine the most probable of the 10 previous movements X_i ($i = 1 \dots 10$) to have produced wake turbulence resulting in a reported occurrence by the affected aircraft Y.

1. If X_i was in the same direction Y, $P(\text{direction}_i) = 1$ else 0.
2. If X_i arrived/departed from the same, or parallel, runway as Y, $P(\text{runway}_i) = 1$ else 0.
3. If time difference T_i (in minutes) between X_i and Y on the same runway, or the time difference between when wind from a parallel runway would be expected to cross Y's runway and Y, is less than T_{var} then $P(T_i)_i = (T_{\text{var}} - T_i) / T_i$ else 0. Where T_{var} is a random number between 3 and 5.
4. If $T_{\text{diff}} \leq T_{\text{wind}}$ and X_i is operating on the parallel T_{wind} is calculated for, or X_i is operating on the same runway as Y, then then $P(\text{wind}_i) = 1$ else 0. Where T_{wind} is the time taken for wind to travel from a parallel to the runway Y is operating on.
5. Determine the relative probability—with respect to each aircraft model—of aircraft X_i to create wake turbulence³², $P(AC_i) = \frac{\text{MTOW}(X_i)^2}{\text{WA}(X_i) \times \text{AR}(X_i) \times \text{V}(X_i)^2} \times AC_{\text{var}}$. Where $\text{MTOW}(X_i)$ is the maximum take-off weight of X_i , $\text{WA}(X_i)$ is the total wing area of X_i , $\text{AR}(X_i)$ is the wind aspect ratio of X_i , $\text{V}(X_i)$ is the average velocity of X_i throughout the take-off, climb, initial climb, landing, approach and descent phases of flight and AC_{var} is a random number between 0.9 and 1.1.
6. If the wake turbulence category of X_i is less than that of Y, then $P(\text{WTC}_i) = 0$ else 1.
7. If the aircraft model of X_i is the same as that reported by then $P(\text{reported}_i) = 3$ else 1.
8. The most probable aircraft $P(X_i)$ was calculated via the equation:

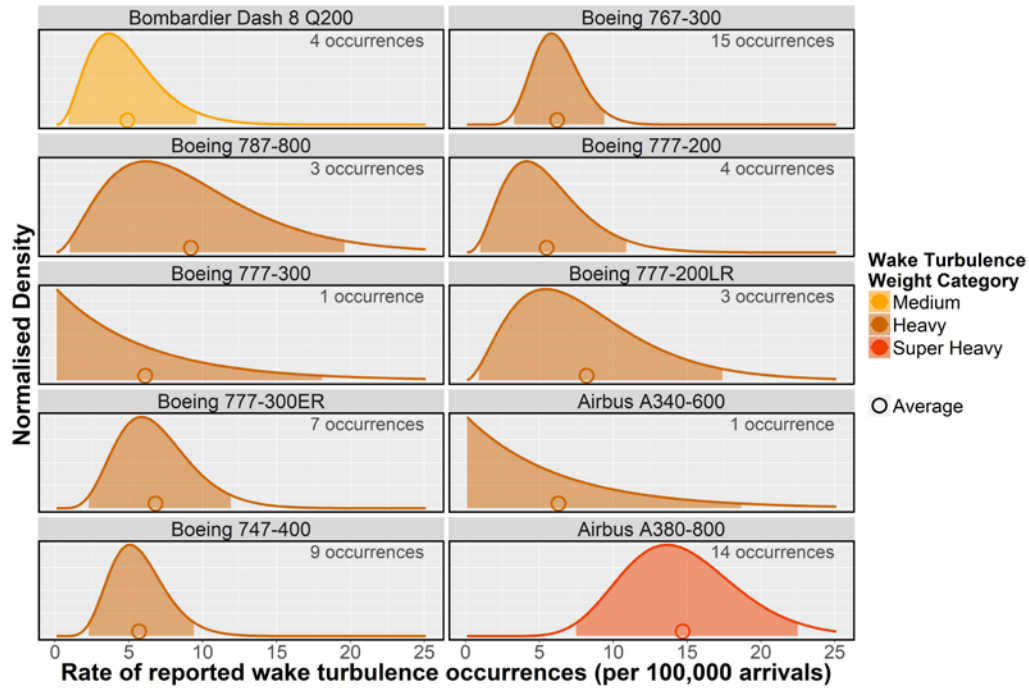
$$P(X_i) = P(\text{direction}_i) \times P(\text{runway}_i) \times P(T_i) \times P(\text{wind}_i) \times P(AC_i) \times P(\text{WTC}_i) \times P(\text{reported}_i).$$

9. Repeated steps 1 to 8 10,000 times—with new random numbers generated—for each wake turbulence occurrence.
10. Overall, the most probable aircraft X_i of the ten prior movements for each wake turbulence occurrence was determined as that with the greatest sum of $P(X_i)$ over the 10,000 repeated simulations.

³² This formula assumes that the strength of wake turbulence an aircraft generates, relative to other aircraft, is proportional to their induced drag.

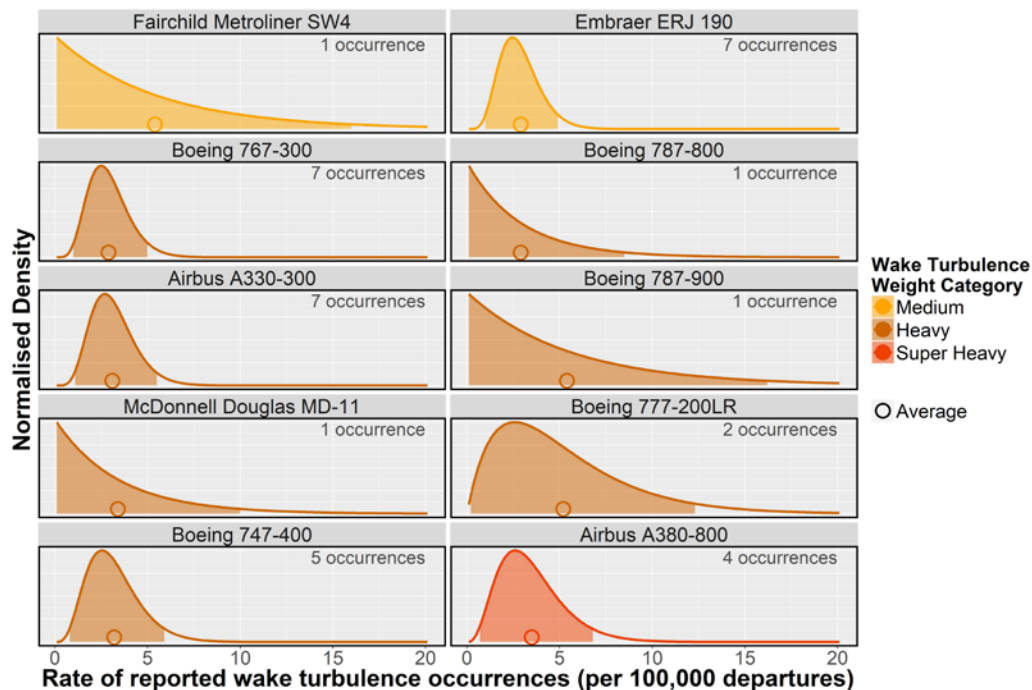
Appendix H: Aircraft models in close proximity prior to a wake turbulence occurrence

Figure 29: Rate of reported wake turbulence occurrences (per 100,000 arrivals) for arrivals at Sydney Airport (2012–2016) by whether a arriving aircraft model was in the 10 previous movements.



Data sources: Airservices movements data and ATSB occurrence database. Only the top 10 aircraft with the greatest average rates are displayed. Plots are ordered by the aircraft's maximum take-off weight. For ease of comparison, all density values were normalised with respect to one for the highest value.

Figure 30: Rate of reported wake turbulence occurrences (per 100,000 departures) for departures at Sydney Airport (2012–2016) by whether a departing aircraft model was in the 10 previous movements.



Data sources: Bureau of meteorology weather observations, Airservices movements data and ATSB occurrence database. Only the top 10 aircraft with the greatest average rates are displayed. Plots are ordered by the aircraft's maximum take-off weight. For ease of comparison, all density values were normalised with respect to one for the highest value.

Sources and submissions

Sources of information

The sources of information during the investigation included the:

- The ATSB aviation occurrence database
- Airservices Australia
- Australian Bureau of Meteorology.

Submissions

Under Part 4, Division 2 (Investigation Reports), Section 26 of the *Transport Safety Investigation Act 2003* (the Act), the Australian Transport Safety Bureau (ATSB) may provide a draft report, on a confidential basis, to any person whom the ATSB considers appropriate. Section 26 (1) (a) of the Act allows a person receiving a draft report to make submissions to the ATSB about the draft report.

A draft of this report was provided to Airservices Australia, Sydney Kingsford Smith International Airport and the Civil Aviation Safety Authority.

Submissions were received from Airservices Australia, Sydney Kingsford Smith International Airport and the Civil Aviation Safety Authority and, where considered appropriate, the text of the draft report was amended accordingly.

Australian Transport Safety Bureau

The Australian Transport Safety Bureau (ATSB) is an independent Commonwealth Government statutory agency. The ATSB is governed by a Commission and is entirely separate from transport regulators, policy makers and service providers. The ATSB's function is to improve safety and public confidence in the aviation, marine and rail modes of transport through excellence in: independent investigation of transport accidents and other safety occurrences; safety data recording, analysis and research; fostering safety awareness, knowledge and action.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to operations involving the travelling public.

The ATSB performs its functions in accordance with the provisions of the *Transport Safety Investigation Act 2003* and Regulations and, where applicable, relevant international agreements.

Purpose of safety investigations

The object of a safety investigation is to identify and reduce safety-related risk. ATSB investigations determine and communicate the factors related to the transport safety matter being investigated.

It is not a function of the ATSB to apportion blame or determine liability. At the same time, an investigation report must include factual material of sufficient weight to support the analysis and findings. At all times the ATSB endeavours to balance the use of material that could imply adverse comment with the need to properly explain what happened, and why, in a fair and unbiased manner.

Developing safety action

Central to the ATSB's investigation of transport safety matters is the early identification of safety issues in the transport environment. The ATSB prefers to encourage the relevant organisation(s) to initiate proactive safety action that addresses safety issues. Nevertheless, the ATSB may use its power to make a formal safety recommendation either during or at the end of an investigation, depending on the level of risk associated with a safety issue and the extent of corrective action undertaken by the relevant organisation.

When safety recommendations are issued, they focus on clearly describing the safety issue of concern, rather than providing instructions or opinions on a preferred method of corrective action. As with equivalent overseas organisations, the ATSB has no power to enforce the implementation of its recommendations. It is a matter for the body to which an ATSB recommendation is directed to assess the costs and benefits of any particular means of addressing a safety issue.

When the ATSB issues a safety recommendation to a person, organisation or agency, they must provide a written response within 90 days. That response must indicate whether they accept the recommendation, any reasons for not accepting part or all of the recommendation, and details of any proposed safety action to give effect to the recommendation.

The ATSB can also issue safety advisory notices suggesting that an organisation or an industry sector consider a safety issue and take action where it believes it appropriate. There is no requirement for a formal response to an advisory notice, although the ATSB will publish any response it receives.

Australian Transport Safety Bureau

Enquiries 1800 020 616

Notifications 1800 011 034

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Research

ATSB Transport Safety Report Aviation Research

Analysis of wake turbulence occurrences at Sydney Airport
2012–2016: A Bayesian analysis

AR-2017-011

Final – 15 February 2019