Australian Government

Australian Transport Safety Bureau

Runway excursion involving Boeing 737, VH-VUI

Darwin Airport, Northern Territory | 6 December 2016

Investigation

ATSB Transport Safety Report

Aviation Occurrence Investigation

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Postal address: PO Box 967, Civic Square ACT 2608
Office: 62 Northbourne Avenue Canberra, Australian Capital Territory 2601
Telephone: 1800 020 616, from overseas +61 2 6257 2463 (24 hours)
Accident and incident notification: 1800 011 034 (24 hours)
Email: atsbinfo@atsb.gov.au
Internet: www.atsb.gov.au

Addendum

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Safety summary

What happened

On 6 December 2016, with thunderstorm activity in the area, a Boeing 737-800 aircraft operated by Virgin Australia on a scheduled passenger flight from Melbourne, Victoria was on approach to runway 29 at Darwin Airport, Northern Territory. The flight crew established and maintained clear visual reference to the runway and surrounds until they encountered heavy rain shortly before reaching the runway threshold. Under the influence of a light but increasing crosswind, the aircraft drifted right without the flight crew being able to discern the extent of the drift.

The aircraft landed 21 m to the right of the runway centreline and, shortly after touchdown, the right landing gear departed the sealed surface of the runway, destroying six runway lights before the aircraft returned to the runway. The aircraft incurred minor damage from ground debris and there were no injuries.

What the ATSB found

A relatively small increase in crosswind resulted in a significant deviation from the runway centreline at a critical time during final approach. The absence of adequate visual cues influenced the flight crew’s ability to detect and correct the deviation.

International guidelines recommend, but do not mandate, the use of centreline lighting on wider runways. In recent years, two runway veer-offs have occurred at runway 29 at Darwin, which is the only runway in Australia that is wider than 50 m and not equipped with centreline lighting. No similar occurrence has happened at any other of the busier airports in Australia, where the runways are either narrower, or are a similar width but with centreline lighting.

A study of relevant occurrences world-wide found that the likelihood of a runway veer-off on landing increases significantly when using a runway that is wider than 50 m and does not have centreline lighting. This is likely due to limitations in the visual cues available in such circumstances.

There was no advisory information about this hazard in the operator’s manuals or in the aerodrome information provided to operators by Darwin Airport.

The ATSB also found limitations in the weather information provided to the flight crew while on approach to land.

What's been done as a result

The aircraft operator and airport operator initiated a number of safety actions as a result of the occurrence, including providing flight crews with information about the specific risks of approaches to Darwin Airport at night in conditions with reduced visibility.

The ATSB has issued a safety recommendation to the International Civil Aviation Organization and Darwin Airport to consider measures to reduce the safety risk identified in this report relating to wide runways without centreline lighting.

Safety message

Approaches in darkness and poor weather can be challenging. Centreline lighting greatly assists flight crews align the aircraft with the runway but many runways, including most in Australia, are not equipped with it. A wide runway without centreline lighting, such as that in Darwin, poses a particular challenge. Pilots and operators who are aware of any circumstances that are different to what is usually encountered and account for it in their planning are more likely to avoid being ‘caught out’ at a critical time.

Contents

The occurrence

Overview

On 6 December 2016, a Boeing 737-800 aircraft, registered VH-VUI and operated by Virgin Australia, was used for a scheduled passenger flight from Melbourne, Victoria to Darwin, Northern Territory. During the final approach to runway 29 at Darwin at night, the aircraft entered very heavy rain. The aircraft landed 21 m to the right of the runway centreline and, shortly after, the right main landing gear departed the sealed surface of the runway. Runway 29 was 60 m wide, which was 15 m wider than almost all the other runways used by air transport aircraft in Australia.

Flight planning

Prior to departing Melbourne, the flight crew reviewed relevant meteorological information for the flight including the latest aerodrome forecast (TAF) for Darwin, which was issued at 1400 Central Standard Time[1] and valid from 1530. The forecast conditions for their arrival time were good, with wind 300° at 5 kt, visibility at least 10,000 m and few cloud[2] at 2,000 ft.

There were no weather-related or other requirements for the flight crew to nominate alternate fuel or holding fuel for the flight. However, the captain ordered 1,500 kg more fuel than the minimum required for the flight (including the required reserves) due to the possibility that adverse weather conditions could develop.

Take-off and cruise

The aircraft was scheduled to depart Melbourne at 1825 (1955 AEDT) and actually departed at 1842. The captain was pilot flying (PF) and the first officer was the pilot monitoring (PM).[3]

During the flight, the flight crew obtained weather updates, which initially indicated that the weather conditions at Darwin remained good and were consistent with the forecast. A new TAF issued at 2053 and valid from 2130 was the same as the 1400 forecast.

At 2207, with the flight about 1 hour from landing, the Bureau of Meteorology (BoM) issued an amended TAF for Darwin. The amended TAF included a TEMPO,[4] which indicated that between 2230 and 0030 there could be periods of up to 1 hour with wind of variable direction at 20 kt gusting to 35 kt, visibility 4,000 m in showers of rain, and cloud broken at 1,500 ft.

Darwin air traffic control was required to pass on the availability of amended TAFs for the airport in accordance with the Manual of Air Traffic Services. The Darwin approach controller advised the Brisbane Centre en route controller of the amended TAF, and the Brisbane controller broadcast the TAF's availability and key details at 2211. The flight crew interpreted the forecast weather as 'thunderstorm material' and noted that the TEMPO period covered their expected arrival time.

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1 Central Standard Time (CST) was Coordinated Universal Time (UTC) + 9.5 hours. Times in this report are CST unless otherwise stated.

2 Cloud cover: in aviation, cloud cover of the sky is reported using words/abbreviations that denote the extent of the cover. 'Sky clear' (SKC) indicates no cloud, 'few' (FEW) indicates 1–2 oktas (or eighths) is covered, 'scattered' (SCT) indicates 3–4 oktas is covered, 'broken' (BKN) indicates 5–7 oktas is covered, and 'overcast' (OVC) indicates that 8 oktas is covered.

3 Pilot Flying (PF) and Pilot Monitoring (PM): procedurally assigned roles with specifically assigned duties at specific stages of a flight. The PF does most of the flying, except in defined circumstances; such as planning for descent, approach and landing. The PM carries out support duties and monitors the PF's actions and the aircraft's flight path.

4 TEMPO: a temporary deterioration in the forecast weather conditions, during which significant variation in prevailing conditions are expected to last for periods of between 30 and 60 minutes.

At 2212, the Brisbane controller who broadcast the availability of the 2207 amended TAF handed over duties to another controller. The incoming controller was advised that the amended TAF had been broadcast to all aircraft.

At 2218, the Brisbane controller issued the flight crew with a standard instrument arrival clearance to runway 29.

At 2223, the flight crew listened to the automatic terminal information service (ATIS) for Darwin Airport, which indicated the conditions were wind 300° at 8 kt, visibility at least 10,000 m, rain showers and scattered cloud[5] at 2,000 ft.

At 2224, the flight crew commenced the approach briefing. The briefing covered all the standard items, including the approach minima (290 ft elevation or 209 ft above the runway elevation and 800 m visibility) and the missed approach procedure for the runway 29[6] instrument landing system (ILS) approach procedure.

The flight crew selected an approach speed of 143 kt (reference landing speed plus 5 kt) and autobrake setting 2. They noted that the weather conditions were well above the minima at this stage, but if required they had sufficient fuel to conduct four missed approaches or hold for at least an hour.

At 2230, a SPECI[7] was issued for Darwin, which indicated that there had been a change in the actual weather conditions and that thunderstorms with rain were likely to be present. Subsequent SPECIs issued from 2247 indicated conditions were deteriorating. The flight crew did not obtain or receive these weather reports, but were aware of the developing situation. From 2232, they could see lightning in the distance and soon after, they could see rain cells on the aircraft's weather radar.

At 2237, when VH-VUI was about 25 minutes from Darwin, BoM issued a second amended TAF for Darwin. The change to the previous (2207) amended TAF was that during the TEMPO period there was now thunderstorms with rain and visibility could be 2,000 m. For reasons that could not be established, the Darwin approach controller did not advise the Brisbane controller of the availability of the second amended TAF. Therefore, the Brisbane controller did not broadcast the 2237 amended TAF's availability or details.

The operator's flight following staff attempted to check that VH-VUI's flight crew knew of the 2237 amended TAF via HF radio. Due to poor radio reception, the flight crew could not hear the message clearly but discerned that the call was about an amended TAF, and advised that they were aware of it. However, the call was about the 2237 TAF and not the 2207 amended TAF that the Brisbane controller had earlier broadcast. The flight following staff contacted Brisbane air traffic control at about 2247, and asked whether the flight crew had 'the amended TAF for Darwin'. The controller advised that they did.

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5 Cloud cover: in aviation, cloud cover of the sky is reported using words/abbreviations that denote the extent of the cover. 'Sky clear' (SKC) indicates no cloud, 'few' (FEW) indicates 1–2 oktas (or eighths) is covered, 'scattered' (SCT) indicates 3–4 oktas is covered, 'broken' (BKN) indicates 5–7 oktas is covered, and 'overcast' (OVC) indicates that 8 oktas is covered.

6 Runways are numbered in relation to their magnetic direction rounded off to the nearest 10°. This is the runway designation. Runway 29 at Darwin has a runway direction of 286° magnetic.

7 SPECI: a special weather observation report that is triggered by a significant change in a set of parameters, including wind, visibility and cloud. Routine weather observation reports (METARs) are normally issued every 30 minutes, and a SPECI issued at about the time of a scheduled METAR would replace the METAR.

Descent and approach

At 2241, the flight crew commenced descent from flight level (FL) 380.[8] Shortly afterwards, they could discern a rain cell on the weather radar and discussed the extra fuel they had on board, and that they did not want to fly under or through any thunderstorms.

At 2249, the Brisbane controller handed over control of VH-VUI to the Darwin approach controller. The first officer contacted the approach controller and stated they were descending through FL 120 and had received (ATIS) information 'Delta'. The approach controller advised the flight crew to expect the runway 29 ILS approach. He also advised that (ATIS) information 'Foxtrot' was current, and he provided the differences between 'Delta' and 'Foxtrot', which included that the wind was now 220° at 20 kt. The approach controller also advised that this wind information was only an estimate, because the airport anemometer was now unserviceable.

The flight crew discussed the situation, noting that the wind would be a predominant crosswind for the landing. They also discussed the weather around the airport and what impact it may have for their arrival on several occasions throughout the rest of the descent. The captain asked the first officer to add 10 kt to the landing reference speed to help alleviate the effect of wind gusts or changes, resulting in a selected approach speed of 148 kt.

At 2252, the approach controller provided the crew with another wind update, advising the wind speed to be 20 to 35 kt and that the crosswind for landing could be up to 20 kt. About a minute later the approach controller made an all stations broadcast, advising the runway was wet and the visibility at the airport was reducing to 5,000 m in rain.

At 2255, the flight crew requested approval to track direct to the initial approach fix (LAPAR) to avoid some of the weather, and the controller approved the request.

At 2256, when passing 5,000 ft, the flight crew began a further discussion about the airport weather. Their comments recorded on the cockpit voice recorder indicated they could see lightning ahead, and were using weather radar to determine the position of rain cells. They agreed a rain cell to the north-east of the airport would not impact the approach. In a later interview, the captain reported that it appeared as though they would easily land before the rain arrived. They began discussing the potential impact of another rain cell south-west of the airport but were interrupted by other priority tasks and did not conclude this discussion.

The flight crew selected flaps 5 at 2258 and the first officer advised Darwin tower that they were approaching LAPAR. The tower controller advised rain was now directly over the airport and the visibility was reducing to about 3,000 m. At around the same time, the flight crew selected flaps 15.

The tower controller also advised the flight crew of the settings of the high intensity approach lighting (stage three) and the high intensity runway lighting (stage five) and requested the flight crew advise if changes to the settings were necessary. The first officer asked if there was any update on the wind information, and the tower controller stated that the wind estimate remained the same as previously advised by the approach controller, and they were trying to get additional information. The first officer acknowledged the reply, and noted they now had the runway lights in sight.

At about 2259, the aircraft descended through the lowest level of the cloud base from about 2,500 ft. The crew later reported that they could see the runway and airport surrounds. They saw a rain shower at the airport, towards the far end of runway 29.

The crew again discussed the weather conditions and they discussed their options in the event a missed approach was required, and agreed they would divert to the right rather than straight

[8] Flight level: at altitudes above 10,000 ft in Australia, an aircraft's height above mean sea level is referred to as a flight level (FL). FL 380 equates to 38,000 ft.

ahead as published on the missed approach track (286°). The captain requested the first officer be ready to use the aircraft windscreen wipers.

At 2300, the aircraft descended through 2,000 ft at about 150 kt and the flight crew selected flap 30. The Darwin tower controller updated the wind information based on data obtained from a second, test anemometer located to the south of the runway 29 threshold that the wind was 290° at 16 kt, gusting to 22 kt. The first officer acknowledged the information and advised that if a missed approach was conducted the crew planned to turn to a heading of around 320° to 'avoid the storm on the other side of the field.'

At 2301, the flight crew commenced the landing checklist, and the captain asked the first officer for his opinion on the situation. The first officer noted the approach was stable, the missed approach altitude was set and it was apparent they would be able to land. They could see the runway lights clearly, and although there was rain ahead, it looked like it was some distance down the runway.

Final approach and landing

The events during the final approach and landing are summarised in Table 1, including the time, airspeed and radio height (or height above ground) from 500 ft. Figure 1 also shows the aircraft's lateral displacement from the runway centreline.

Table 1: Summary of events during final approach and landing

Time	Speed[9]	Radio height	Event
2301:46	148 kt CAS	500 ft	The captain asked the first officer to turn the wipers on using the fast setting, which was actioned.
2302:01	153 kt CAS	267 ft	The captain disengaged the autopilot. At this point, the aircraft was on the glidepath, on track and close to the extended runway centreline. The first officer advised that the wind was 280° and up to 25 kt.
2302:07	148 kt CAS	207 ft	The aircraft passed through the decision height for the ILS approach, and the aircraft's automated 'minimums' annunciation occurred. The captain stated they would try to land. The first officer acknowledged and stated the wind was steady.
2302:12	148 kt CAS	179 ft	The aircraft entered rain, which intensified over the next few seconds.
2302:18	152 kt CAS	131 ft	The crossbars of the approach lights would no longer have been visible to the crew under the aircraft's nose. The crosswind dropped from about 4 kt to 1 kt for 2 seconds, and then began a slow increase
2302:21	151 kt CAS, 133 kt GS	98 ft	The automated '100 feet' annunciation occurred. The runway threshold lights would have no longer been visible to the crew under the aircraft's nose. Later analysis indicated that, at about this time, there was an increase in the average crosswind from 3 kt to 6 kt, and the aircraft started drifting to the right of the extended runway centreline.
2302:23	152 kt CAS, 134 kt GS	50 ft	The aircraft crossed the runway threshold, about 3 m to the right of the runway centreline and drifting about 3° to the right. The automated '50 feet' annunciation occurred.
2302:25	134 kt GS	35 ft	The captain initiated the landing flare.[10] The aircraft was about 11 m to the right of the runway centreline.

9 Computed airspeed (CAS) or groundspeed (GS). The recorded CAS becomes less reliable at low speed.

10 Flare: the nose-up pitch of a landing aeroplane used to reduce the rate of descent at touchdown.

2302:30	135 kt GS	0 ft	The aircraft touched down wings level within the touchdown zone, 440 m from the threshold, about 21 m to the right of the centreline and drifting about 3° to the right.
2302:31	133 kt GS	0 ft	The aircraft's nose gear touched down.
2302:33	126 kt GS	0 ft	The right main landing gear departed the sealed surface of the runway about 235 m after touchdown, 675 m from the runway threshold at about 126 kt groundspeed. The gear's maximum distance from the runway edge was around 1.5 m.
23:02:41	92 kt GS	0 ft	The right main landing gear returned to the sealed runway surface at a groundspeed of about 92 kt, after having been off the sealed surface for about 394 m.
23:02:45	78 kt GS	0 ft	The captain deployed the thrust reversers.
23:02:52	60 kt GS	0 ft	The aircraft reached 60 kt groundspeed.

The approach was stable at 500 ft, and the captain disconnected the autopilot at about 270 ft. The wind was gusty, requiring constant correction, and the crosswind varied between 0 kt and 5 kt from the aircraft's left. At the decision height (about 210 ft) the flight crew were still visual and decided to proceed with the landing. Soon after, at about 180 ft, the aircraft entered heavy rain. The crew later reported that they had expected to land well before encountering the rain.

The air traffic controllers in the Darwin tower reported that they could see the aircraft's lights (including the logo light on the near side) throughout the final approach and landing from the tower, about 1.8 km north-west of the runway threshold.

From about 100 ft, the flight crew would not have been able to see the approach lights or runway threshold lights below the aircraft's nose (see *Aerodrome information*). In addition, the crew later described the rain from this point as a 'heavy deluge'. Their vision of the runway and the surrounding airport environment was obscured. Only the runway edge lights and precision approach path indicators remained visible, and they became blurred and no longer sharp and distinct, particularly between each pass of the windscreen wipers. The crew reported that they felt at the time that the visibility remained sufficient to complete the landing.

At about 100 ft (2302:21), the aircraft started to drift to the right of the runway centreline, and this deviation increased until the aircraft landed 8 seconds later (2302:29). Other than the lateral deviation, all other aspects of the final approach and landing were normal.

The aircraft touched down within the touchdown zone, about 21 m to the right of the centreline. The maximum recorded vertical acceleration was 1.74 g, within the normal range for landing, and there was no evidence that the aircraft bounced.

When the captain lowered the aircraft's nose he realised the aircraft had landed 'well right' of the centreline but with the obscured visibility he could not readily ascertain how far. He later recalled trying to steer the aircraft towards the centre of the runway but being very wary of oversteering and losing control on the wet runway.

At 2302:33, 4 seconds after landing, the right main landing gear departed the right side of the runway. The captain recalled hearing a repeated, light thudding noise. He asked the first officer if they had hit the runway lights and the first officer responded that that they were just missing the lights. The aircraft's nose was oriented to the left of the direction of travel, placing the flight crew and nose gear over the sealed surface and inside the painted runway edge markings. The first officer later reported feeling a shudder, as though the wheels were skidding. Both flight crew recalled that the physical sensation and noise were not as strong as they would have expected from the wheels departing the runway.

Figure 1: Final approach and landing roll of VH-VUI

Image shows the aircraft's path crossing the runway threshold near the centreline and deviating to the right edge of the runway before returning. Source: ATSB / Google Earth

Taxi and disembarkation

The flight crew taxied to the bay and stopped short at 2309, remaining there until the weather eased enough for safe ground work and disembarkation. During this time, the crew discussed the approach and landing. The captain asked whether the first officer was sure the aircraft had stayed on the runway, and the first officer reiterated that he was sure they had.

At 2322, the ground marshaller installed the wheel chocks and the passengers soon started disembarking. At 2329, one of the flight crew also disembarked and inspected the aircraft. He observed the aircraft damage and immediately realised they had departed the sealed surface of the runway on landing. After returning to the aircraft, the flight crew reported the incident to the operator and air traffic control at 2331.

The airport operator inspected the runway and identified that at least four runway lights were inoperable, but at the time saw no debris other than grass on the runway. The flight crew of the next arriving flight was advised of the situation and elected to continue, landing at 2336. Subsequent inspections found debris from the runway lights on the runway surface.

Damage and injuries

Six runway edge lights were hit and destroyed as the landing gear impacted concrete pads located just off the runway edge (Figure 2). Debris from the lights and ground impacted the aircraft and littered the edge of the runway surface.

The right main gear tyres sustained deep cuts during the impacts with the runway edge lights and concrete pads (Figure 3).

Debris impacted the aircraft resulting in minor damage to areas of the right aft fuselage and right horizontal stabiliser (Figure 4). A large quantity of grass accumulated in the vicinity of the right wheel well, landing gear and wing flaps.

There were no injuries.

Figure 2: Wheel tracks where VH-VUI departed the runway 29 sealed surface and destroyed runway edge lights[11]

Image shows the tracks from the right main landing gear through grass and over concrete pads near the runway edge. Photo facing the opposite direction to the landing. Source: ATSB

Figure 3: VH-VUI tyre damage

Image shows cut damage to the right main landing gear outboard tyre. The chevrons in the centre of the tread are normal. Source: ATSB

11 The photograph was taken after displayed high intensity runway lights that were damaged by impact were replaced.

Figure 4: VH-VUI fuselage damage, marked with green tape

Image shows the locations of skin damage to the right side of the aircraft fuselage marked with short sections of tape on the underside of the fuselage. Longer sections of tape mark the locations of longitudinal and vertical fuselage reference lines. Source: Virgin Australia

Context

Personnel information

At the time of the occurrence, the captain had a total of 22,559 hours flight time with 9,206 hours on Boeing 737 variants. The first officer had a total of 7,000 hours flight time with 3,500 hours on 737 variants. Both flight crew were appropriately qualified to conduct the flight.

The flight crew's last night landing was conducted together the previous night, and each had conducted several night landings into various Australian airports in the previous month. The captain's last flight into Darwin Airport was five and a half months previous, and the first officer's most recent landing there was 16 months previous. Both were night landings. The captain reported having flown to Darwin many times before.

The first officer reported not having encountered rain conditions like those on approach during the occurrence flight before. The captain recalled having seen such conditions only once before, about 30 years prior, during a flight into Darwin that resulted in a hard landing.

Both flight crew were based in Melbourne. They had no duty on 3 and 4 December 2016. On 5 December, they both flew as passengers to Canberra in the afternoon, and then conducted a series of flights, ending their duty time at about 2300 AEDT.[12]

On 6 December, they signed on for duty at Canberra Airport at 1600 AEDT. They then operated a flight from Canberra to Melbourne, before beginning preparations for the Melbourne to Darwin flight. They had both been on duty for 8.5 hours at the time of the occurrence.

The captain reported getting about 6 hours sleep the night before the occurrence and normal sleep in the nights before. The first officer reported getting a normal amount of sleep the night before the occurrence, and the nights before that. Both crew reported being a little tired at the time of the occurrence. However, there was insufficient evidence to suggest that the flight crew were operating at a fatigue level known to affect performance, and both had sufficient sleep opportunity in the nights prior to the occurrence.

Aircraft information

VH-VUI, a Boeing 737-800 aircraft, was manufactured in 2006. No problems with the serviceability of any relevant aircraft systems were reported or identified. The aircraft was fitted with the appropriate equipment for category I, II, and III ILS approaches and was capable of autoland at suitably equipped airports.[13] The aircraft was not fitted (nor required to be fitted) with an aircraft communications addressing and reporting system (ACARS) to receive data messages.

Boeing 737-800 aircraft (as well as the 600, 700 and 900 series 737s) were certified for operation with windscreen wipers and without any other rain removal system. The aircraft was not fitted with a rain repellent fluid dispensing system, which had been fitted to earlier versions of the 737. This system was no longer in use because of environmental concerns about the fluid available at the time.

Additional visual enhancements available for 737-800 windscreens include a hydrophobic coating. The aircraft manufacturer stated these coatings were an enhancement to the wiper system but were not required for safe operation of the aircraft. It stated that the service life of hydrophobic coatings varied significantly from operator to operator due to the operating environment,

12 Australian Eastern Daylight Time (AEDT) was Coordinated Universal Time (UTC) + 11 hours.

13 An autoland is a precise, repeatable landing that can be conducted in poor weather conditions where insufficient visual cues are available to the pilots. It uses a number of automatic flight control systems on board the aircraft, combined with specific ground-based ILS and runway environment requirements

particularly in terms of how often windscreen wipers were used and the areas where particulates such as dust were encountered on flights.

The operator reported that 43 of its 79 Boeing 737 aircraft had a hydrophobic coating applied at the time of aircraft production. However, regular maintenance of the coatings was not required by the operator's system of maintenance, and the coatings had not been routinely replaced in service. The windscreen of VH-HUI was delivered to the operator in 2013 with a new hydrophobic coating.

The aircraft was fitted with anti-skid wheel brakes. Post-occurrence inspections found no evidence of rubber reversion hydroplaning (which leaves distinctive marks on the runway and tyres); however, other types of hydroplaning leave no direct evidence. The touchdown point could not be identified, suggesting that some initial hydroplaning may have occurred. There were black particles in the runway surface that indicated a transfer of rubber from the aircraft's tyres continuously along the aircraft's path from near where the aircraft touched down, consistent with some degree of traction.

Meteorological information

Weather observations

The approach and landing were conducted in darkness. Weather radar data provided by the Bureau of Meteorology (BoM) showed two areas of rain near and over Darwin Airport on the night of the occurrence (Figure 5).

Table 2 summarises meteorological information from routine weather reports (METARs) and special weather reports (SPECIs) during the period from 2100 local time. As indicated in the table, visibility started decreasing at about 2247, and it decreased to 2,000 m at 2257. There was heavy rainfall recorded by a rain gauge near the runway 29 threshold at Darwin Airport after 2247, peaking at about 24 mm/hour for a period of several minutes around the time the aircraft landed.

A 2300 observation from the test anemometer at Darwin Airport (see *Weather information services*) recorded a westerly surface wind of 16 kt. The Darwin tower controller reported the windsock nearest the runway 29 threshold indicated a relatively steady wind but as with windsocks in general, it was not responsive to short gusts.

Closed-circuit security video showed rain at the terminal (2 km north-west of the runway 29 threshold) starting and increasing from about 2250, and becoming heavy by 2302. Over this period, the video showed four brief, bright flashes consistent with lightning strikes.

Recorded lightning strike data showed significant activity in the area. In the 5 minutes before VH-VUI landed (at 2302), there were several lightning strikes within 5 NM of the airport and two within 5 NM of the aircraft. Some of these may not have been visible to the flight crew due to them potentially being obscured by cloud.

Figure 5: Ground-based radar images showing rainfall near Darwin Airport (blue arrow) during the approach, with the aircraft's position at 2300 indicated by an aircraft symbol

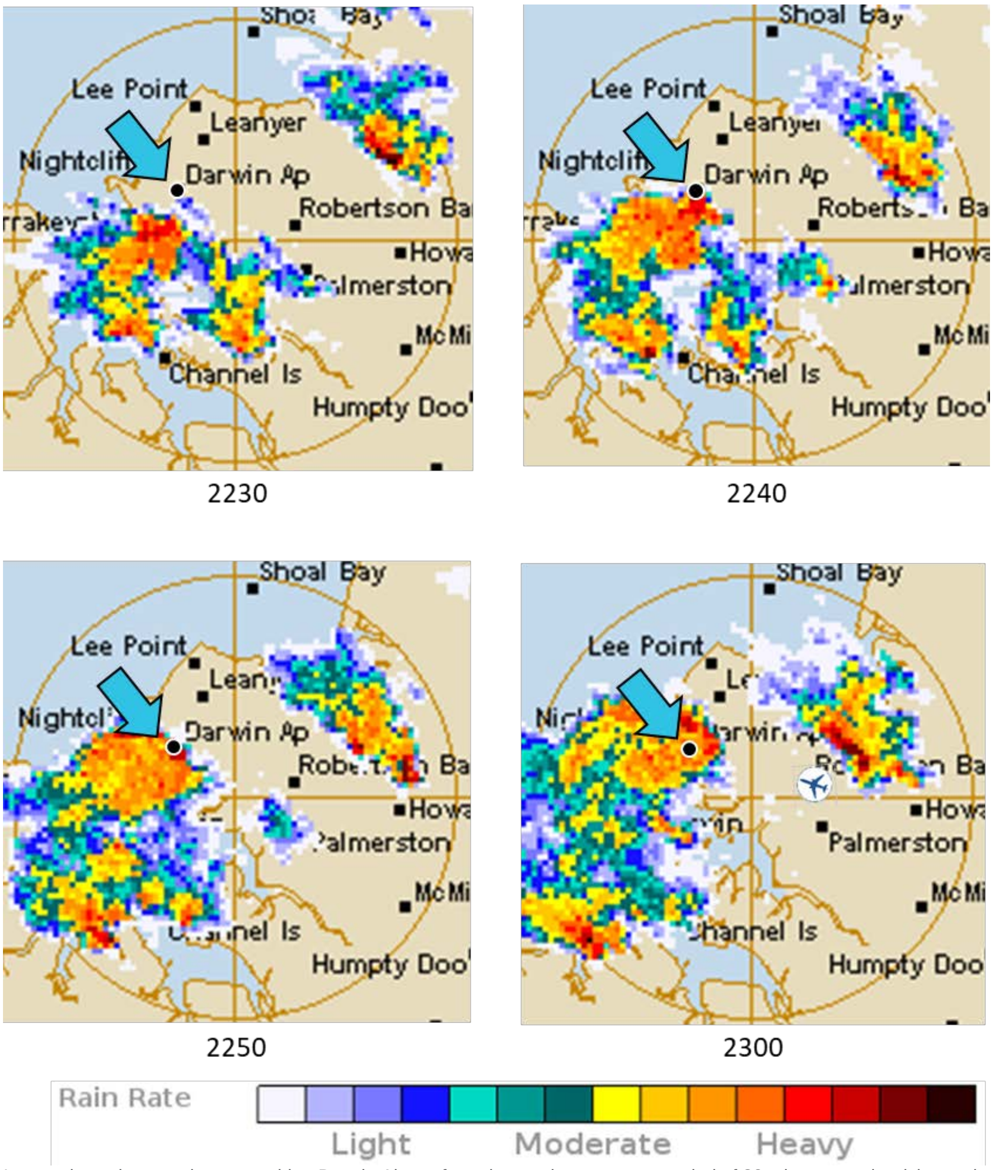

Image shows heavy rain approaching Darwin Airport from the south-east over a period of 30 minutes, and arriving at the airport while VH-VUI approached. The tan circle has a 20 km (10.8 NM) radius. Note that the picture displayed on the aircraft's weather radar would not be the same. Source: Bureau of Meteorology, modified by ATSB

Table 2: Darwin METAR and SPECI summary

Time	Wind direction (° M)	Wind speed (kt)	Visibility	Precipitation
2100	290	7	> 10 km	None
2130	320	10	> 10 km	Light rain
2200	310	9	> 10 km	Showers in the vicinity
2230	250 (variable)	7	> 10 km	Light thunderstorm and rain
2247	230	9	7 km	Moderate thunderstorm and rain
2257	290	16	2 km	Heavy thunderstorm and rain
2300	290	15	2 km	Heavy thunderstorm and rain
2312	320	11	5 km	Light thunderstorm and rain
2330	310	7	> 10 km	Showers in the vicinity
0000	340	4	> 10 km	Showers in the vicinity
0030	340	2	> 10 km	None

Weather information services

BoM was responsible for the provision of aerodrome forecasts and weather reports at Darwin Airport. An aerodrome forecast (TAF) was issued every 6 hours with a validity period of either 24 or 30 hours from defined commencement times. When significant variations from the mean conditions, of a temporary nature, were expected to occur within the forecast period they were indicated by the use of the term TEMPO in the forecast.

Aerodrome weather reports were generated by an automatic weather station with manual input from approved weather observers. Routine reports (METAR) were issued every 30 minutes. Special reports (SPECI) were triggered by a significant change in a set of parameters, including wind, visibility and cloud.

In Australia, air traffic control (ATC) was required to pass on TAF and amended TAF information to flight crews that were within an hour of their destination. ATC was not required to pass on SPECI reports if those reports were available through a local broadcast service such as the Aerodrome Weather Information Service (AWIS) available at Darwin.

Availability of wind information

The Darwin control tower was equipped with displays that showed the wind direction and speed sourced from the airport anemometer via the BoM Observations office. This anemometer was located near the centre of the airport, about 2.4 km west of the runway 29 threshold (Figure 6).

Figure 6: Location of anemometers at Darwin Airport

Image shows the primary anemometer's location near the centre of the airport and the second (test) anemometer near the runway 29 threshold. Source: ATSB / Google Earth

Due to a failure attributed to a lightning strike,[14] the airport anemometer was unserviceable at the time of the occurrence and no wind information was being displayed in the control tower. Darwin tower controllers obtained wind information from windsocks located at the airport, and through BoM observers via telephone for information from a second, test anemometer about 550 m south of the runway 29 threshold. Wind data from this anemometer was relayed to the tower controllers by a trained BoM observer.

BoM reported that the last performance checks on the test anemometer were conducted in June 2014. BoM was unable to verify the integrity of the anemometer's wind data but stated that it was a standard installation using the same type of anemometer as the airport anemometer, and BoM considered the wind information to be a reasonable indication of local conditions. Performance checks before and after the occurrence showed the test anemometer to be operating within specifications. There may be some difference in wind speed and direction readings between the two sites due to local variations, and obstructions near the secondary site.

According to fault records, the primary anemometer was unavailable or exhibited faults on 32 occasions from February 2013 to December 2016, including 21 occasions in the wet season (November to April). The median time to repair was about 2.5 hours and the average was 14.5 hours. On four occasions, the repair took longer than 24 hours.

BoM advised that its anemometers were installed and maintained to meet International Civil Aviation Organization (ICAO) Annex 3 standards and recommended practices. For anemometers at Australian airports, there was no minimum availability[15] requirement and no requirement to have a secondary anemometer.

Landing visibility criteria

Civil Aviation Regulation (CAR) 257(4) stated that an aircraft may not land if any element of the meteorological minima was below that published for the operation. The published ceiling minimum (and decision height)[16] for an ILS category I approach to Darwin was 200 ft, and the visibility minimum was 800 m.

CAR 176A(2) stated that:

> In determining visibility, the pilot in command of an aircraft must take into account the meteorological conditions, sunglare and any other condition that may limit his or her effective vision through the windscreen of the cockpit of the aircraft.

CAR 257 noted that determinations about the meteorological minima for landing must be published in the Aeronautical Information Publication (AIP). The AIP (ENR 1.5, paragraph 4.11) stated that conditions were below the minima when 'the total amount of cloud below the ceiling minimum specified is continuously greater than SCT' [scattered], or 'the visibility is continuously below the visibility specified'.

Flight data recording

The aircraft manufacturer performed kinematic analysis of the recorded flight data, which provides a more accurate representation of wind than the raw recorded data.

With the autopilot engaged, the aircraft accurately maintained the glideslope and localiser during the approach. To maintain the steady approach in turbulence, constant corrections were required

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14 The ATSB was unable to determine the exact time when the failure occurred due to an error in the fault log. Information from METAR/SPECIs indicated that it occurred at some time between 2230 and 2247. The anemometer was unserviceable for about 15 hours.

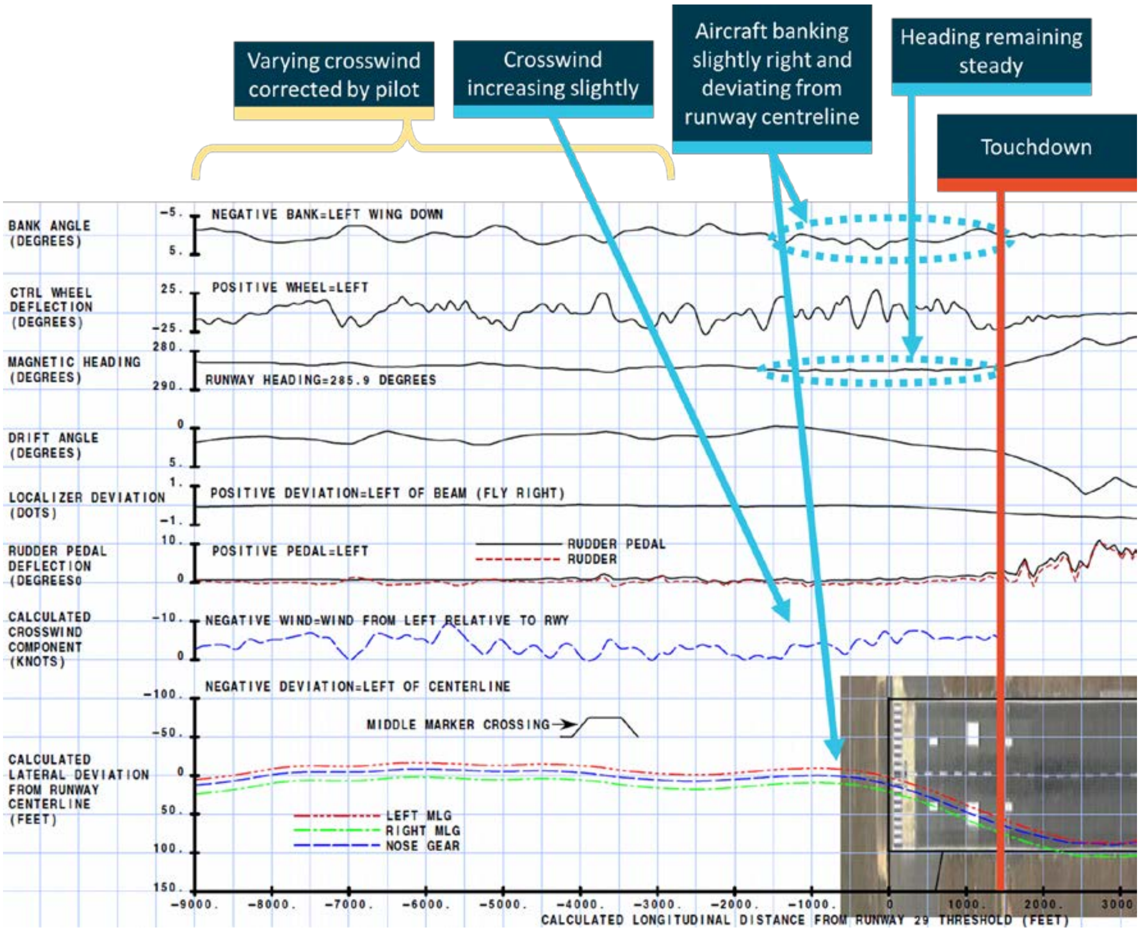
15 Availability: in reliability engineering, availability is the proportion of time a system is able to function correctly.

16 Decision height: the height at which a missed approach must be conducted if the required visual reference has not been established.

including control wheel (yoke) deflections up to 20°. The captain maintained runway alignment after disengaging the autopilot at 2302:01 until almost at the threshold.

The kinematic analysis indicated that in the few seconds before crossing the threshold (2303:23), the crosswind varied but it was not significantly more than it had been previously (Figure 7). However, in a gradually increasing crosswind from about 140 ft, about 5 seconds before crossing the threshold, the aircraft banked slightly right and began drifting right, without correction. A combination of momentum and continuing crosswind meant that the drift to the right continued until touchdown.

Figure 7: Recorded data showing the aircraft's drift from centreline. The runway width is exaggerated and the markings are different to those at the time of the occurrence.



Source: Boeing, annotated by ATSB

Aerodrome information

General information

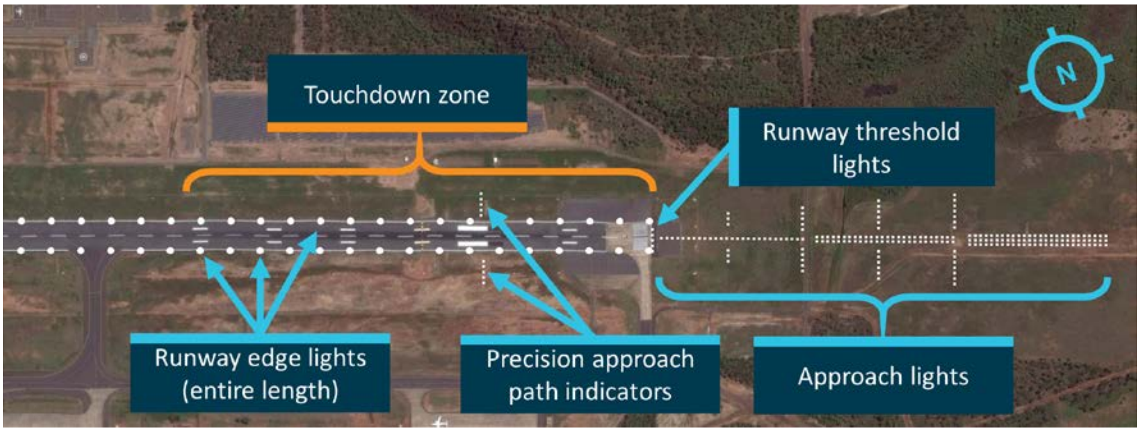
Darwin Airport consists of both civil and military facilities and is classified as a joint-user aerodrome. The civilian airport operator is Darwin International Airport. Responsibilities between the Department of Defence and Darwin International Airport are defined in a joint-user deed. The runway infrastructure is the responsibility of the Department of Defence.

Runway information

Runway 29 was 3,354 m long and 60 m wide, and the centre 45 m was grooved to aid water displacement and had a retractable arrestor cable in the touchdown zone for military use. The runway was equipped with an instrument landing system (ILS) that allowed for precision approaches in operations to category I minima (without autoland).

The runway had white markings along the centreline, an aim point starting 342 m from the threshold, and five touchdown zone markings from the threshold to 900 m. The runway had high intensity approach lights, runway threshold lights, and runway edge lights spaced at 60 m intervals.[17] There were also precision approach path indicator lights each side of the aim point (Figure 8).

Figure 8: General arrangement of runway lighting at Darwin Airport runway 29



Light locations are approximate, and actual light colours are not represented. Source: ATSB / Google Earth

Runway 11/29 at Darwin was significantly wider than most others in Australia (see *Related occurrences in Australia*), resulting in the visual cues and runway perspective being different to those normally available to complete a landing. The runway was not equipped with centreline or touchdown zone[18] lights.

There were two distinct crests that could obstruct distant portions of the runway and some edge lights when viewed very close to touchdown. ATSB analysis of topographic survey data indicated that runway 29 met relevant standards for slope and variation.

The Civil Aviation Safety Authority (CASA) outlined Australian requirements for aerodromes in Civil Aviation Safety Regulation (CASR) 139 and the associated Manual of Standards (MOS) for CASR Part 139. Testing conducted in 2016 and 2017 found that the ungrooved runway edge on the northern side of runway 11/29 at Darwin did not meet the surface texture or friction requirements of the MOS.

Runway design standards and guidance

The International Civil Aviation Organization (ICAO) specifies standards and recommended practices (SARPS) for international aviation operations in a series of Annexes. ICAO Annex 14 (*Aerodromes, Volume 1 Aerodrome Design and Operations*, 7th edition July 2016) stated that runway centreline lights and touchdown zone lights shall be provided for runways with a category II or III[19] precision approach. It also stated:

> 5.3.12.2 Recommendation— Runway centre line lights should be provided on a precision approach runway category I, particularly when the runway is used by aircraft with high landing speeds or where the width between the runway edge lights is greater than 50 m.

Annex 14 had included the same or similar recommendation since 1966. There was no recommendation for touchdown zone lights for category I runways.

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[17] One space at each end had a different distance to allow a pair of lights to align with the thresholds.

[18] The touchdown zone is the portion of a runway, beyond the threshold, intended as the first point of contact between landing aircraft and the runway.

[19] The decision height for a category II approach is lower than 200 ft but above 100 ft, and for a category III approach it is lower than 100 ft.

ICAO also published other guidance about aerodrome lighting. For example, ICAO document 9157 (*Aerodrome Design Manual, Part 4 Visual Aids*) stated:

> The function of the centre line lighting is to provide the pilot with lateral guidance during the flare and landing ground roll or during a take-off. In normal circumstances, a pilot can maintain the track of the aircraft within approximately 1 to 2 m of the runway centre line with the aid of this lighting cue. The guidance information from the centreline is more sensitive than that provided from the pilot's assessment of the degree of asymmetry between the runway edge lighting. In low visibility conditions, the use of the centre line is also the best means of providing an adequate segment of lighting for the pilot to use. The greater distances involved in viewing the runway edge lighting together with the need for the pilot to look immediately ahead of the aircraft during the ground roll also contribute to the requirements for a well-lit runway centre line.

Another section of the manual stated:

> …Some of the most difficult tasks when flying an aircraft visually are judging the approach to a runway and the subsequent landing manoeuvre. During the approach, not only must the speed be carefully controlled, but continuous simultaneous corrections in all three dimensions are necessary in order to follow the correct flight path.
>
> …There are two reasons why approach and runway lighting systems are provided with patterns that emphasize the centre line. One obvious reason is that the ideal landing position is along the centre of the runway. The other is that the fovea of the eye, the region of sharp vision, is only about 1.5 degrees in width…
>
> Studies have shown that the average time required for a pilot to switch from outside visual cues to instruments and back to outside cues is about 2.5 seconds. Since high performance aircraft will travel at least 150 m in this time period, it is apparent that in so far as possible the visual aids should provide the utmost in guidance and information, enabling the pilot to proceed without the necessity of cross-checking the instruments…

Consistent with Annex 14, the MOS for CASR Part 139 required centreline and touchdown zone lighting for runways with category II or II approaches and recommended centreline lighting for category I runways with a width of more than 50 m.

Simulation of visual cues provided by runway lights

The ATSB examined the relative effectiveness of the visual cues provided by runway edge lights on late final approach at Darwin during the 6 December 2016 occurrence flight compared with other situations.

Visual images were created to simulate a captain's view of runway lights when on approach to a runway. These simulations were based on a highly simplified model of the cues that would normally be available to flight crews. For example, they did not include visual cues available from approach lighting, runway texture or surrounding areas, and did not account for the effects of rain and windshield wipers on the visual appearance of the runway edge lights. They also did not account for the effects of aircraft movement and associated visual cues such as optic flow. Nevertheless, they provided some indication of the relative ability to identify a lateral deviation from the runway centreline during the later stages of the final approach.

The simulations indicated:

- A significant deviation from the runway centreline (11 m lateral displacement at 24 ft above the ground) appears much easier to detect on a 60 m wide runway if runway centreline lights are provided.
- A significant deviation from the runway centreline is more difficult to detect on a 60 m wide runway without centreline lighting compared to a 45 m wide runway without centreline lighting.
- It may be difficult to distinguish being on centreline and wings level from being off centreline with a slight bank in the direction of the closest row of edge lights. However, the deviation from the centreline is much easier to detect when runway centreline lights are present.

Further details of the simulation method and simulation images are provided in Appendix A.

En route supplement information

CASR 139 required an aerodrome operator to ensure there was adequate particulars about the aerodrome published in the En Route Supplement Australia (ERSA).[20] The types of information required included telephone numbers, runway specifications, lighting, visual aids, available ground services, special procedures and local precautions.

The MOS for Part 139 provided more details regarding the types of information to be included in the ERSA. This included the width and lighting information for each runway and 'important cautionary or administrative information relating to the use of the aerodrome'. The 'Additional information' section of the ERSA for the aerodrome was also required to include 'significant local data', such as animal or bird hazards or areas to avoid overflying.

The ERSA information for many Australian aerodromes includes some types of hazards in the 'Additional information' section, such as birds, weather balloon launches, or the likelihood of turbulence on approach to particular runways. Specific guidance with regard to visual issues on approach was uncommon. One example was the ERSA entry for Mackay Airport, which stated that in conditions of light mist or fog, high intensity floodlighting adjacent to the final approach to a runway could 'cause distraction'. A small number of entries cautioned that nearby roads or other objects may be mistaken for a runway.

The ERSA information for Darwin stated there was a possibility of windshear or turbulence on short final approach for all runways and bird hazards. No advisory information was provided about the potential for visual illusions or potential problems with visual guidance during landing associated with the runway width, lack of centreline lighting or touchdown zone lighting, or the crests in the runway.

Operator information

Approach to land near storms

The Virgin Australia flight crew operations manual stated:

> In the interests of safety, prevention of aircraft damage, and passenger comfort, avoiding thunderstorms is of paramount importance.
>
> - Visually avoid thunderstorm cells, or radar returns, including those with prominent 'hooks', 'scallops' or 'fingers' which indicate severe hail and signify strong vertical shear
> - Avoid flying under anvils
> - Avoidance shall be upwind of the weather, where possible
> - Do not attempt to overfly a thunderstorm…

In terms of the descent and approach to land, the manual also stated:

> Fly the aircraft clear of thunderstorms either by holding or adopting an alternative approach track. The circuit and approach to land should not be closer than 5 nm to an approaching storm at any time.

A note in the relevant section stated:

> During take-off and landing, storms that have passed may be approached closer than 5 nm, as the rear of storms is considered to be comparatively inactive.

[20] The ERSA was part of the AIP and published by Airservices Australia. However, the details for each aerodrome were provided by the aerodrome operator.

Transition to manual flight

In relation to flight path management, the operations manual stated that the auto flight system (AFS) on an aircraft 'should be used to enhance operational capability, improve safety and reduce workload'. In addition:

> Flight crew should use available AFS to the fullest extent that meets operational requirements considering the current flight conditions.

The manual also stated that the autopilot should be engaged:

> … On all Instrument approaches, when cloud is within 500 ft of the minima or when the reported visibility is less than required visibility +2000 m…

In a section discussing the flare and touchdown, the operator's flight crew training manual for the 737 stated:

> When a manual landing is planned from an approach with the autopilot connected, the transition to manual flight should be planned early enough to allow the pilot time to establish airplane control before beginning the flare. The PF should consider disengaging the autopilot and disconnecting the autothrottle 1 to 2 nm before the threshold, or approximately 300 to 600 feet above field elevation.

Guidance for Darwin Airport

An examination of the Virgin Australia's flight operational quality assurance data suggested off-centreline landings were very rare, including at Darwin.

Virgin Australia used aeronautical charts that were provided by a third party (Jeppesen), and also published its own supplementary port information when there was a need to provide additional information to flight crews. The supplementary port information for Darwin Airport included a caution for flight crew about turbulence and windshear on short final, and bird hazards. There was no specific guidance for other weather conditions, runway characteristics, or local lighting.

The ATSB reviewed the supplementary guidance for Darwin Airport provided by two other major Australian airlines. Following a veer-off runway excursion at Darwin in 2003 (see *Related occurrences in Australia*), one operator introduced additional guidance to flight crews for approaches to Darwin, including notes about runway surface, slope, width, lighting, and ambient light. The guidance stated:

> CAUTION:
>
> Be aware of the possibility of loss of visual cues when landing on RWY 29 at night, particularly in conditions of reduced visibility.
>
> Contributing factors include:
>
> - Runway surface condition;
> - Runway slope;
> - Runway width of 60 m;
> - No centreline lighting;
> - No touchdown zone lighting;
> - Lack of surrounding ambient light, particularly approaching the flare, i.e. black hole effect.
>
> It is recommended that approach and landings at night onto RWY 29 auto-coupled to the ILS for as long as possible, commensurate with the limitations. Crew must exercise vigilance and if any doubt exists as to the safe continuation of the approach, a Missed Approach must be executed.

The second operator, which had an association with the first operator, provided similar guidance to its flight crews.

Related occurrences

Previous studies of runway excursions

A study by the ATSB (2009) examined 141 runway excursions involving commercial jet aircraft during 1998–2007. About 40 per cent were veer-offs[21] on take-off or landing. Weather was a significant factor in many of the occurrences. The ATSB report stated:

> Appropriate lighting of the runway centreline and edges has the potential to provide pilots with better spatial awareness at night or in poor visibility conditions, and may reduce the likelihood of veer-offs.

A Flight Safety Foundation (FSF) study (2009) examined 548 runway excursions, including 230 veer-offs on landing. This study also highlighted the significant effect of weather. The FSF report stated:

> The frequent presence of runway contaminants in runway excursions strongly implies that they…are a significant risk factor, along with weather conditions such as rain, crosswinds, gusting winds, and low visibility.

The FSF found that runway excursions on landing were closely associated with rain, snow and wind. Importantly, about half of all landing veer-off occurrences in crosswinds or gusty, turbulent winds, followed a stabilised approach.

In July 2015, Airbus published an article titled 'Lateral runway excursions upon landing: a growing safety concern?' It stated that an increasing proportion of accidents were runway excursions (including both veer-offs and overruns) and that, unlike other accident types, the rate of runway excursion accidents had not changed significantly in 20 years. It also noted that generally the consequences of an overrun were more severe than a veer-off, but the reported number of veer-offs had increased in recent years. It examined 25 reported veer-offs involving Airbus aircraft and, acknowledging limitations of the data, stated:

> Three main environmental factors came out of the analysis:
>
> - Runway state, wet or contaminated
> - Turbulences or cross-wind
> - Visibility deterioration

Most (19) of the 25 occurrences involved at least two of these environmental factors. Twelve were associated with a deterioration in visibility, 12 involved turbulence or crosswind, and four involved both. All but two of the 12 occurrences that were associated with poor visibility involved a deviation prior to touchdown.

Related occurrences in Australia

Search criteria for related veer-off occurrences

The ATSB reviewed its occurrence database for any veer-off occurrence in Australia from 1997 to 2017 that involved:

- an air transport aircraft
- a loss of runway centreline alignment prior to and at touchdown
- no notable problems with the serviceability of relevant aircraft equipment, runway lighting or the runway surface that significantly contributed to the veer-off
- no significant problems with the stability of the approach in terms of height or airspeed.

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21 There are two types of runway excursion: veer-offs, where the aircraft exists the side of the runway, and overruns, where the aircraft exits the end of the runway. Overruns, and veer-offs occurring late in the landing roll, were excluded from this analysis because they often involve factors not relevant to a lateral deviation on late final approach.

In addition to the 6 December 2016 occurrence involving VH-VUI, two other relevant occurrences were identified: a 2003 occurrence at Darwin and a 2003 occurrence at Emerald, Queensland.

2003 veer-off at Darwin

On 19 February 2003, a Boeing 737 veered off runway 29 at Darwin while landing at night and in conditions of rain and reduced visibility.[22]

At the approach minima (about 210 ft), the flight crew were still visual and decided to proceed with the landing. About 2 to 3 seconds later, the captain disengaged the autopilot. At that time, the aircraft was established on the localiser and glideslope. About 7 seconds after the autopilot was disengaged (and 13 seconds prior to touchdown), the aircraft started deviating right. At about this time, the approach lighting was no longer in the flight crew's view. The captain considered that there was sufficient visual reference to complete the landing but did not detect the aircraft's increasing lateral displacement from the runway centreline.

The aircraft touched down close to the right edge of the runway about 520 m from the threshold. The right main gear ran off the runway 590 m from the threshold and the left main gear ran off 760 m from the threshold. All wheels had returned to the runway about 1,300 m from the threshold.

The ATSB investigation found that the flight crew may have encountered an abnormal situation where few reliable visual cues were available for determining the aircraft's position relative to the centreline of the runway. The investigation report highlighted the potential for visual illusions during a night approach to runway 29 at Darwin Airport, noting the wider than normal runway, the absence of centreline lighting and the weather conditions.

As a result of the occurrence, the operator provided flight crews with more specific information for Darwin Airport.

2003 veer-off at Emerald

On 1 May 2003, while landing in a storm at night, a DHC-8-200 veered partially off runway 24 at Emerald Airport, Queensland.[23]

The flight crew were conducting a non-precision approach. As the captain flared the aircraft for landing, the crew lost virtually all external visual reference when the aircraft encountered very heavy rain. The runway was 45 m wide and did not have centreline lighting.

The Emerald occurrence was different to the 2003 and 2016 occurrences at Darwin because it involved sudden, near zero visibility at the time of the flare. In contrast, although the two occurrences at Darwin involved a significant loss of visual references, the deviations commenced slightly earlier in the approach and the runway edge lights were still visible.

Other notable occurrences at Darwin Airport

Although not veer-off occurrences, there were two other notable occurrences at Darwin Airport:

- A 2002 runway overrun involving a 737 occurred at night in clear weather.[24] The investigation report stated that the ‘operational environment was conducive to visual illusions, such as the black hole effect, during the approach and landing’. The overrun followed an unstable approach and, at the time, the runway had a displaced threshold.
- A 2008 hard landing involving a Boeing 717 at night.[25] The investigation report stated ‘the degraded visual information during the landing may have increased the difficulty of judging the

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[22] ATSB investigation 200300418, Runway Excursion - Darwin Airport, Boeing 737-376, VH-TJB, 19 February 2003.

[23] ATSB investigation 200301941, de Havilland Canada DHC-8-201, VH-SDE, Emerald, Qld, 1 May 2003.

[24] ATSB investigation 200202710, Runway overrun at Darwin International Airport, Boeing 737-800 VH-VOE, 11 June 2002.

[25] ATSB investigation AO-2008-007, Hard landing - Darwin Airport, Northern Territory, 7 February 2008, VH-NXE, Boeing Company 717–200.

aircraft's rate of closure with the runway and the required flare'. The report also included the following two safety factors (neither of which was classified as contributing to the occurrence):

- The aircraft operator's Route Manual did not include all relevant information on the potential for visual illusions during a night approach to runway 29 at Darwin Airport that would have improved the awareness of flight crews.
- The lack of runway centreline lighting reduced the available visual cues during the latter stages of the approach and landing to runway 29 at Darwin Airport.

As a result of the occurrence, the operator updated its route manual to provide more specific information for each aerodrome, including Darwin.

Further analysis

In summary, including the 6 December 2016 occurrence involving VH-VUI, there were three veer-off occurrences matching the selected criteria in Australia between 1997 and 2016. All were on runways without centreline lighting, and two were on Darwin's runway 29.

Darwin runway 11/29 was the only runway in Australia that was 60 m wide and had no centreline lighting. The only other runway in Australia that was 60 m wide was runway 16/34 at Melbourne Airport, which had centreline lighting. All of the other runways in Australia that had centreline lighting were 45 m wide: runways 01/19 at Brisbane, runway 27 at Melbourne, and runways 16L, 16R, 34L and 34R at Sydney.[26]

As previously stated, Darwin runway 29 could host category I ILS approaches. Compared with category I ILS approaches, category II/III ILS approaches permit lower decision heights and landings in reduced visibility. Among other things, category II/III approaches require runway centreline lighting (or touchdown zone lighting in the case of special authorisation category II approaches). At the time of the occurrence, category III ILS approaches were only available at Melbourne Airport and category II ILS approaches only at Brisbane, Melbourne, and Sydney airports.[27]

To evaluate against exposure rates, the ATSB examined traffic, runway, and weather information for the 10 busiest airports in Australia, including Darwin (Table 3). Emerald Airport is also included in the table. As indicated in the table, Darwin experiences the most storm activity and the heaviest rainfall, but hosts only a small proportion of traffic (2 per cent of the top 10 airports).

[26] During 2017 and 2018, centreline lighting was installed on Canberra runway 17/35 and Perth runway 03/21. All these runways were 45 m wide.

[27] During 2017 and 2018, Sydney Airport was upgraded to enable category III approaches and Perth Airport was upgraded to enable category II approaches including the installation of centreline lighting.

Table 3: Information for the 10 busiest airports in Australia, and Emerald Airport

Airport	Number of landings in 2016[28]	Runways[29]				Approximate number of lightning strikes per km² per year[30]	Approximate number of days with >25 mm rainfall per year
		Without centreline lighting		With centreline lighting			
		≤50 m	>50 m	≤50 m	>50 m		
Busiest airports							
Sydney	158,810	4	0	2	0	5 - 10	10 - 15
Melbourne	118,006	3	0	1	2	1 - 5	5 - 10
Brisbane	95,716	2	0	2	0	10 - 15	5 - 10
Perth	47,253	2	0	2	0	1 - 2	5 - 10
Adelaide	39,523	4	0	0	0	0.5 - 2	0 - 2
Cairns	24,654	2	0	0	0	5 - 10	20 - 30
Gold Coast	21,246	2	0	0	0	10 - 15	15 - 20
Canberra	18,591	4	0	0	0	5 - 10	5 - 10
Darwin	13,949	2	2	0	0	15 - 20	20 - 30
Townsville	12,806	4	0	0	0	5 - 10	10 - 15
Other airports							
Emerald	4,992	2	0	0	0	5 - 10	5 - 10

In summary, Darwin had the only runway that was 60 m wide without centreline lighting, and it hosted less than 2 per cent of the total traffic of the 10 busiest airports. It is very unlikely that the only two veer-off occurrences that took place at these 10 airports should have occurred on this runway. Although another occurrence took place at Emerald, the extreme loss of visual references during the flare in that occurrence was very likely a more significant factor than the runway width or runway lighting.

Related veer-off occurrences in Canada

During the investigation, the ATSB identified that some veer-offs associated with runway misalignment during final approach had occurred in Canada. It also identified that Canada had a higher proportion of runways that were 60 m wide compared to other countries. Accordingly, the investigation examined the number and characteristics of veer-off occurrences in Canada.

The Transportation Safety Board (TSB) of Canada provided the results of a search of its database for potentially similar occurrences during the period 1997 to 2017. The ATSB reviewed this data and associated investigation reports to identify relevant occurrences, using the same criteria as listed above for occurrences in Australia. Occurrences were only considered if a final investigation report was available. During this process, some additional occurrences from the period 1991 to 1996 were identified.

In total, seven veer-off occurrences were identified that met the relevant criteria. All seven veer-off occurrences in Canada occurred at night on 60 m wide runways with no centreline lighting. In each case, there were some weather-related factors reducing visibility.

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28 Traffic statistics are for landings of regular public transport flights that land on any runway at each airport. Source: Bureau of Infrastructure, Transport and Regional Economics.

29 Runways at least 1,000 m (3,280 ft) long and 30 m wide. One physical runway surface comprises two numbered runways, each in opposite directions; here each numbered runway is counted separately.

30 The number of lightning strikes per unit area is used as an indicator of storm activity, which is associated with heavy rain, wind changes, and microbursts. Source: Bureau of Meteorology.

One occurrence was somewhat different to the others. It involved a Learjet, with the flight crew hand-flying a category I ILS approach. The crew attempted a missed approach after the aircraft touched down off the runway. The aircraft subsequently impacted terrain in an inverted attitude, and the two flight crew (the only occupants) were fatally injured.

All six of the other Canadian occurrences had similar characteristics to the two at Darwin:

- All six involved the flight crew of a high-capacity air transport aircraft conducting a category I ILS approach at night.
- Five involved a deviation from the centreline that occurred soon after the autopilot was disconnected just prior to landing (at heights ranging from 65 to 115 ft above the ground). In the other case, the approach was hand-flown.
- All resulted in destroyed runway lights and/or signs, and most had some aircraft damage. None resulted in any injuries.

In addition to those seven occurrences, there were some other notable occurrences:

- Two other potentially related veer-off occurrences were identified, but because they were not investigated by the TSB the full nature of the events and their circumstances could not be determined. One involved a DC9 at Calgary in 1998 and the other an A320 at Ottawa in 2017. Both occurred at night on 60 m wide runways with no centreline lighting.
- A 1997 occurrence at Fredericton involved a Canadair CL600 at night during a category I ILS approach. When the aircraft was about 35 ft above the ground, the captain was aware that they were left of the centreline but was not sure how far down the runway they were. Recognising that they were not in a position to land safely, he ordered the first officer to go around. During the go around, the aircraft stalled and then struck the runway, and subsequently it struck a tree, resulting in nine serious injuries. The accident occurred on a 60 m wide runway with no centreline lighting.
- A 2014 veer off occurrence at Montréal involved an Airbus A320 during the day during a category I ILS approach. The runway lights were out of service at the time. Other characteristics of the occurrence were similar to the related occurrences discussed above. It occurred on a 60 m wide runway.

In summary, all seven veer-off occurrences in Canada involving centreline misalignment during final approach occurred on 60 m wide runways without centreline lighting. Some other potentially related occurrences also involved this type of runway, but no potentially related occurrences were identified on other types of runways in Canada.

Canada's civil air navigation service provider, Nav Canada, provided landing statistics for 115 of the busiest airports in Canada in 2017. Table 4 shows the percentage of landings at runways with and without centreline lighting, and at runways that are wider than 50 m compared with narrower runways. Data is only included for aircraft with a maximum take-off weight of more than 7,000 kg. Although this data was not presented separately for night versus day operations, and it is only for 2017, it was considered to provide a reasonable approximation of the proportion of operations occurring on different types of runways during the relevant period.

Table 4: Aircraft landing statistics in Canada

	Width < or = 50 m	Width > 50 m	Total
Centreline lighting	4 %	39 %	**43 %**
No centreline lighting	26 %	31 %	**57 %**
Total	**30 %**	**70 %**	**100 %**

As indicated in the table, about 31 per cent of landings occurred at wider runways with no runway centreline lighting. It is statistically very unlikely that seven veer-off occurrences in 20 years with similar characteristics took place on these types of runways without any having occurred on the narrower runways, or on wider runways with centreline lighting.

In its most recent investigation report into a veer-off occurrence, the TSB stated:[31]

> …On runways without centreline lighting, as the distance between runway edge lights increases, it becomes more difficult to judge lateral movement solely by assessing the degree of asymmetry between the runway edge lights—especially when the aircraft is close to the ground and the flight crew's attention is focused directly ahead of them.
>
> The TSB has investigated a number of lateral runway excursions that occurred on runways without centreline lighting. If the distance between runway edge lights is greater than 50 m and runways are not equipped with centreline lighting, there is a risk that visual cues will be insufficient for flight crews to detect lateral drift soon enough to prevent an excursion, while operating aircraft at night during periods of reduced visibility.

Related veer-off occurrences in other countries

The ATSB also searched for potentially related veer-off occurrences in other countries using internet search tools, reviewing the United States National Transportation Safety Board (NTSB) aviation database of accidents and selected incidents and reviewing relevant research reports. The search covered the period 1997 to 2017, and occurrences were only included if they met the same criteria as used for the Australian and Canadian occurrences, and a final investigation report was available. The search was not comprehensive, and it is likely that there were many more occurrences during this period.

Overall, five additional veer-off occurrences involving runway misalignment during final approach were identified. Two occurred in the United States, and one each in Finland, Sweden and the Solomon Islands. The basic details of these additional occurrences are provided in Table 5 (in blue shading).

All five occurrences occurred at night, during instrument approaches in conditions with reduced visibility to runways without centreline lighting. None of the occurrences resulted in serious injuries. Two of the occurrences occurred on 60 m wide runways, and three on 45 m wide runways. One of the three occurrences involving 45 m wide runways occurred during a non-precision approach in very heavy rain (Honiara, 2008), like the Emerald occurrence.

Summary of related occurrences

In summary, 15 related occurrences were identified in Australia, Canada and other countries. Basic details of these occurrences are summarised in Table 5, with the Australian occurrences highlighted in red and Canadian occurrences highlighted in blue.

With regard to all 15 occurrences:

- All occurred at night.
- All occurred at runways without centreline lighting.
- Most (11) occurred at runways that were wider than 50 m.
- Most (13) occurrences involved a category I ILS approach. The other two occurrences (Honiara 2008 and Emerald 2003) were during non-precision approaches and involved runways narrower than 50 m.
- All occurred in conditions of reduced visibility (in terms of rain, fog and/or snow), with most also involving wet runways (reducing the visible texture of the runway) or snow-covered runways.

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[31] TSB investigation A17O0025, Runway excursion, Air Canada Airbus Industrie A320-211, C-FDRP, Toronto/Lester B. Pearson International Airport, Ontario, 25 February 2017.

- Three occurrences were in visibility conditions reported to be below the permissible minimum for an ICAO-standard category I ILS approach and landing (800 m ground visibility or 550 m runway visual range; the same distances are used in Australia). Canada applied different rules.
- Most (13) occurrences involved high capacity air transport aircraft (with a capacity exceeding 38 seats). The exceptions were at Emerald in 2003, involving a low capacity air transport aircraft, and the business jet at Stephenville, Canada in 1996.
- Other than the DHC-8 turboprop aircraft at Emerald, all involved turbofan (jet) aircraft.

A review of global runway databases indicated that about 30 per cent of runways[32] are wider than 50 m, which is a much lower proportion than the number of relevant occurrences at such runways. In addition, the busiest runways tend to be equipped with centreline lighting. Although statistics regarding the number of movements to different types of runways was not obtained for all of the relevant countries, it is likely that there are significantly fewer landings on runways that are 60 m wide without centreline lighting than others. Subsequently, there appears to be a disproportionately high number of related occurrences at those runways, even in Canada where more runways are 60 m wide.

Table 5: Veer-off occurrences involving runway misalignment during final approach

					Runway conditions		Weather conditions		
Date	**Aircraft type**	**Location**	**Country**	**Category I ILS approach**	**No centreline lighting**	**>50m wide**	**Precipitation**	**Fog**	**Below Cat I visibility[1]**
14/10/1991	DC8	Moncton	Canada	•	•	•		•	•
02/04/1993	A320	Calgary	Canada	•	•	•	•	•	
06/12/1996	L36A	Stephenville	Canada	•	•	•	•		
30/12/1997	DC9	Turku	Finland	•	•	•	•		
25/08/2001	737	Kansas City	United States	•	•		•		
19/02/2003	737	Darwin	Australia	•	•	•	•		
01/05/2003	DHC8	Emerald	Australia		•		•		
24/05/2003	737	Amarillo	United States	•	•	•	•		
25/02/2004	737	Edmonton	Canada	•	•	•		•	•
20/01/2005	DC9	Calgary	Canada	•	•	•		•	•
26/12/2005	A319	Winnipeg	Canada	•	•	•		•	
27/07/2008	E170	Honiara	Solomon Islands		•		•		
13/02/2013	JS31	Pajala	Sweden	•	•		•		
06/12/2016	737	Darwin	Australia	•	•	•	•		
25/02/2017	A320	Toronto	Canada	•	•	•	•	•	
TOTAL: 15 occurrences				**13**	**15**	**11**	**11**	**6**	**3**
			Proportion (%)	*87*	*100*	*73*	*73*	*50*	*20*

[1] Reported conditions less than 800 m ground visibility or 550m runway visual range.

32 This data excludes small and private runways.

Previous ATSB recommendations

In 2004, during the investigation into the 2003 veer-off at Darwin, the ATSB advised Darwin International Airport that it was considering making a recommendation for the installation of runway centreline lighting. On 31 December 2004, Darwin International Airport advised:

> A standard runway centerline system would be prohibitively expensive and is not currently a standard for our runway category.

As a result of the investigation into the 2003 veer-off occurrence, the ATSB made a recommendation on 4 March 2005:[33]

> The Australian Transport Safety Bureau recommends that the Department of Defence (airport infrastructure owner) and Darwin International Airport Pty Ltd (civilian facilities operator) consider installation of centreline lighting and touchdown zone lighting, consistent with CASA recommended practices on runways wider than 50 m.

No formal response was received at the time, and the recommendation was classified as 'Closed – Partially accepted' based on further correspondence with the Department of Defence.

Following the release of the ATSB's report into the 2008 hard landing at Darwin involving a Boeing 717, published in May 2010, the ATSB sought further response from the Department of Defence. On 7 July 2011, the Department of Defence responded:

> Air Force has reviewed the [AO-2008-007] report, and has consulted with Darwin International Airport [DIA] on the issue of runway centreline lighting. Initial cost estimates for installation are approximately $3M, however additional costs may ensue with a potential upgrade to the lighting equipment rooms and repairs due to incompatibility of arrestor hook equipped military aircraft with centreline lighting.
>
> The Air Force position is as follows:
>
> a. Existing approach lighting at Darwin is appropriate for a Cat I [category I instrument landing system] precision approach runway.
>
> b. Installation, upgrade and maintenance costs do not represent value for money.
>
> c. The installation of runway centreline lighting is not imperative and will not be pursued (DIA are in agreement).
>
> d. The option of reverting the runway lighting to 45m width would be costly and viewed as a low priority infrastructure change.

The ATSB reclassified the issue as 'Closed – Not accepted'.

[33] Recommendation R20040090, available at www.atsb.gov.au.

Safety analysis

Introduction

During the landing on runway 29 at Darwin at night, the aircraft touched down 21 m to the right of the runway centreline while tracking about 3° to the right. Apart from the sudden degradation of visibility, other aspects of the landing (in terms of the aircraft's configuration, airspeed, distance down the runway and descent rate) were normal. Soon after touching down, the right main gear departed the sealed surface.

The runway excursion (veer-off) was due to the aircraft deviating from the runway centreline during the final stages of the final approach. There were no aircraft serviceability issues. The crosswind was not sudden or strong enough to be significant under most circumstances.

This analysis will firstly discuss the reasons for the aircraft's deviation from the centreline. It will then discuss a range of other safety factors identified during the investigation.

Visual cues during final approach

After transitioning from autopilot to manual flight control, a flight crew needs to manage the aircraft's airspeed, flight path (lateral and vertical), and three-dimensional attitude, and the crew must then initiate the flare at the correct height for landing. Misjudging any of these can result in a hard landing, veer-off or overrun. The landing task becomes additionally challenging when the aircraft is constantly moving in gusty, turbulent conditions. In reduced visibility, the pilot has less information to assess the aircraft's behaviour and respond appropriately.

During a normal landing at night, a flight crew has a range of visual cues to help judge the lateral position of the aircraft:

- Approach lighting gives effective cues for the key elements needed for runway alignment, and is required (where practicable) for category I ILS approaches such as to runway 29 at Darwin airport. However, from about 100 ft height to touchdown, approach lighting is no longer visible under the aircraft's nose. Similarly, runway threshold lighting is also no longer visible.
- Runway centreline markings and other surface textual cues on or near the runway can provide some useful information in appropriate ambient lighting. However, such cues may not be visible on a night approach to a wet runway when there is little or no ambient lighting available.
- Runway edge lights are visible to the flight crew in most weather conditions when landing (and crews are required to conduct a missed approach if they are not visible). The relative angle and degree of asymmetry of the two rows of lights can provide useful cues in many situations. However, the salience of lights can be reduced to some extent due to environmental factors, such as rain and water on the aircraft's windscreen.
- Runway centreline lighting and touchdown zone lighting can provide very useful visual cues. However, they were not available at Darwin and they are only available at a small proportion of runways, generally those associated with a Category II/III ILS approach.

In summary, the main visual cues the flight crew of VH-VUI had in the last few seconds prior to touchdown (from 100 ft above ground level) were the runway edge lights. It was during this period that the aircraft started and then continued to deviate from the runway centreline.

It appears that the aircraft started drifting right under the influence of an increasing (although light) crosswind, and a small amount of right bank. However, deviations occur during manual control for a number of reasons, and the important aspect in this case is that the deviation was not detected and corrected. The deviation occurred in turbulent conditions, which required continuous corrections to the aircraft's attitude and flight path, and there were insufficient external visual cues during this high workload period for the flight crew to effectively detect the deviation and make appropriate adjustments. The available evidence did not indicate fatigue, medical issues or distraction affected the flight crew's performance.

A significant factor reducing the effectiveness of the visual cues in this case was the wider than normal width of the runway (60 m compared to the much more common 45 m), and the corresponding increased distance between the two rows of runway edge lights. As indicated by simple graphical representations (see Appendix A), it is more difficult to detect a deviation when approaching a wider runway compared to a narrower runway. By the time a deviation is identified on a wider runway, the momentum of the lateral movement may be such that the deviation is difficult to correct prior to touchdown.

More importantly, the rate of veer-off occurrences due to misalignment during late final approach is much higher at 60 m wide runways than 45 m wide runways. All of these occurrences have taken place at night in situations where rain or other environmental factors reduced other visual cues.

This problem has been recognised for a long time, with the International Civil Aviation Organization (ICAO) and regulatory authorities recommending the use of centreline lighting on runways wider than 50 m that are used for Category I ILS approaches.

Following a similar occurrence at Darwin in 2003, the ATSB made a specific recommendation that the Department of Defence and Darwin International Airport consider installing runway centreline lighting and touchdown zone lighting on its wide runways. The relevant parties advised that they did not consider any changes cost-effective.

The ATSB understands there is significant expense and logistical difficulties associated with installing centreline lighting. However, without it, there is a realistic prospect of further veer-off or related occurrences at Darwin or any other airport that has a wider runway without centreline lighting.

The 2016 occurrence involving VH-VUI at Darwin resulted in damage to six runway edge lights and minor damage to the aircraft. Most of the other veer-off occurrences due to misalignment during final approach have resulted in a similar level of damage. However, with this type of occurrence, there is the potential for more serious consequences such as undercarriage collapse, veering into other aircraft or vehicles on the ground, or a mishandled go-around with the aircraft near the ground and the engines at low power resulting in a collision with terrain. The ATSB previously found that 2 out of 48 landing veer-off accidents over a 10-year period were fatal, resulting in 93 fatalities (ATSB 2009).

Advisory material regarding hazards at airports

If a hazard such as ineffective visual cues for landing in some situations cannot be effectively mitigated by redesign, then a less desirable though beneficial option is to ensure appropriate advisory information is provided to flight crews.

At the time of the occurrence, the aircraft operator had limited guidance for flight crews approaching Darwin Airport to consider the increased risk arising from the combination of a wide runway and the absence of centreline lighting. This meant that crews were less likely to consider the risk when deciding whether to continue an approach, and potentially less prepared for the potential for undetected deviation away from the centreline on late final approach.

Both flight crew had operated to Darwin before. However, they had not done so recently, with the captain's last flight there over 5 months before and the first officer 16 months before. As a result, neither crewmember had recent familiarity with the visual cues present on the approach, and would probably have studied any available information on hazards that was provided. Although reviewing such information would have reduced the potential risk during an approach, the extent to which it would have affected the flight crew's decision-making or performance in this situation was difficult to determine.

The ATSB has previously identified that other operators did not provide advisory information about visual cues on approach to runway 29 at Darwin. The Boeing 737 operator involved in the 2003 veer-off occurrence did not have relevant advisory information at that time (although it introduced such information following the occurrence). Similarly, the Boeing 717 operator involved in a hard landing occurrence at Darwin in 2008 also did not have relevant advisory information for its flight crews.

The guidance that operators provide to flight crews is primarily based on the En Route Supplement Australia (ERSA). However, this document also did not provide advisory information about visual cues on approach to runway 29 at Darwin. Including relevant information in the ERSA would help ensure that all air transport operators (including international operators) conducting flights to Darwin adequately consider the potential problems associated with visual cues at night.

Provision of weather information

At the time of planning the flight, aerodrome forecast (TAF) indicated fine conditions at Darwin for the expected landing time. At 2207 Central Standard Time, with the aircraft about 1 hour from landing, an amended TAF was issued, which indicated deteriorating conditions.

The Brisbane en route controller broadcast the availability of the 2207 amended TAF. However, the flight crew were not made aware of a subsequent amended TAF, issued at 2237, which indicated a further deterioration in conditions (although the conditions were still above the landing minima).

Between the two amended TAFs, there was a handover from one Brisbane en route controller to another. When the incoming controller was queried at the time by the operator's flight following staff as to whether the crew had received 'the amended TAF', the controller replied that they had. However, the Darwin approach controller had not made the Brisbane en route controller aware of the updated TAF as was done with the previous update.

Not advising the flight crew of the second amended TAF is unlikely to have influenced the flight crews' decision to continue the approach. The wind information was the same as the first amended TAF. In addition, the crew interpreted the first amended TAF as being indicative of 'thunderstorm material'. Within a few minutes of the second amended TAF being issued, the flight crew could also see thunderstorm activity ahead visually and with the aircraft's weather radar. Furthermore, they were obtaining observation reports through Darwin tower, which are more relevant than forecasts when near the destination airport.

Provision of wind information

While the aircraft was on descent, the airport's primary anemometer failed due to a lighting strike. Consequently, the Darwin approach and tower controllers were unable to provide the flight crew with real-time wind information from that anemometer during the approach and landing.

After recognising the problem, the controllers were able to obtain information by telephone from a meteorological observer with access to information from a second (test) anemometer, and through observations of the airport's windsocks. However, the second anemometer's integrity was unconfirmed and it could not be read in real time. In addition, the information available from windsocks was subject to interpretation. As a result, the wind information that the controllers could provide to flight crews was degraded.

Decision to continue approach and landing

The approach and landing occurred during a period of deteriorating weather conditions, which were observed by the flight crew directly and on the weather radar display, and was indicated to them by frequent updates about the conditions provided by controllers. The operator's policies recommended that flight crews not approach within 5 NM of an approaching thunderstorm.

However, this was not a strict requirement, and the decision was left to each flight crew's judgement.

Previous research and safety investigation reports have identified that it is not unusual for flight crews to approach or penetrate thunderstorms when landing. For example, Rhoda and Pawlak (1999) reviewed radar data in the Dallas–Fort Worth airspace in the United States. They identified most (about two thirds) of the encounters with storms resulted in penetrations. The proportion of penetrations was lower as the intensity of the storms increased. However, the proportion of penetrations increased with the storm's proximity to the airport. It also increased when flight crews were following another aircraft, flying after dark, or if they were behind schedule by more than 15 minutes.

In a recent investigation report associated with a flight crew landing close to the edge of a 60 m wide runway during daytime and in the presence of a storm, the Transportation Safety Board of Canada (TSB) noted that other flight crews had also decided to land in proximity of the storm.[34] The TSB also stated:

> The hazards generated by thunderstorms are well known in the aviation industry. Crews who fly near a thunderstorm can expect to encounter the following conditions: erratic wind and gusts, squalls (violent wind blasts), turbulence, extremely violent rain, low visibility, hail, and lightning. Furthermore, there is no correlation between the appearance of a thunderstorm and the intensity of its events…
>
> Since [the operator] relies on the experience of its crews to determine the trajectory of the flight in the presence of thunderstorms in the vicinity of airports, the margin of safety varies from flight to flight, depending on the crew…This occurrence is an excellent example of the sudden and simultaneous appearance of hazards associated with thunderstorms at a critical point during landing. This occurrence highlights the unpredictability of thunderstorms and the necessity to maintain a safe distance during the critical stages of flight.

Research has shown that many aviation accidents involve a 'plan continuation bias' or 'plan continuation error' associated with situations involving dynamically changing risk and pilots underestimating the risk level. That is, a flight crew decides to continue with the original plan of action despite the presence of cues or information that suggests changing the course of action would be the safer option (Orasanu and others 2001). Other researchers have noted that previous encounters with a situation (such as approaching near a storm) without negative consequences may reinforce such behaviour or enable flight crews to reduce their perception of the association risks (Dismukes and others 2007).

In this case, the flight crew could see lightning ahead and, during the later part of the descent, closely monitored the location of rain cells in the vicinity of the airport using the aircraft's weather radar.

The flight crew regularly discussed the situation and their planned actions. This including obtaining additional information at times, as well as planning to vary their missed approach path (if required) in order to avoid the worst of the weather. The flight crew arrived at the decision height in conditions better than the minimum requirements for visibility and crosswind.

Soon after the aircraft descended through the decision height, it encountered very heavy rain. After this point the visibility deteriorated, and although it was not possible to reliably determine whether the visibility was below the minimum of 800 m, the aircraft's logo light could be seen from the tower 1.8 km away. The crew could still see the runway edge lights, although they were very blurred between windscreen wiper passes, and considered that they had sufficient visual cues available for landing. Overall, the flight crew's interpretation of the information available to them gave no compelling reason to initiate a missed approach, and they did not detect the deviation from centreline until after touchdown.

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[34] TSB A14Q0155, Runway excursion, Air Canada Airbus A330-343, C-GFAF, Montréal/Pierre Elliott Trudeau International Airport, Montréal, Quebec, 07 October 2014.

It was not possible to establish the extent to which the flight crew considered the risk of a loss of visibility before it occurred. Furthermore, the weather reports deteriorated gradually during the descent and approach and each incremental change in risk was probably not fully appreciated by the flight crew.

The crew's decision to continue the approach after entering heavy rain would usually not result in an adverse outcome. However, the combination of a wider runway and relatively limited visual cues available at Darwin increases the potential for adverse consequences.

As with the flight crews in many previous occurrences, the flight crew may not have fully appreciated the increased risk arising from the limited visual cues presented during an approach to a wider runway without centreline lighting. A flight crew that is informed about the potential risk associated with a sudden reduction in visibility close to landing, particularly at airports with 60 m wide runways and no centreline lighting, should have greater readiness to perceive and respond to it.

Recovery actions after touchdown

When the aircraft touched down the flight crew were aware they had landed to the right of the centreline but did not fully comprehend the extent of the deviation and the rate of drift. The captain applied corrective control inputs but, by the time the situation was apparent, was unable to prevent the right main landing gear departing the sealed surface of the runway.

The amount of corrective control input applied by the captain was influenced by the potential to lose control on the wet runway, in combination with the advice from the first officer who thought that the aircraft was clear of the runway lights.

The captain delayed the application of reverse thrust after landing until the aircraft was established on the runway. This action probably helped prevent further excursion off the runway.

Given the extent of the deviation from the runway centreline at touchdown, and the time required to assess the situation, it was very likely the excursion would have happened regardless of the available traction. Traction was probably reduced to some extent after touchdown, and it may have slightly delayed the subsequent recovery back onto the runway. The ATSB notes that the outer 7.5 m of the runway was not grooved, and did not meet the relevant surface texture or friction requirements. Although not contributing factors to this occurrence, such problems could degrade aircraft control in future situations where an aircraft has significantly deviated from the runway centreline.

Post-landing actions

After the landing the crew were unsure whether the aircraft had left the runway. The flight crew discussed whether they had hit the runway lights. Based on the first officer's perception of the situation, they thought that they had not.

There was no opportunity for ground crews to examine the aircraft and confirm a potential veer-off until the storm had cleared, but there remained a risk that following aircraft could be affected by debris on the runway, and having fewer runway lights available.

This occurrence indicates that it is important to be conservative after a potential veer-off occurrence. A timely report of the possibility that a veer-off had occurred, even if there was doubt, would have provided the airport operator and air traffic control with a better opportunity to ensure the runway was serviceable for other aircraft.

Findings

From the evidence available, the following findings are made with respect to the runway excursion (veer-off) involving Boeing 737-800, registered VH-VUI, which occurred at Darwin Airport on 6 December 2016. These findings should not 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.

Contributing factors

- After passing the decision height for the approach, the aircraft drifted under the influence of a slight crosswind and landed 21 m to the right of the runway centreline.
- Due to heavy rain, darkness and limited visual cues, the flight crew did not detect the aircraft's deviation from the runway centreline prior to landing.
- **The absence of centreline lighting and the 60 m width of runway 11/29 at Darwin result in very limited visual cues for maintaining runway alignment during night landings in reduced visibility. [Safety issue]**

Other factors that increased risk

- **Category I runways that are wider than 50 m and without centreline lighting are over-represented in veer-off occurrences involving transport category aircraft landing in low visibility conditions. The installation of centreline lighting on wider category I runways is recommended but not mandated by the International Civil Aviation Organization Annex 14. [Safety issue]**
- **Virgin Australia did not have formal guidance for flight crews regarding the limited visual cues for maintaining alignment to runway 11/29 at Darwin during night landings in reduced visibility. [Safety issue]**
- **The En Route Supplement Australia (ERSA) did not have formal guidance for flight crews regarding the limited visual cues for maintaining alignment to runway 11/29 at Darwin during night landings in reduced visibility. [Safety issue]**
- While the aircraft was on descent, the airport's primary anemometer failed due to a lightning strike. Although there were windsocks and a second, test anemometer at the airport, the reliability and timeliness of the wind information that the controllers could provide to flight crews was temporarily degraded.
- Although air traffic services broadcast details of an amended aerodrome forecast (TAF) for Darwin issued at 2207, the flight crew were not made aware of a subsequent amended TAF issued at 2237. However, the flight crew were provided with multiple updates of current weather conditions prior to landing at 2302.
- Because they were unsure what had occurred, the flight crew did not report the possibility of a runway excursion to air traffic control until 29 minutes after it occurred. This delayed the response by the airport operator and air traffic control to ensure that the runway was safe for subsequent operations.

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 industry, the ATSB may issue safety recommendations or safety advisory notices as part of the final report.

Standards for installation of runway centreline lighting on wider runways

Safety issue number:	AO-2016-166-SI-01
Safety issue owner:	International Civil Aviation Organization
Operation affected:	Aviation: Airports
Who it affects:	Operators using runways wider than 50 m without centreline lighting

Safety issue description:

Category I runways that are wider than 50 m and without centreline lighting are over-represented in veer-off occurrences involving transport category aircraft landing in low visibility conditions. The installation of centreline lighting on wider category I runways is recommended but not mandated by the International Civil Aviation Organization Annex 14.

Status of the safety issue

Issue status:	Safety action pending

ATSB safety recommendation to the International Civil Aviation Organization

Action number:	AO-2016-166-SR-013
Action status:	Released

The Australian Transport Safety Bureau recommends that the International Civil Aviation Organization review the effectiveness of Annex 14, recommendation 5.3.12.2 (for the installation of runway centreline lighting on Category I runways that are wider than 50 m), given that Category I runways that are wider than 50 m and without centreline lighting are over-represented in veer-off occurrences involving transport category aircraft landing in low visibility conditions.

Limited visual cues for approach at Darwin runway 11/29

Safety issue number:	AO-2016-166-SI-02
Safety issue owner:	Darwin International Airport
Operation affected:	Aviation: Airports
Who it affects:	Pilots operating into Darwin airport

Safety issue description:

The absence of centreline lighting and the 60-m width of runway 11/29 at Darwin result in very limited visual cues for maintaining runway alignment during night landings in reduced visibility.

Status of the safety issue

Issue status: Safety action pending

Response by Darwin International Airport and Defence Flight Safety Bureau

On 18 September 2017, Darwin International Airport (DIA) advised:

> The Department of Defence position in 2011 was as follows and DIA is not aware of any change to that:
>
> a. Existing approach lighting at Darwin is appropriate for a Cat 1 precision approach runway.
>
> b. Installation, upgrade and maintenance costs do not represent value for money.
>
> c. The installation of runway centreline lighting is not imperative and will not be pursued (DIA are in agreement).
>
> d. The option of reverting the runway lighting to 45m width would be costly and viewed as a low priority infrastructure change.
>
> In previous correspondence Defence did indicate a concern for potential damage to tail hook equipped aircraft.
>
> Under the terms of the Joint User Agreement, Defence is responsible for airfield pavements and lighting and is considering resurfacing of Runway 11/29 in about 2022. Replacement of runway lighting may occur as part of that project. Provision of centreline lighting could be considered at that time.

On 25 January 2019, DIA advised:

> Darwin Airport is a Joint User aerodrome with the Department of Defence. As previously advised, and under the terms of the joint User Deed, the Department of Defence is responsible for forward planning of pavement overlays and upgrading or replacement of airfield lighting.
>
> DIA will continue to consult with Defence on whether lighting upgrades, including centreline lighting could be considered for future works. A planning meeting is proposed for March 2019.

On 8 February 2019, the Defence Flight Safety Bureau advised:

> The lack of centre line lighting at Darwin has been an ongoing issue for some time. Under the Joint User Deed, Defence and DIA are required to work together on any infrastructure matters. To date, Defence and DIA have been in agreement that runway centreline lighting is not supported for reasons that include upfront capital cost, ongoing maintenance issues and consideration of the potential effects of runway centreline lighting on aircraft taking the arrestor cables.

On 26 March 2019, DIA advised:

> Northern Territory Airports (NTAP) and Defence met on Wednesday 13th March in Canberra to discuss maintenance, projects and operational matters associated with the Joint User Area at Darwin International Airport / RAAF [Royal Australian Air Force] Darwin. A topic of tabled discussion was Airfield Ground Lighting (including a session on Runway Centreline Lighting) for RWY 11/29. Both NTAP and Defence agreed that the use of Hook Arrestor Cable System on RWY 11/29 prevented the safe introduction of CASA MOS139 compliant Runway Centreline Lighting since the risk of FOD

> [foreign object debris] caused via damage to Runway Centreline Lights by the Hook Arrestor Cable was of significant concern. It was however tabled that both Runway Centreline Lighting and reducing the runway width from 60m to 45m would be re-considered in future major project design briefs.

ATSB comment

After a similar occurrence in 2003, the ATSB issued a recommendation that the Department of Defence (airport infrastructure owner) and Darwin International Airport (civilian facilities operator) consider the installation of centreline lighting and touchdown zone lighting on runway 29. The ATSB later reclassified the issue as ‘Closed – Not accepted’.

In response to safety issue AO-2016-166-SI-04, Darwin International Airport has undertaken safety action enhancing the en route supplement guidance to flight crews, which will help flight crews conducting operations into Darwin to more effectively plan for and respond to a partial loss of visual cues during approach. However, this action is not a completely effective way of addressing the risk: crew preparedness can reduce the likelihood of, but not prevent, an undetected loss of adequate visual cues.

The ATSB acknowledges the practical limitations of installing and maintaining runway centreline lighting, and notes that DIA have also stated that the feasibility will be reconsidered in future major project design briefs. The ATSB continues to encourage additional safety action by DIA and Defence, and has released the following safety recommendation.

ATSB safety recommendation to Darwin International Airport

Action number: AO-2016-166-SR-014

Action status: Released

The Australian Transport Safety Bureau recommends that Darwin International Airport address the risk of very limited visual cues for maintaining runway alignment during night landings in reduced visibility that arise from the combination of the absence of centreline lighting and the 60-m width of runway 11/29 at Darwin.

Operator guidance to flight crews

Safety issue number: AO-2016-166-SI-03

Safety issue owner: Virgin Australia Airlines

Operation affected: Aviation: Air transport

Who it affects: Virgin Australia Airlines flight crews operating into Darwin airport

Safety issue description:

Virgin Australia did not have formal guidance for flight crews regarding the limited visual cues for maintaining alignment to runway 11/29 at Darwin during night landings in reduced visibility.

Status of the safety issue

Issue status: Adequately addressed

Justification: The operator’s action, in conjunction with other safety actions, should provide crews with adequate guidance to enable them to assess risk and prepare for approaches in low visibility conditions at Darwin Airport.

Proactive safety action

Action taken by: Virgin Australia Airlines

Action number: AO-2016-166-NSA-012

Action date: 20 January 2017

Action type: Proactive safety action
Action status: Closed

Safety action taken: On 20 January 2017, the operator introduced additional guidance to flight crews for approach to Darwin airport, including notes about runway surface, slope, width, lighting, and ambient light.

En route supplement guidance to flight crews

Safety issue number:	AO-2016-166-SI-04
Safety issue owner:	Darwin International Airport
Operation affected:	Aviation: Airports
Who it affects:	Pilots operating into Darwin airport

Safety issue description:

The En Route Supplement Australia (ERSA) did not have formal guidance for flight crews regarding the limited visual cues for maintaining alignment to runway 11/29 at Darwin during night landings in reduced visibility.

Status of the safety issue

Issue status:	Adequately addressed
Justification:	The additional information provided in the ERSA should improve the risk awareness and decision-making of flight crews during low visibility approaches to Darwin airport.

Proactive safety action

Action taken by:	Darwin International Airport
Action number:	AO-2016-166-NSA-015
Action date:	28 January 2019
Action type:	Proactive safety action
Action status:	Closed

Safety action taken: On 28 January 2019, Darwin International Airport initiated amendments to the ERSA entry for Darwin Airport. These amendments were introduced into the 23 May 2019 issue of the ERSA, and stated:

- Under *Additional information*: 'During low visibility conditions pilots of ACFT landing RWY 29 HN may experience loss of visual references due RWY WID 60 with no CL or TDZ LGT.'
- Under *Aerodrome and approach lighting*: 'RWY 11/29 CL and TDZ LGT not provided.'

Additional safety action

Whether or not the ATSB identifies safety issues in the course of an investigation, relevant organisations may proactively initiate safety action in order to reduce their safety risk. The ATSB has been advised of the following proactive safety action in response to this occurrence.

Virgin Australia Airlines

On 5 May 2017, Virgin Australia advised ATSB of the following additional safety actions:

- initiated specific training to pilots for loss of visibility in heavy rain
- investigated enhancements to simulator modelling of degraded visibility at low level
- reviewed risk profiles for each airport including Darwin

- commenced a program to investigate the potential to install hydrophobic windshield coatings on its 737 fleet
- initiated a review of callouts for loss of visibility
- reviewed the use of autopilot in poor weather.

Darwin International Airport

On 25 September 2018, Darwin International Airport (DIA) initiated the following amendment to the ERSA entry under *Physical characteristics*: ‘Central 45M grooved SFC of 7.5M outer ungrooved sections BLW MNM friction LVL when wet. 91M concrete ends RWY 11 and RWY 29 ungrooved.’

DIA also advised that the runway is due to be resurfaced in about 2022, and the airport and Department of Defence will be considering having the entire width of the runway grooved at that time.

Royal Australian Air Force Darwin

On 8 February 2019, the Defence Flight Safety Bureau advised that Royal Australian Air Force Darwin ‘will continue to investigate serviceability of MET [meteorological] instruments.’

General details

Occurrence details

Date and time:	06 December 2016 – 2303 CST	
Occurrence category:	Serious incident	
Primary occurrence type:	Operational-Runway Events-Runway Excursion	
Location:	Darwin Airport, Northern Territory	
	Latitude: S12° 24.88'	Longitude: E130° 52.60'

Aircraft details

Manufacturer and model:	Boeing 737-800	
Year of manufacture:	2006	
Registration:	VH-VUI	
Operator:	Virgin Australia Airlines Pty Ltd	
Serial number:	34441	
Type of operation:	Scheduled	
Persons on board:	Crew – 6	Passengers – Unknown
Injuries:	Crew – Nil	Passengers – Nil
Damage:	Minor	

Sources and submissions

Sources of information

The sources of information during the investigation included the:

- aircraft's flight data and cockpit voice recordings
- air traffic control recorded audio
- Bureau of Meteorology
- Department of Defence
- Airservices Australia
- Bureau of Infrastructure, Transport and Regional Economics
- Boeing
- Virgin Australia Airlines
- flight crew
- Transportation Safety Board (Canada).

References

Airbus S.A.S. (2015). *Lateral runway excursions upon landing: a growing safety concern?*. In *Safety First #20*.

Australian Transport Safety Bureau (2009). *Runway excursions. Part 1: a worldwide review of commercial jet aircraft runway excursion*. ATSB transport safety report No. AR-2008-018(1).

Flight Safety Foundation (2009). *Reducing the risk of runway excursions*.

International Civil Aviation Organization (2004). *Aerodrome Design Manual. Part 4: Visual Aids*. Document 9157, 4th ed.

Orasanu J, Martin L & Davison J (2001). Cognitive and contextual factors in aviation accidents, in E Salas and G Klein (Eds.) *Linking expertise and naturalistic decision making*, Lawrence Erlbaum Mahwah NJ, pp. 209–226.

Rhoda, DA & Pawlak, ML (1999). *An assessment of thunderstorm penetrations and deviations by commercial aircraft in the terminal area*. Massachusetts Institute of Technology, Lincoln Laboratory, Project Report NASA/A-2.

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 the:

- flight crew
- Virgin Australia Airlines
- Airservices Australia
- Bureau of Meteorology (BoM)
- Darwin International Airport
- Defence Flight Safety Bureau (DFSB)
- Civil Aviation Safety Authority (CASA)
- International Civil Aviation Organization (ICAO).

Submissions were received from the:

- captain
- Virgin Australia Airlines
- Airservices Australia
- BoM
- Darwin International Airport
- DFSB
- CASA.

The submissions were reviewed and, where considered appropriate, the text of the report was amended accordingly.

Appendices

Appendix A – Simulation of visual cues provided by runway lights

The ATSB examined the relative effectiveness of the visual cues provided by runway edge lights at Darwin during the 6 December 2016 occurrence flight compared with other situations.

This examination involved the use of simple simulations based on a model with the following characteristics:

- Static images were developed with white dots representing the position of runway lights on a black background.
- The arrangement of the dots in each image was based on the relative location of each light from an observer in a fixed position corresponding to an aircraft's flight path on final approach. Some fixed positions used the approximate lateral position of the aircraft during the occurrence flight over the threshold (3.4 m right of centreline) and when the flare was initiated (11.0 m right of centreline). The aircraft height was adjusted
- The model assumed the observer was in the captain's seat on the aircraft, 1 m to the left of the longitudinal axis of the aircraft and accounted for the approximate eye height above the aircraft's nominal position. The model used a level runway.
- The size of the dots varied in proportion to distance away from the observer's position.
- Visual cues from the runway texture, sky or surrounding areas were not modelled. Factors such as precipitation and other effects on visibility, windscreen effects and other influences on the brightness of the lights were not modelled. The simulations also did not account for the effects of aircraft movement and associated visual cues such as optic flow.

Figure A1 illustrates the pattern of runway edge lights visible to a pilot on approach to a 60 m wide runway. The top image shows the pattern at 60 ft, with the aircraft about 3.4 m right of centreline, and the bottom image shows the pattern at 24 ft, with the aircraft about 11 m right of centreline. The elapsed time between each view in a normal landing would be about 4 seconds. The deviation from the centreline in the top image is almost undetectable, and in the bottom image it is inconspicuous. In a high workload environment, with degraded visibility and from a constantly moving aircraft, the deviation from centreline may not be detected until it is too late to correct.

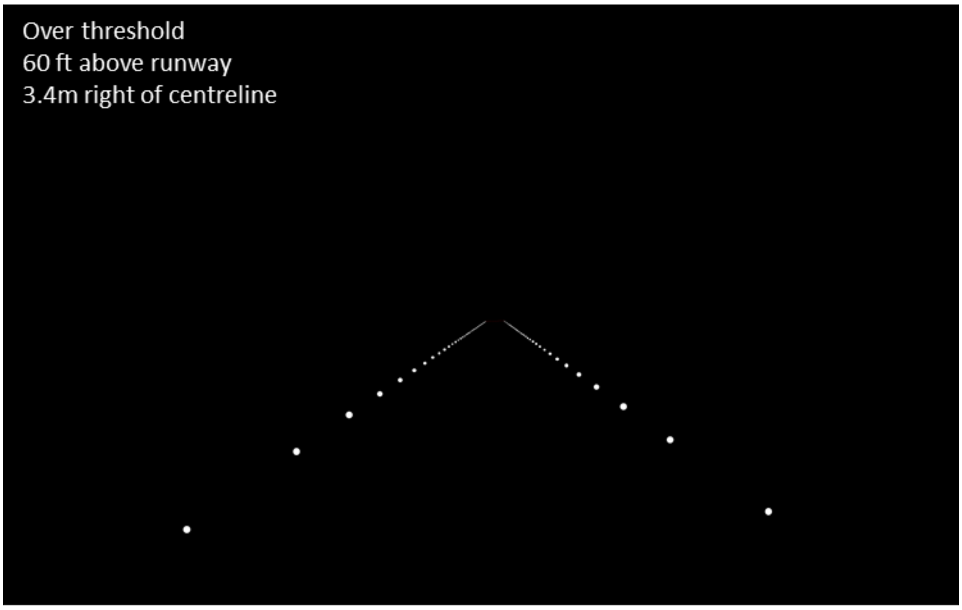
Figure A2 shows the same two situations as Figure A1, but with centreline lighting added. The aircraft's slight deviation from centreline at 60 ft (top image) is more apparent than without the centreline (top image of Figure A1), and the deviation at 24 ft (bottom image) is easily discernible.

Figure A3 shows the potential influence of aircraft bank when only runway edge lights are visible. The top image shows the pattern of runway lights when the aircraft is on centreline at 24 ft, and the bottom image shows the pattern when the aircraft is at the same height but 11 m right of centreline with a 6° right bank. The two images look very similar. Therefore, when an aircraft is off centreline, a small bank in the direction of the nearest row of edge lights may make the aircraft appear closer to the centreline than it is.

Figure A4 shows the same two situations as Figure A3, with centreline lighting added. The deviation from the centreline in the bottom image is obvious.

Figure A5 compares a 60 m wide runway without centreline lighting (top) with a 45 m wide runway without centreline lighting (bottom). In both cases, the aircraft is 24 ft above the ground, 11.0 m right of centreline. The relative asymmetry of the two rows of lights is much easier to detect for the 45 m runway than the 60 m wide runway.

Figure A1: Simulated misaligned approach without centreline lighting



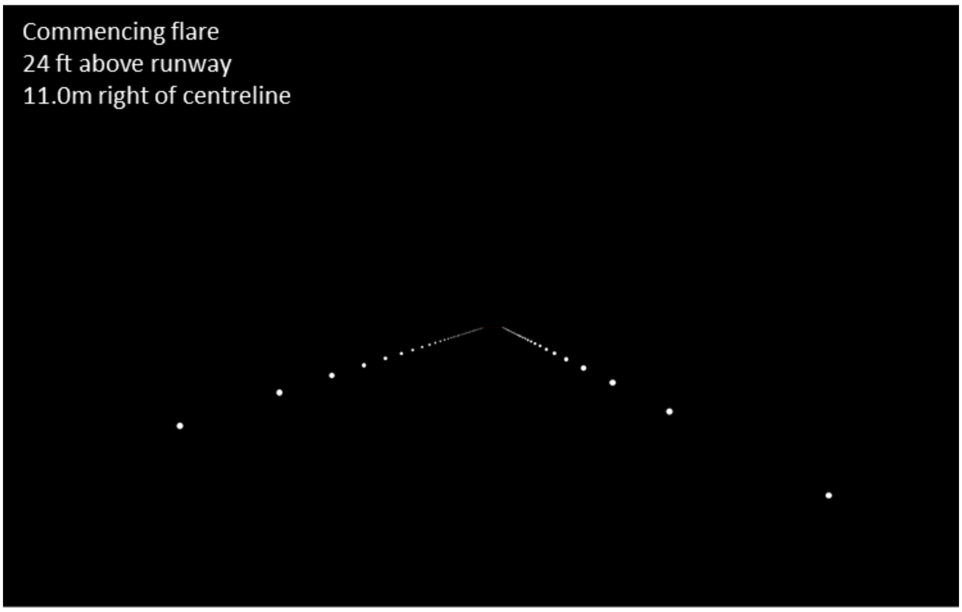
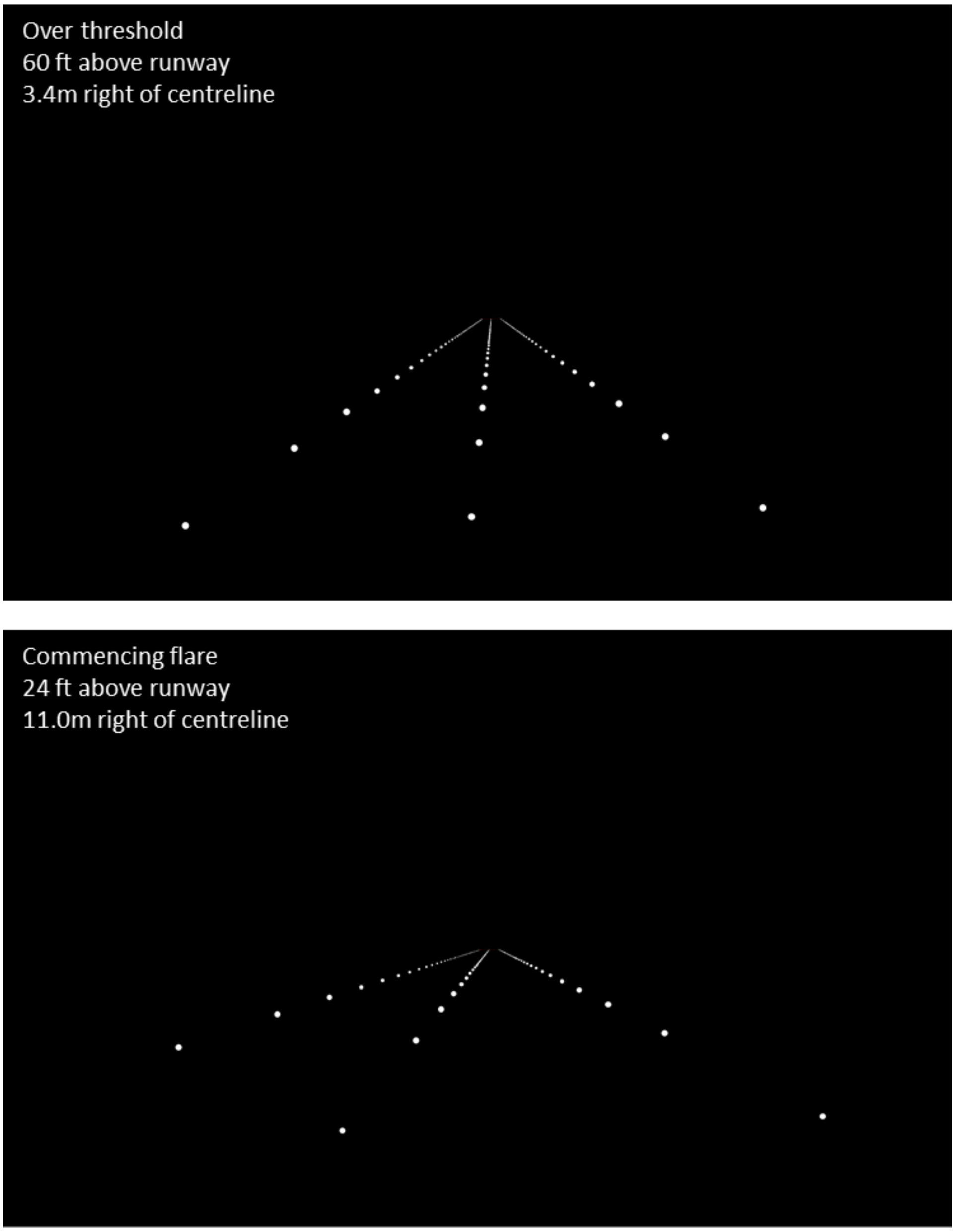
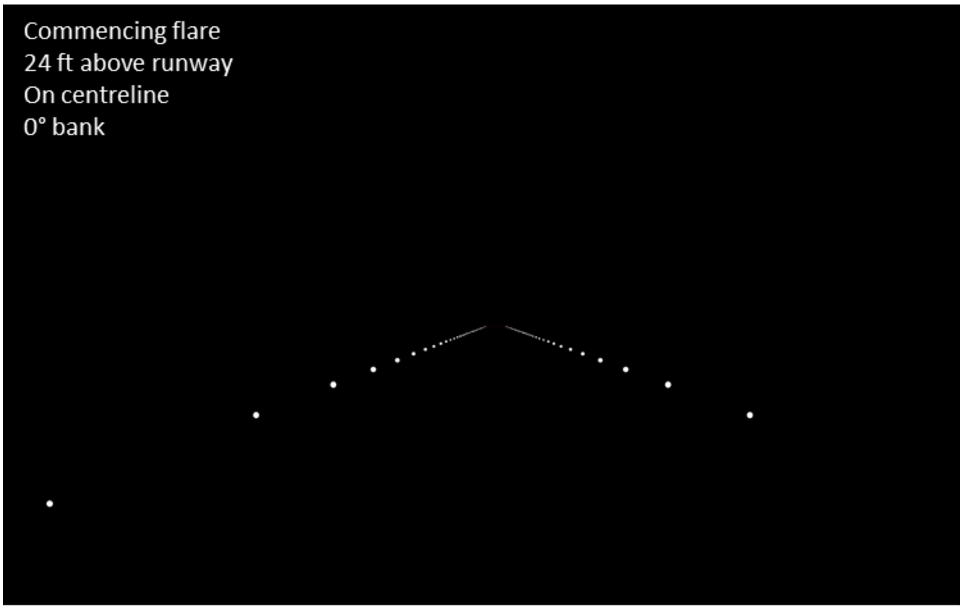


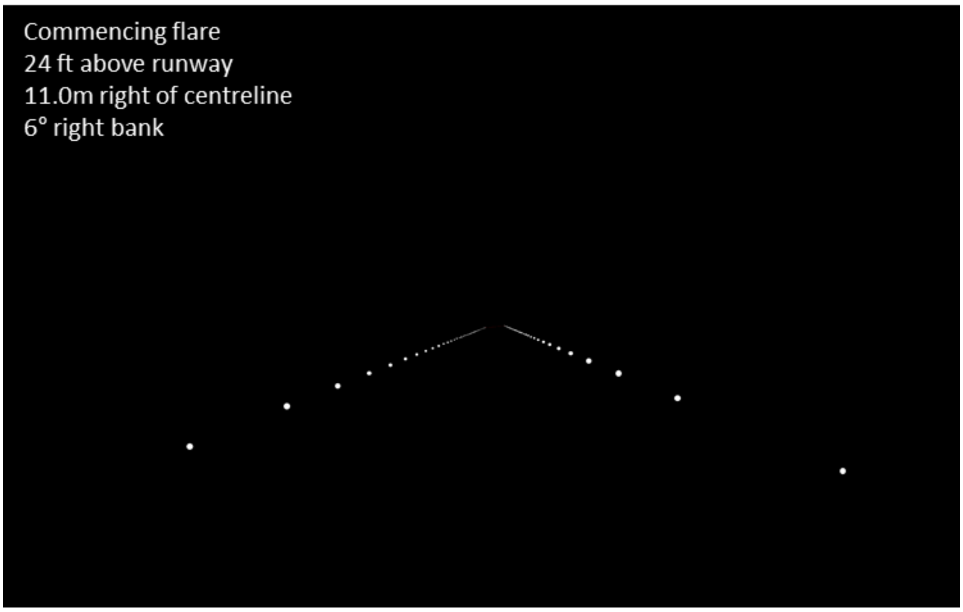
Figure A2: Simulated misaligned approach with centreline lighting



Source: ATSB

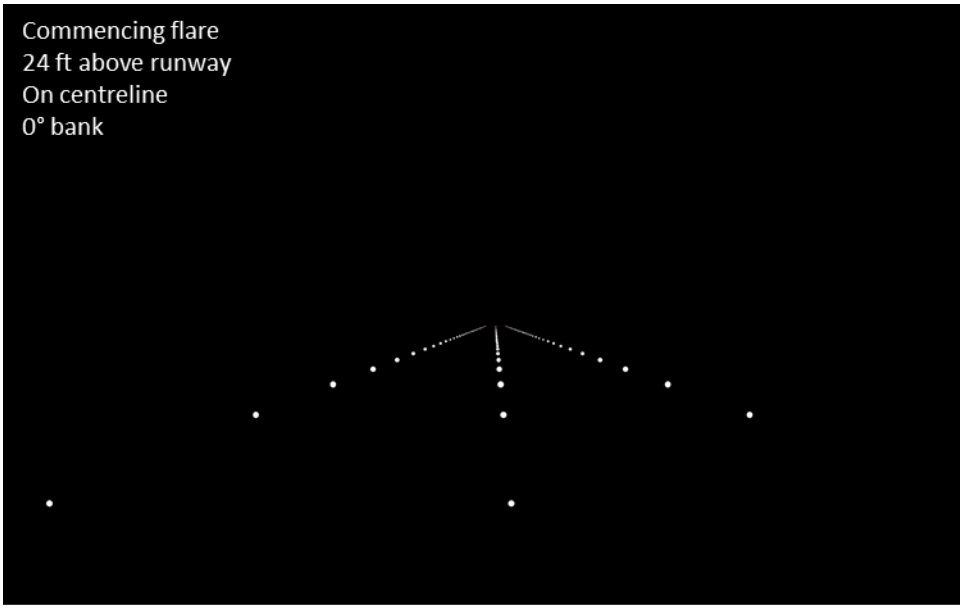
Figure A3: Simulated approaches without centreline lighting showing on centreline with wings level (top) compared to a misaligned approach with 6° right roll (bottom)

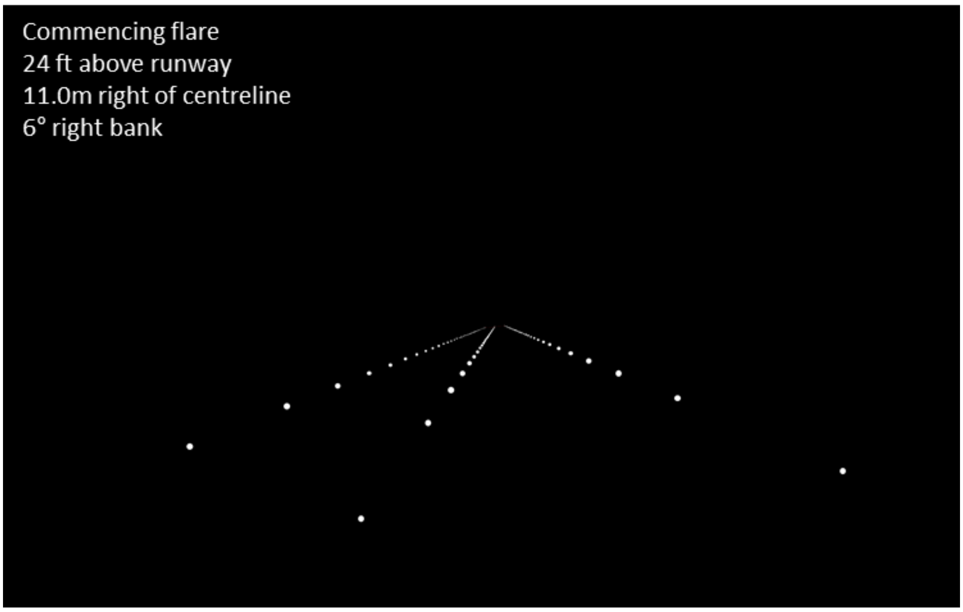




Source: ATSB

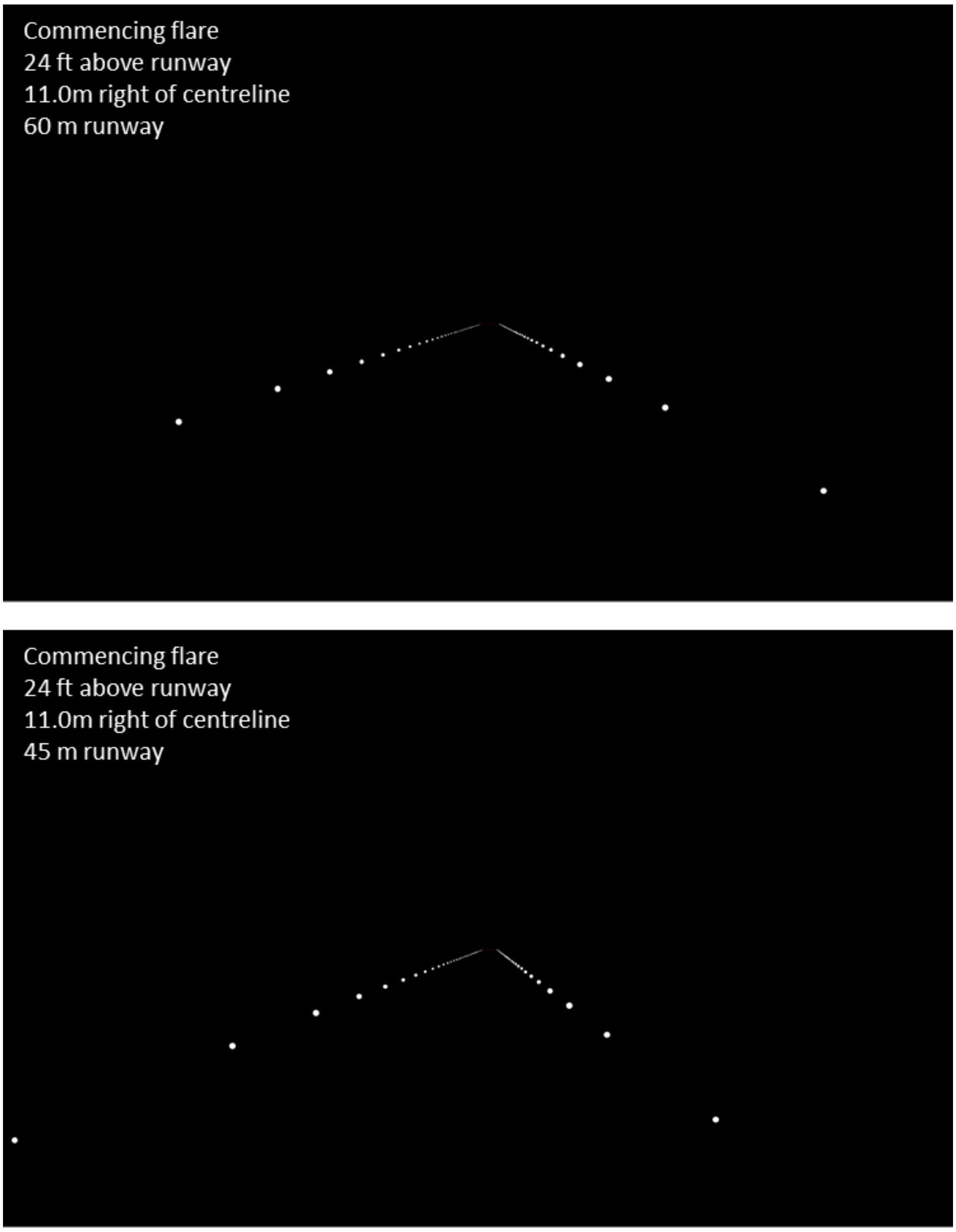
Figure A4: Simulated approaches with centreline lighting showing on centreline with wings level (top) compared to a misaligned approach with 6° right bank (bottom)





Source: ATSB

Figure A5: Simulated approaches to runways of different widths, without centreline lighting



Source: ATSB

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.

Terminology used in this report

Occurrence: accident or incident.

Safety factor: an event or condition that increases safety risk. In other words, it is something that, if it occurred in the future, would increase the likelihood of an occurrence, and/or the severity of the adverse consequences associated with an occurrence. Safety factors include the occurrence events (e.g. engine failure, signal passed at danger, grounding), individual actions (e.g. errors and violations), local conditions, current risk controls and organisational influences.

Contributing factor: a factor that, had it not occurred or existed at the time of an occurrence, then either:

(a) the occurrence would probably not have occurred; or

(b) the adverse consequences associated with the occurrence would probably not have occurred or have been as serious, or

(c) another contributing factor would probably not have occurred or existed.

Other factors that increased risk: a safety factor identified during an occurrence investigation, which did not meet the definition of contributing factor but was still considered to be important to communicate in an investigation report in the interest of improved transport safety.

Other findings: any finding, other than that associated with safety factors, considered important to include in an investigation report. Such findings may resolve ambiguity or controversy, describe possible scenarios or safety factors when firm safety factor findings were not able to be made, or note events or conditions which ‘saved the day’ or played an important role in reducing the risk associated with an occurrence.

Australian Transport Safety Bureau

Enquiries 1800 020 616
Notifications 1800 011 034
REPCON 1800 020 505
Web www.atsb.gov.au
Twitter @ATSBinfo
Email atsbinfo@atsb.gov.au
Facebook atsbgovau
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Investigation

ATSB Transport Safety Report
Aviation Occurrence Investigation
Runway excursion involving Boeing 737, VH-VUI
Darwin Airport, Northern Territory, on 6 December 2016

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