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Stall warnings in high capacity aircraft: The Australian context

2008 to 2012

Research

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Safety summary

Why the ATSB did this research

Stall warning events have always been an area of interest for airlines and aviation safety investigators as they indicate that an aircraft is operating at the margins of safe flight. As these occurrences are reportable to the ATSB, the ATSB can analyse trends across airlines and Australia. By publishing such analysis, it is hoped that the wider aviation industry will be able to learn from the experience of others.

What the ATSB found

A review of 245 stall warnings and stall warning system events reported to the ATSB over a 5–year period showed that almost all were low risk events which were momentary in duration, and were responded to promptly and effectively by the flight crew to ensure positive control of the aircraft was maintained. No occurrences resulted in a stall or an irrecoverable loss of aircraft control, and only a few were associated with minor injuries to passengers or crew (generally those that occurred in severe turbulence) or a temporary control issue.

About 70 per cent of stall warnings reported to the ATSB were genuine warnings of an approaching stall, with the remainder being stall warning system problems. In only a minority of cases were system problems reported that resulted in false or spurious stall warnings such as a stick shaker activation.

Stall warnings (and in particular stick shaker activations) were well reported by Australian air transport operators, and occurred in a range of flight phases and aircraft configurations, not exclusively those related to low speed, high pitch attitude flight, or flight in poor meteorological conditions. Fifty-five per cent occurred in visual (VMC) conditions, and those in instrument (IMC) conditions mostly occurred in cruise. In typical stall warning events during cruise, the aircraft was operating at an altitude where there was a narrow band (about 20 knots) between the maximum operating speed and the stall warning speed (V_{SW}). Common precursors to these events were rapid changes of pitch angle or airspeed. In about one-fifth of these occurrences, the stall warning system was activated when the autopilot tried to correct the aircraft’s speed or flight path due to a disturbance. Stall warnings during VMC flight were most common on approach, often involving aircraft being affected by turbulence while manoeuvring around weather.

The ATSB identified 33 serious and higher risk incidents in which a stall warning occurred. The majority of these involved brief stick shaker activations, and were associated with moderate or severe turbulence. Most happened on approach to land, when aircraft were in a low speed, high angle of attack configuration, and in several cases the stall warning speed was higher than normal (due to a higher wing loading (g) factor in a turn, or an incorrect reference speed switch setting). In these cases, the risk of a stall developing was increased by a lack of awareness of decreasing airspeed and increasing angle of attack prior to the stall warning, and/or an approach to land where the flight crew were focused on trying to correct the approach prior to the stabilised approach height instead of conducting a go-around.

Safety message

Stall warnings occur in normal operations, and are normally low risk events. In Australia, even the most serious events have not resulted in a loss of control, and have been effectively managed by flight crew to prevent a stall from occurring. To avoid higher risk stall warning events, pilots are reminded that they need to be vigilant with their awareness of angle of attack and airspeed, especially during an approach on the limits of being stable.

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Stall warnings

Stall warning events are an area of interest for high capacity airlines and aviation safety investigators as they indicate that an aircraft was operating at the margins of safe flight. Inappropriate management of stall warnings by flight crew increases the risk of a stall, and a resulting temporary (but normally recoverable) loss of aircraft control.

Stall warnings are a warning only, and are a defence provided to ensure flight crew take corrective action to prevent a stall from developing. They have a low risk in themselves, but indicate a possibility for a more serious outcome because the aircraft is flying at a speed that is lower than it should be for the flight condition and configuration it is in, or the wing has a higher angle of attack than is suitable. Many stall warnings, such as those that occur in turbulence during cruise, are not likely to indicate a loss of control will occur, and are low risk. Some stall warnings, such as those that occur on final approach at a high angle of attack and at a low airspeed, are high risk because of insufficient altitude to recover from a stall if one was to follow and the likelihood of a subsequent terrain collision. In all instances, stall warnings should be treated as an approach to stall (even if the warning may be spurious or low risk), and immediate action taken to reduce the angle of attack.

What is a stall?

A stall occurs when the smooth airflow over an aeroplane's wing is disrupted, and it loses lift rapidly. This causes the aircraft to descend. This is caused when the wing exceeds its critical angle of attack (the angle of the wing relative to the direction of the airflow). This can occur at any airspeed, at any attitude, and at any power setting (FAA, 2004).

Proactive approach to safety monitoring

Aviation safety incidents and accidents in Australia, or involving Australian-registered aircraft operating overseas, are reportable to the Australian Transport Safety Bureau (ATSB) under the provisions of the Transport Safety Investigation Regulations 2003. Most accidents and incidents that pose a serious risk to aviation safety are investigated. All reported occurrences, however, are used to help the ATSB monitor the health of aviation across Australia and assist in the identification of emerging safety issues before they manifest into accidents. Furthermore, by publishing such analysis, it is hoped that the wider aviation industry will be able to learn from the experience of others.

Background

What is a stall warning?

Stall warnings indicate to the flight crew that the aircraft will approach a stall if action is not taken to reduce the angle of attack. There is significant variation in the types of stall warning systems available on aircraft, and the flight conditions under which they activate.

All modern air transport aircraft have automated stall warning systems that provide visual warnings and audible alarms to the flight crew in the first instance. In most of these aircraft, a motor (commonly referred to as a stick shaker) is fitted to the pilot's control column, causing it to vibrate as an additional warning.

Some aircraft have flight control systems that monitor the flight conditions and aircraft configuration, and automatically limit the angle of attack to prevent the aircraft from approaching a stall in the first place.

If the pilot does not take action to reduce the angle of attack after a stall warning, most commercial aircraft have a stick pusher system to automatically reduce the angle of attack.

A pilot's own senses also give important cues for recognising an approaching stall. A reduction in airflow noise, buffeting, changes to the 'feel' of flight controls or a reduction of pitch and roll control, or changes to the pilot's sense of movement (direction of motion and speed) can also be useful warnings of a decrease in airspeed or a loss of lift (FAA, 2004).

Stall warnings do not mean that the aircraft is in a stalled condition, or is not under control by the flight crew. However, repeated activations of the stick shaker or activation of the stick pusher are not normal situations.

Stall warnings (like stick shakers and stall warning horns) provide a warning to flight crew to take corrective action to prevent a stall from developing (reducing angle of attack). While stall and stall warning speeds are published in the aircraft flight manual (AFM) for each type of transport aircraft, pilots must consider that stall speeds can be affected by:

- aircraft weight
- attitude changes affecting the load factor on the wing (for example, the stall speed (V_S), increases in a turn)
- use, position, and combination of high-lift devices, which change the effective angle of attack of the wing and the amount of lift it is generating
- the accretion of ice on the wing
- atmospheric conditions
- localised atmospheric disturbances such as turbulence.

Stall speeds may also be affected by aircraft system problems, such as partial flap, or uncommanded flap / slat operation.

Certain combinations of the above factors mean that stall warnings can activate at other points which the flight crew may not be expecting. For example, the margin between the minimum speed for the normal configuration (V_{Ref}) and the stall speed is reduced when the aircraft is flying at high (or rapidly changing) bank or pitch angles, which impose a load factor (also referred to as N_Z) greater than 1 g when applying elevator back pressure. This can also occur when turbulence or wind gusts apply forces on the aircraft, or when the flight crew are decelerating the aircraft.

On most aircraft, stall warning devices activate when the margin between V_S and the current airspeed of the aircraft reduces to about 20 per cent above V_S (V_{SW}). If the pilot does not or is unable to increase this margin by reducing the angle of attack, defence measures (the stick pusher) may activate if the margin reduces to less than 10 per cent. If the aircraft exceeds the critical angle of attack, a stall has developed, and the aircraft will descend due to the sudden loss of lift (but recoverable by reducing angle of attack, and increasing engine power).

What is the stall speed (V_S)?

To maintain lift and control of an aeroplane in flight, the aircraft must be above a certain minimum airspeed (called the stall speed, or V_S).

The stall speed depends on a complicated relationship of factors such as gross weight, wing load factor, the use of high-lift devices such as flaps and slats, and the density of air at the altitude the aircraft is flying at.

When an aircraft approaches the stall speed, the effects of flight controls are diminished, airframe buffeting may occur, and it can be difficult for the pilot to maintain altitude.

An important feature of pilot training is to develop the pilot’s ability to estimate the margin of safety above the stalling speed in different situations, environmental conditions, and aircraft configurations, and ensure that the aircraft is above this speed at all times. Stall warning devices are an additional help, activating when the aircraft’s speed is about 20 per cent above V_S (FAA, 2004).

Stall speed in level flight increases in proportion to the square root of the aircraft’s bank angle. To maintain level flight in a turn the pilot needs to raise the nose (increase angle of attack), but if the aircraft is banking this also increases the load factor (g load). For example, in normal level flight, the aircraft’s stall speed is V_s. In a 60° turn to maintain altitude, the pilot would need to apply a load factor of 2 g by applying elevator back pressure. However, increasing the wing load factor to 2 g increases the stall speed to approximately $1.4V_s$, so the aircraft would stall at a speed higher than V_s.

As a result, a stall warning may occur due to the corresponding increase in the aircraft’s actual stall speed for those conditions, even though the airspeed of the aircraft is normal or only slightly lower than normal for the phase of flight. This is particularly a risk to flight crews operating aircraft with control systems that do not provide full flight envelope protection against stall warnings at airspeeds close to V_{Ref} (like V_{Ref} + 5 or 10 kts), or in situations where the flight control mode has degraded.

A situation like this occurred in 2008 involving the Boeing 717 on approach into Alice Springs Airport where the flight crew rolled the aircraft to about 30° angle of bank to tighten the aircraft's turning circle and intercept the final approach path. This increased wing loading, and combined with roll, pitch, high air density while flying at low altitude, low power, and changes to the relative wind, the aircraft lost airspeed and the angle of attack increased. Subsequently, there were two momentary stick shaker activations.

Boeing 717 stick shaker near Alice Springs, NT

ATSB investigation AO–2008–064

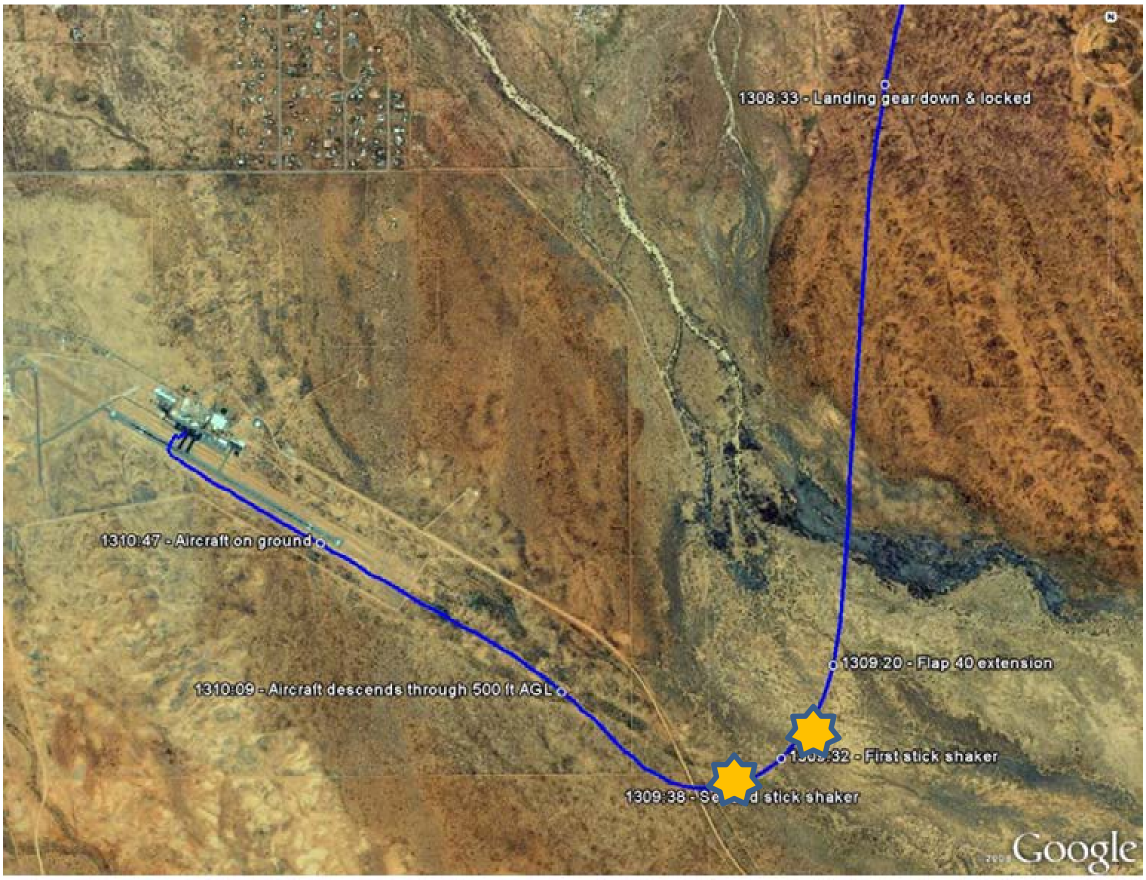
In September 2008, the flight crew of a Boeing 717 were conducting a manually–flown visual approach into Alice Springs Airport when the aircraft's stick shaker activated. The pilot flying lowered the nose while continuing the turn onto final approach. The stick shaker activated again before the flight crew stabilised the approach to within the operator's criteria and landed without further incident.

Figure 1 below shows the final approach track of the aircraft into Alice Springs, and when and where the stick shaker activations occurred with respect to the flight crew's turn on to final.

The investigation found that the stick shaker activated because of a combination of bank angle, high nose-up pitch change rate and airspeed slightly below the normal approach speed. The aircraft was higher and closer to the aerodrome than was suitable for the direct-to-final approach being attempted. The investigation also found some other safety factors that may have contributed to this incident, including fatigue and work stress, and the flight crew's response to the standard operating procedures for situations when stick shaker activation occurred.

In response to this occurrence, the operator proactively issued a number of notices to pilots to enhance their awareness of autopilot and low speed warnings in the Boeing 717, to highlight the aircraft's buffet protection system, and to discuss recent stick shaker events and to describe the stall recovery procedure to be used when flying that aircraft type. In addition, the operator amended a number of its command upgrade and recurrent simulator training requirements and worked with the aircraft manufacturer to reduce the incidence of stick shaker events across the operator's Boeing 717 fleet.

Figure 1: **Final approach track of the Boeing 717 into Alice Springs Airport on the incident flight, 28 September 2008**



Source: ATSB

At the time the stick shaker activated in this occurrence, the airspeed of the aircraft was only slightly lower than the normal approach speed (but was close to V_{Ref} for the 'flaps 40' configuration being used on the approach). However, the low approach speed was combined with a 28° bank angle, and a high rate of nose-up pitch change. A classic case of pulling up to the stall, these factors caused an increase in the wing load factor to 1.35 g, which meant that there was a reduced margin between the minimum speed for approach (V_{Ref}) and the stall warning speed of the aircraft (V_{SW}).

In a normal coordinated 30° bank angle turn at close to V_{Ref}, the manufacturer (Boeing) calculated that there should have been enough margin between the load factor in the turn (1.15 g) and the load factor at which the stick shaker would activate (1.4 g). However, the load factor of 1.35 g, and a sudden change in pitch attitude during the turn (the pitch angle increased from 2° to 6° in 1 second) meant that the load factor exceeded the margin required to activate the stick shaker at this approach speed.

In this case, the flight crew responded to the stick shaker by lowering the nose to reduce angle of attack and increasing the power setting, but did not reduce the bank angle as required by Boeing in the aircraft flight manual in response to stick shaker activations. The flight crew continued with the approach (ATSB, 2011).

Safety analysis

In the 5 years from 2008 to 2012, 245[1] stall warnings and stall warning system issues were reported to the ATSB by high capacity[2] air transport operators and flight crews. These included both Australian civil (VH-) registered and foreign-registered high capacity air transport aircraft operating within, to, or from Australia. Of these, four were classified as *serious incidents* (involving circumstances indicating that an accident nearly occurred). These serious incidents are discussed in further detail later in this report. There was also a stall warning associated with an Airbus A380 *accident* in November 2010, where an uncontained engine failure occurred on a flight departing from Singapore that resulted in a number of aircraft system malfunctions and failures.[3]

A number of modern aircraft types have fly-by-wire control systems that include flight envelope protection functions. Protections such as *alpha prot* (protection) and *alpha floor* prevent the aircraft from approaching the stall and so these aircraft do not provide stall warnings. As these protections provide a similar function to stall warnings on other aircraft, the data below includes alpha prot and alpha floor occurrences as equivalent to stall warnings.

These 245 occurrences represent about 1 per cent of the 27,000 occurrences reported to the ATSB over the same period involving high capacity air transport aircraft. Reporting of safety incidents from Australia's airlines is very robust. As the ATSB and airlines work closely to continually improve the level and quality of reporting, there has been a gradual increase in the number of all reported safety occurrences over time that is independent of growth in flying activity.

Figure 2 shows changes in the number of stall warnings reported to the ATSB in the 5 years since 2008. The growth observed since 2009 is reflective of increased reporting levels by operators, and improved capture by the ATSB of all stall warnings and stall warning system issues, not just those that resulted in activation of a stick shaker.

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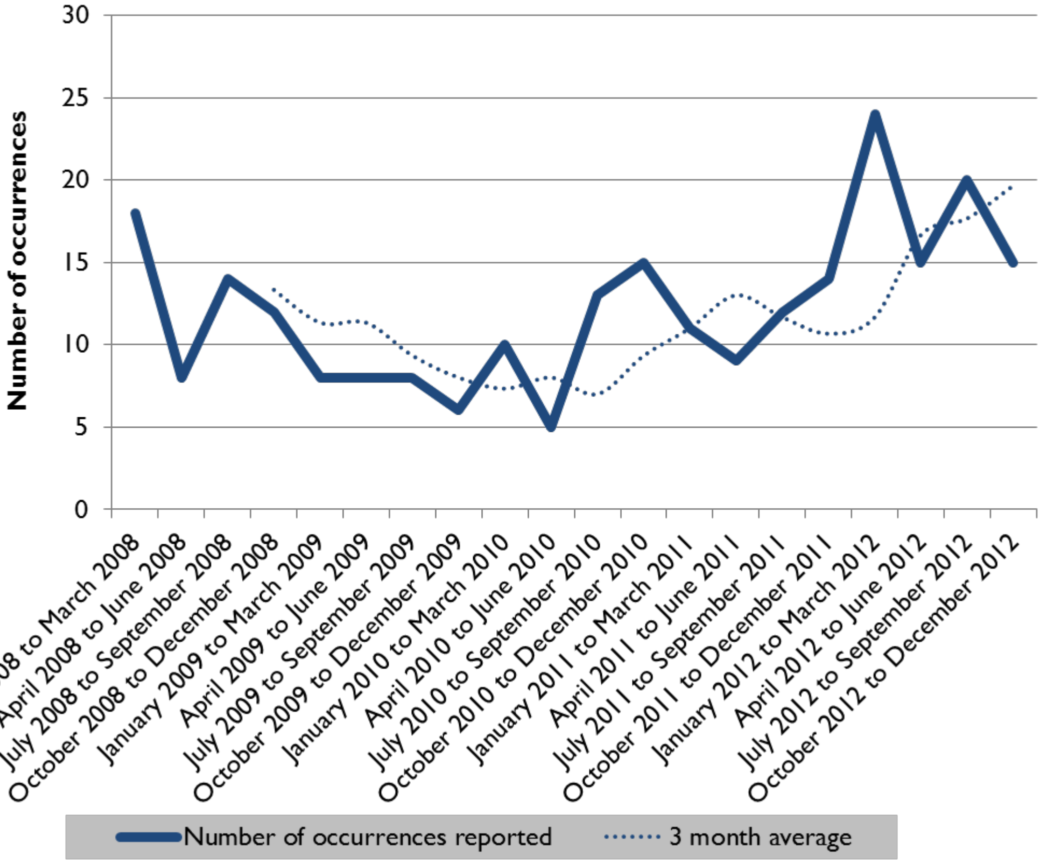
[1] Including 37 reports which were determined not to be transport safety matters as defined by the *Transport Safety Investigation Act* 2003.

[2] A high capacity aircraft refers to an aircraft that is certified as having a maximum seating capacity exceeding 38 seats, or having a maximum payload capability that exceeds 4,200 kg.

[3] The engine failure caused significant damage to many aircraft systems, and led the flight crew to make a return to Singapore Changi Airport. One effect of this damage was the aircraft's control system reverting from Normal to Alternate 1A law. Under the Alternate 1A law, alpha floor protection was lost, and the stall warning function (not normally required due to flight envelope protections provided by Normal law) was restored. On the final approach and immediately before the aircraft touched down on the runway, the stick shaker activated. Post-accident analysis by Airbus identified that, as a result of the control system laws and damage to the aircraft, the stall warning was genuine and that the flight envelope margins were maintained (ATSB investigation AO-2010-089).

Figure 2: Stall warnings reported to the ATSB involving high capacity aircraft, 2008 to 2012



What stall warnings have occurred?

Most of the 245 stall warnings reported to the ATSB during this time have:

- been associated with stick shaker activations (209 occurrences)
- been momentary in duration (only six stall warnings reported since 2008 have lasted longer than two seconds)
- been associated with aircraft tracks in the vicinity of thunderstorms, clear air turbulence, sudden wind gusts, or windshear in both visual (VMC) and instrument meteorological conditions (IMC)
- most often occurred in cruise, or during the approach to land.

None have resulted in a stall or a loss of control, nor have any led to major injuries to passengers or crew.

No stick pusher events were reported in Australian high capacity air transport operations in the 2008 to 2012 period. All reported stick pusher-related occurrences were actually system failures that did not result in activation of the stick pusher.

Most stall warnings reported to the ATSB (at least 69 per cent – 169 of the 245 occurrences) involving high capacity air transport aircraft were genuine warnings of an impending stall where the aircraft's stall warning systems were operating normally. Of these 169 occurrences, 163 were a genuine activation of a stick shaker (Table 1).

Almost all of these 169 occurrences were associated with only one activation of the stick shaker (sometimes in association with other stall warnings or system alerts); only 10 occurrences involved multiple stick shaker activations. In three of the 169 genuine stall warning occurrences, an aircraft configuration issue (position of the stall warning reference speed switch) or the operation of the autopilot altitude capture feature caused a stall warning that was early or inappropriate for the actual environmental conditions, but the stall warning system was working correctly. These cases were reflective of problems with the flight crew's situational and aircraft configuration awareness and task overload during some phases of flight (such as descent and approach). Four of the 169 genuine stall warnings were activations of the aircraft's alpha protection system.

There were an additional 31 stall warnings reported to the ATSB where there was not enough information provided to determine whether the stall warning was genuine or false.

The remaining 45 occurrences involved a false stall warning, most commonly due to a stall warning system failure. Most of these failures were momentary and unable to be replicated, and did not affect normal operations. In most cases, the flight crew continued the flight normally and made a note in the aircraft's defect log, or if the warning occurred on the ground, returned to the gate. Six involved the stick shaker activating, and the remaining 39 occurrences were stall warning system failure annunications, or stall warning computer failures.

Of the 209 stall warnings reported where the stick shaker activated, 33 (16 per cent) were reported by the flight crew to be false (spurious) in nature. This figure includes stick shaker activations caused by stall warning system defects. It also includes reports in which the flight crew reported that a stick shaker activation was not genuine, but the activation may have been genuine as no information was provided to the ATSB on whether or not the activation related to a system failure. Included in these occurrences were seven stick shaker activations that were reported as spurious by flight crew, but engineering follow-up found that the stall warning system was probably operating normally at the time of the occurrence. This indicates that flight crew occasionally assumed that real stall warnings were false. This reinforces the importance of treating all stall warnings the same as an approach to stall, and immediately executing stall recovery actions (in particular reducing angle of attack).

Most spurious stall warnings (both those reported as false by the flight crew, as well as those which were confirmed to be due to stall warning system failures) were momentary in nature (only one lasted for more than one second). None of those that occurred in flight resulted in the autopilot disconnecting. Post-flight engineering inspections of these issues commonly found problems with the stall warning computer or with the alpha vane (which measures angle of attack). In four occurrences, erroneous data from the flap and leading edge slat position sensor inputs into the aircraft's stall warning computer were associated with spurious stall warnings, or with stall warning system failures.

What aircraft were involved?

Table 1 also provides a full list of aircraft models in which flight crews reported stall warnings to the ATSB, and the number of genuine and spurious stall warning system activations reported. Aircraft are designed to meet certification requirements for the reliability of stall warning systems. Federal Aviation Regulation (FAR) Part 25 requires air transport aircraft certified by the US Federal Aviation Administration (FAA) to have stall warning systems that have a failure rate that is usually less than 1 in 100,000 flight hours for most aircraft in this category, and less than 1 in 1,000,000 flight hours if the stall cannot be well detected through non-artificial stall warnings (such as in aircraft with a flight envelope protection-based control system) (FAA, 2011).

Even with low failure rates, false or spurious stick shaker/flight envelope protection activations can be expected to occur sometimes in normal operations given the large number of flight hours routinely performed by air transport category aircraft. Table 1 shows that there were only six reported spurious stick shaker activations over the 2008 to 2012 period, and no spurious activations of flight envelope protection. It does, however, show that for some aircraft types a significant proportion of the reported stall warning-related occurrences were stall warning system failures.

Table 1: Aircraft models with reported stall warnings, 2008 to 2012

Aircraft model	Number of stall warning related reports[4]	*Total rate per 100,000 hours*[5]	Number of genuine stick shaker activations [6]	*Genuine rate per 100,000 hours*[5]	Number of spurious stall warnings (excluding system failures)[7]	Number of stall warning system failures	*System failure rate per 100,000 hours*[5]
Bombardier DHC-8-300	54	*28.6*	16	*8.5*	1	19	*10.1*
Boeing 767-300	52	12.6	44	*10.6*	2	2	*0.5*
Boeing 747-400	49	7.3	49	*7.3*	0	0	*0*
Boeing 737-700 / 800	32	1.7	22	*1.2*	2	7	*0.4*
Boeing 717-200	18	10.7	14	*8.3*	0	4	*2.4*
Fokker F100	13	24.9	1	*1.9*	0	12	*23.0*
Bombardier DHC-8-400 (Q400)	8	*3.8*	3	*1.4*	0	5	*2.4*
Embraer E-190	5	2.2	4	*1.8*	0	1	*0.4*
Boeing 737-400	2	0.6	0	*0*	1	1	*0.3*
Boeing 747-300	1	7.6	1	*7.6*	0	0	*0*
Boeing 777-300	2	2.3	2	*2.3*	0	0	*0*
Airbus A320-200	3	0.4	2	*0.2*	0	1	*0.1*
ATR 42-300	1	*3.5*	1	*3.5*	0	0	*0*
British Aerospace BAe 146 / Avro RJ	1	4.4	1	*4.4*	0	0	*0*
Embraer E-170	1	1.4	0	*0*	0	1	*1.4*
Airbus A330-300	1	0.2	1	*0.2*	0	0	*0*
Airbus A380-800	1	0.7	1	*0.7*	0	0	*0*
Bombardier DHC-8-200	1	N/A	1	*N/A*	0	0	*N/A*
TOTAL	**245**	**-**	**163**	**-**	**6**	**53**	**-**

Stall warnings in Australia between 2008 and 2012 were most commonly associated with Bombardier DHC-8-300, Boeing 767-300, Boeing 747-400, and Boeing 737-700/800 aircraft. These aircraft were involved in 76 per cent of the stall warning-related occurrences reported to the ATSB over this period, and 81 per cent of the genuine stick shaker activations. When the flying activity of each aircraft type over this 5 year period is considered, the Bombardier DHC-8-300 and Fokker 100, followed by Boeing 767 and Boeing 717, had the highest rate of stall warning-related occurrences reported, each with over 10 occurrences per 100,000 hours flown. The Boeing 767 had the highest rate of genuine stick shaker activations (10.6 per 100,000 hours flown).

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[4] All 245 stall warning-related occurrences reported to the ATSB between 2008 and 2012. Includes stall warning system failures, many of which did not result in a stick shaker activation.

[5] De-identified domestic and international hours flown (Australian aircraft only) by aircraft type information for the 2008 to 2012 period provided by the Bureau of Infrastructure, Transport, and Regional Economics (BITRE).

[6] Only includes genuine stall warning system activations (stick shaker or flight envelope protection). Stall warning system failures leading to one of these cockpit indications are counted separately in this table.

[7] This column does not include the 23 stall warnings reported to the ATSB where it could not be determined from the information reported whether a stick shaker/flight protection activation was genuine or spurious. A rate is not provided due to the low numbers.

Boeing 717 stick shaker in turbulence, near Perenjori, WA

In October 2008, a Boeing 717 aircraft encountered severe turbulence event during cruise that lasted approximately 30 seconds. The aircraft was cruising at flight level (FL) 350 in a layer of strata–form cloud with only minor turbulence being experienced intermittently. There had been a report of turbulence by a previous aircraft on the same track at a lower level, approximately 100 nm ahead of the 717. As the aircraft approached the area, the seat belt sign was turned on and the captain transferred control of the aircraft to the first officer in order to make an announcement. During this time, there was a sudden increase in the intensity of the turbulence over approximately 10–20 seconds. The aircraft was diverted left of track as the majority of the rapid onset was emerging from the right of track. As the captain resumed control of the aircraft, the aircraft was affected by severe turbulence. The autopilot disconnected, so manual control was taken until stable flight conditions returned. During the event, the stick shaker activated two to three times, and the aircraft's attitude and altitude were uncontrollable. The flight crew declared an emergency (a 'PAN' broadcast) during the event, and diverted from track and commenced a descent. The PAN was cancelled once control of the aircraft was regained. Seat belt signs remained on for the remainder of the flight and while no injuries resulted, several passengers were air sick.

This serious incident shows that keeping cabin crew and passengers informed reduces the potential for injury in environmental conditions where stall warnings are more likely to occur (icing conditions and turbulence), or have been reported by other flight crews.

It is important to note that the above aircraft do not have flight control systems that are designed to prevent the aircraft from entering a high angle of attack situation by automatically limiting aircraft attitude for the current flight condition and aircraft configuration. In aircraft such as the Boeing 777 and fly-by wire Airbus aircraft, stall warnings would not be expected in normal operations, as the control law-based flight envelope protections provided by the aircraft's control system should prevent the aircraft from reaching a point where a stall could be possible. These flight envelope protections are designed to provide control inputs that prevent the aircraft wing from stalling and may also increase engine thrust to maintain or increase airspeed (see *Alpha floor protected aircraft* below).

Variation in stall warning systems between aircraft manufacturers and models means that some aircraft appear to be more prone to false stall warning system activations due to system malfunctions, for example, Bombardier Dash-8-300 and Fokker F100 aircraft. A major Bombardier DHC-8 operator has reported that spurious activations of stick shaker motors (where the stick shaker activated when the aircraft was not approaching a stall condition) are common. In this case, the operator and aircraft manufacturer are investigating whether the design of the motor and associated sensors, or elements of standard operating procedures and aircraft configuration in low speed, high angle of attack phases of flight are leading to spurious stall warnings. For the Fokker 100, almost all reports to the ATSB over the last 5 years involving a stall warning were due to the aircraft's stall warning systems activating spuriously due to stall warning computer failures, and none resulted in a stick shaker activation.

Alpha floor protected aircraft

Some aircraft have flight control systems that are designed to prevent high angle of attack situations by automatically limiting aircraft attitude. In aircraft such as the Boeing 777 and Airbus aircraft, stall warnings would not be expected. The effectiveness of these flight envelope protection systems is shown in Table 1, where there were four alpha protection/floor warnings involving Airbus-manufactured aircraft in Australia in the 2008 to 2012 period, despite these aircraft making up a significant proportion of the Australian airline fleet. In only one case (the Qantas A380 accident described earlier in this report) did the stick shaker activate, and this occurred because the aircraft control systems were operating in a degraded mode where alpha protection was not provided. The remaining three stall warning occurrences listed below (involving Airbus A320 and A330 aircraft) were momentary activations of alpha protection or alpha floor, and were the only alpha protection/floor-related stall warning occurrences reported to the ATSB between 2008 and 2012.

- After take-off from Perth and above 1,500 ft above ground level (AGL), climb thrust was selected and the first officer called for 'flap 1'. After checking that the indicated airspeed was appropriate, the pilot in command selected 'flap 1'. Shortly after, 'Alpha Floor' was annunciated and thrust increased to the take-off and go-around (TOGA) setting followed by a 'TOGA Lock' annunciation. The flight crew decreased pitch attitude, increased thrust and the climb continued normally.
- On decent into Avalon Airport via the runway 18 ILS (instrument landing system), and in a stable visual approach in turbulence and strong wind conditions, a 'speed speed speed' warning was annuciated at 1,500 ft AGL. The autopilot disengaged as the aircraft momentarily entered alpha protection mode, and the flight crew moved the power levers to maximum climb thrust momentarily to increase airspeed. The speed recovered and the aircraft was stable by 1,000 ft, so the crew continued with the approach to landing.
- During moderate turbulence and potential windshear conditions on descent through 10,000 ft above mean sea level (AMSL) into Queenstown Airport, New Zealand, the aircraft experienced multiple rapid fluctuations in speed towards overspeed due to wind strength and wind directional changes. At 8,000 ft AMSL, the flight crew selected 'flap 2' and a reduced speed of 160 kts IAS to prevent an overspeed. The aircraft speed was still trending toward overspeed, so the flight crew lowered the landing gear to assist with speed stability. The aircraft speed then started to reduce to below V_{Ref} with nose attitude increasing, and autothrust was slow to respond to the airspeed and pitch changes. The flight crew started to increase thrust manually, but the alpha floor protection activated just prior to increasing thrust to TOGA. After increasing thrust, the aircraft's speed and performance stabilised and a missed approach was conducted.

The two reported stall warning occurrences reported to the ATSB involving Boeing 777 aircraft (both genuine stick shaker activations) involved the same operator and aircraft, and occurred on separate flights in 2010 after departure from Melbourne Airport. Both were momentary activations, one of which occurred in turbulence during a turn onto a standard instrument departure (SID). In the other occurrence, the aircraft was passing 2,000 ft on climb and the flight crew began to retract the flaps when the aircraft passed through intermittent moderate turbulence. The airspeed was reported to have been 15–20 kts above V_{sw} when the stick shaker activated. After the turbulence ceased, the flight crew continued to retract the flaps and the flight continued normally.

Stall warnings can occur on control law-protected aircraft, but only after they have had serious problems and the flight control system has reverted to lower phases of control law, as occurred in the Air France AF 447 accident in 2009[8].

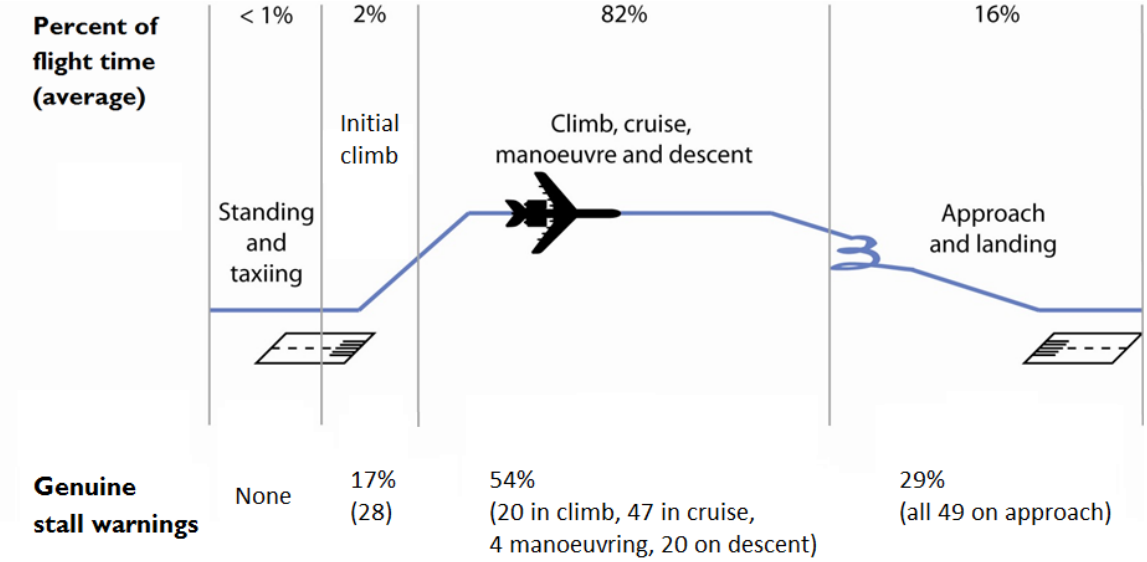
When did the stall warnings occur?

Phase of flight

Over half of the stall warnings happened in the cruise, late climb and descent phases of flight (Figure 3). In cruise, the normal operating altitude and typical aircraft weights mean there is often a narrow band (about 20 knots) between the aircraft's maximum operating speed and the stall warning speed (which is generally 1.2 V_s). The difference between the aircraft's optimum cruise speed and the stall warning speed is even less, and moderate to heavy turbulence can cause airspeed variations of more than 10 kts. This was the trigger for most (about 80 per cent) stall warnings in cruise. In at least 20 per cent of these occurrences, the stall warning system activated when the autopilot tried to correct the aircraft's speed or flight path due to a disturbance.

In contrast to the short amount of time in flight, the relatively lower speed take-off/initial climb and approach phases of flight made up 40 per cent of reported stall warnings that were genuine (not due to a stall warning system failure) (Figure 3). While stall warnings might be expected to occur in these phases of flight (as aircraft on climb and approach are in low speed, high angle of attack configurations), wake turbulence effects from preceding aircraft were frequently attributed to brief stick shaker activations on approach. Several stall warnings reported during approach and initial climb happened during the retraction of high lift devices (leading edge slats and trailing edge flaps), when the resulting increase in stall speed means that the difference between the stall warning activation speed (1.3V_s) and airspeed decreases.

Figure 3: When stall warnings occur, by phase of flight[9]



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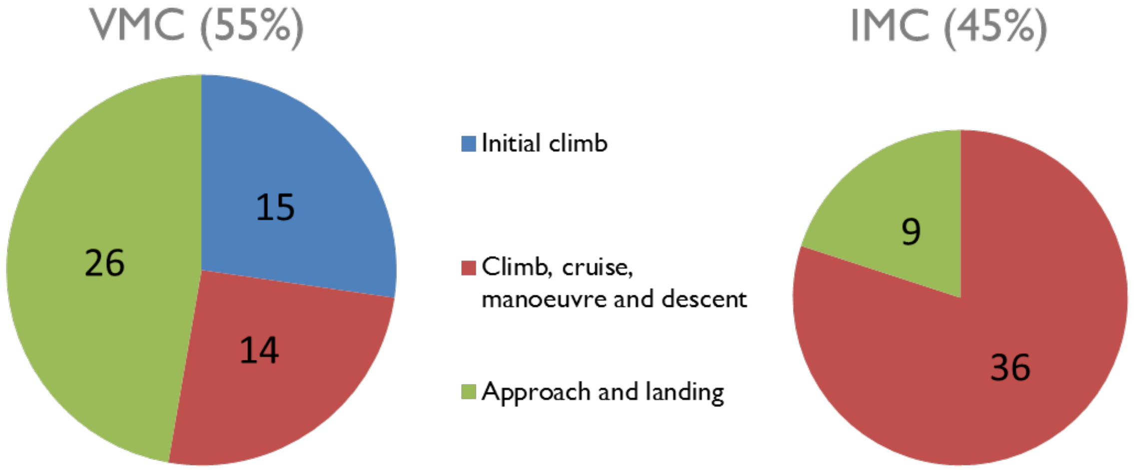
[8] This accident was investigated by the French air safety investigator, the Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA). This investigation report is available online at http://www.bea.aero/en/enquetes/flight.af.447/flight.af.447.php

[9] Phase of flight was recorded for 168 of the 169 genuine stall warnings reported to the ATSB. Stall warning system faults or spurious stall warnings are not included.

Meteorological conditions

Stall warnings are not necessarily only associated with operations in poor weather (IMC). Flight conditions at the time of a stall warning were reported in 100 of the 169 genuine stall warnings that were reported to the ATSB between 2008 and 2012, and more than half of these (55 per cent) occurred in VMC. The graph below shows that there was a stark difference in the phase of flight a stall warning was most likely to occur in VMC versus IMC.

Figure 4: When genuine stall warnings occur, by flight conditions



Genuine stall warnings reported during initial climb all involved VMC flight. About 40 per cent of those stall warnings occurred when the flight crew was retracting high-lift devices. Most other occurrences involved activation due to momentary loss of airspeed in wake turbulence or due to a wind change when aircraft were at pitch angles of about 10°. There were only two occurrences reported where an aircraft was banking on initial climb and was affected by turbulence, leading to a wing loading (g) increase. Three occurrences were stick shaker activations, and coincided with a checklist item to retract the flaps. The effects of increased stall speed (and stall warning activation speed) when the wing load factor increases is discussed later in this report.

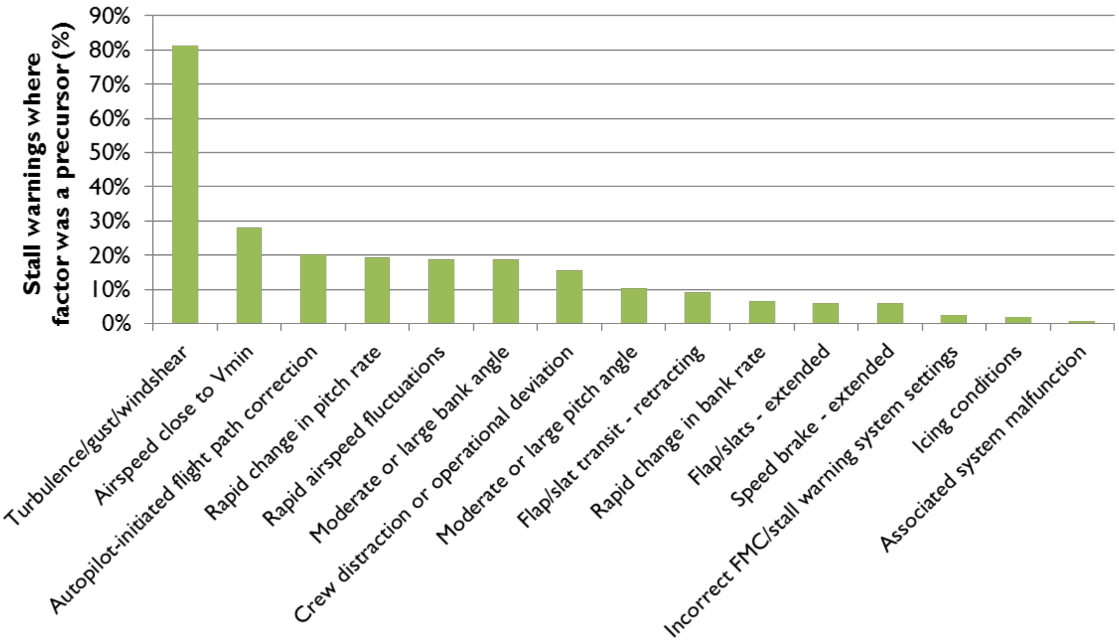
In climb and descent, stall warnings that occurred in VMC were normally due to a wind gust or turbulent conditions causing an airspeed fluctuation while the aircraft was in a high angle of attack condition, or was slowing down to approach a hold point. In most of these cases, the stall warning was as a result of a sudden change in wing loading (g), as the aircraft were operating at an airspeed (generally V_{Ref} + 80 kts) which was well above the stall warning speed, V_{SW} (V_{Ref} is about 8 to 10 per cent higher than V_{SW}). In IMC conditions, stall warnings in cruise were very common. All were associated with turbulence during the cruise, causing either airspeed or altitude fluctuations. In 9 of 21 stall warnings where the aircraft was in cruise in IMC, the aircraft was in a turn while deviating around weather when the fluctuations occurred, increasing wing (g) loading. Of those stall warnings that occurred on climb or descent in IMC, many involved autopilot (autothrottle) disengagement due to unsatisfactory speed control in turbulence, or due to a change in wind direction.

Most stall warnings on approach and landing in IMC occurred during turbulence from windshear, or when manoeuvring around showers or convective cloud on approach. Many of these cases happened during a turn, and were associated with a sudden drop in airspeed and a resulting increase in wing (g) loading. Approach and landing stall warnings were, however, more common in VMC. In VMC, they also occurred in turns where turbulence or windshear affected the aircraft, but there were more occurrences where the flight crew allowed the airspeed to bleed off too much on approach and fall below V_{SW}. Sometimes, this was due to a wind change in turbulent conditions, but in other cases it was due to increased workload on approach or task distraction (such as monitoring for traffic).

What conditions were aircraft in when the stall warning occurred?

Genuine stall warnings reported to the ATSB in the 2008 to 2012 period (169 reports) were reviewed to identify common precursor events, aircraft configurations, or flight profiles that allowed the margin between actual airspeed and V_S to reduce to a point where stall warning system activated. In 154 of these occurrences, enough information was reported to determine what was happening before and after the stall warning (in terms of the aircraft's flight profile, attitude, configuration, crew control inputs, and any weather effects). Figure 5 below shows that most of these stall warnings (81 per cent) occurred in association with a flight disturbance (turbulence, windshear, a gust or change in wind direction). Sixty-five per cent of these occurrences involved a Boeing 747 or 767 aircraft.

Figure 5: Precursor conditions to genuine stall warning system activations reported to the ATSB, 2008 to 2012



Other common precursors were increases in the aircraft's pitch angle or airspeed rate of change, operations in the low speed range, autopilot or autothrottle initiated changes to pitch angle or power setting to maintain a particular glideslope or altitude, or aircraft attitudes that increase wing load factor (bank angle above 20°).

Bombardier DHC-8 stick shaker on approach to Sydney Airport

ATSB investigation AO–2011–036

In March 2011, a Bombardier DHC–8–300 was conducting a regular public transport flight from Tamworth Airport to Sydney Airport. The crew were conducting an area navigation global navigation satellite system (RNAV (GNSS)) approach in Vertical Speed (VS) mode. The aircraft's stick shaker was activated at about the final approach fix (FAF). The crew continued the approach and landed safely.

The stick shaker activated because the aircraft’s speed had slowed to the computed stall reference speed. That reference speed was 10 kts higher than normal for the conditions The stall warning system had computed a potential stall on the incorrect basis that the aircraft was in icing conditions, due to the reference speed switch being left on in the ‘icing conditions’ position. The aircraft’s reference speed system allows stall warnings to be activated at a greater indicated airspeed than normal in potential icing conditions. The use of VS mode, as part of a line training exercise for the first officer, meant that the crew had to make various changes to the aircraft's rate of descent to maintain a normal approach profile.

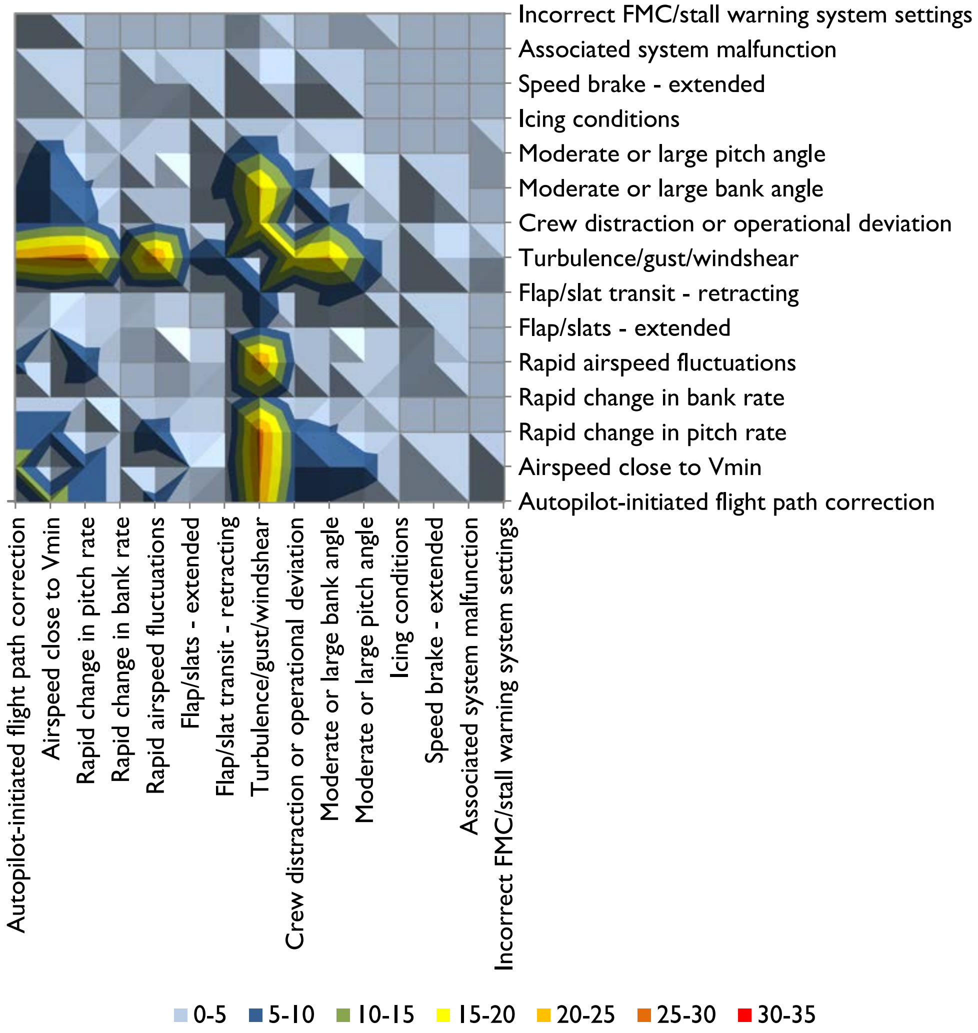
On a number of occasions during the approach the autopilot pitched the aircraft nose up to capture an assigned altitude set by the pilot flying. The last recorded altitude capture occurred at about the FAF, which coincided with the aircraft not being configured for landing, the propeller control levers being at maximum RPM, and the power levers at a low power setting. This resulted in a continued speed reduction below the target airspeed range of 120–130 kts for the approach in the lead-up to the stick shaker activation. The autopilot’s altitude capture feature continued to raise the aircraft’s nose to maintain altitude, which resulted in a further decrease in airspeed, and ultimately activation of the stick shaker.

The operator undertook a number of safety actions to minimise the risk of a recurrence. These included changes to the operator’s training and checking manual, addition of an ‘ice protection’ item to the approach checklist in the aircraft flight manual, and a new procedure to heighten flight crew awareness of the minimum speed for the aircraft’s configuration and the environmental state. The operator also organised an industry workshop forum for operators to share experiences and best practises in regards to situation awareness on the flight deck.

While not common, other stall warning events have occurred in Australia when the reference speed switch has been set to ‘increase’ (reflecting icing conditions) when icing conditions were not present, increasing the risk of an unexpected stall warning.

Figure 6 below shows relationships between different types of precursor conditions, that is, how often were certain combinations likely to exist in the lead up to a stall warning system activation. It shows that in the majority of occurrences, a stall warning occurred when turbulence existed with another precursor factor. The most common combinations were turbulence/gusts/windshear occurring in association with a rapid pitch angle rate of change (18 per cent) or airspeed change (17 per cent). Many of these disturbances occurred when the aircraft was under autopilot control, and an autopilot-initiated flight path correction triggered the stall warning (16 per cent).

Figure 6: Associations between precursors to stick shaker activations reported to the ATSB, 2008 to 2012



Other notable precursors to genuine stall warnings were:

- Turbulence/gusts/windshear AND
  - operation at low airspeeds (26 occurrences)
  - bank angle greater than 20° (21 occurrences)
  - an operational deviation, such as a weather diversion (19 occurrences)
  - retracting flaps or leading edge devices (10 occurrences)
  - rapid bank angle rate of change (10 occurrences)
  - pitch angle greater than 10° (10 occurrences).
- Autopilot-initiated flight path correction AND
  - operation at low airspeeds (12 occurrences)
  - rapid pitch angle rate of change (8 occurrences)
  - rapid changes in airspeed (6 occurrences).
- Operation at low airspeeds AND
  - bank angle greater than 20° (9 occurrences)
  - rapid pitch angle rate of change (8 occurrences)
  - operational deviation or crew distraction (8 occurrences)
  - pitch angle greater than 10° (8 occurrences).
- Rapid changes in airspeed AND
  - rapid pitch angle rate of change (9 occurrences).
- Operational deviation or crew distraction AND
  - rapid pitch angle rate of change (8 occurrences)
  - bank angle greater than 20° (9 occurrences).
- Bank angle greater than 20° AND
  - retracting flaps or leading edge devices (7 occurrences)
  - rapid pitch angle rate of change (6 occurrences).

Of those four stall warnings that were classified as serious incidents between 2008 and 2012, three occurred at airspeeds close to V_{Ref}, and two involved a rapid pitch angle rate of change.

Irrespective of what conditions led to the stall warning, appropriate actions by flight crews to manage the situation commonly were:

- immediately reduce the angle of attack, either by releasing back pressure on the control column, or by moving the elevator control forward
- roll wings level if in a turn
- check engine power settings, RPM, and speeds
- check standby instruments
- advise air traffic control and, when the stall warning occurred in severe turbulence, advise cabin crew of the situation (generally involving a passenger announcement to remain seated and secured, and a limiting of cabin service)
- if the stall warning was suspected to be spurious, make a note in the aircraft's defect log for follow-up.

While there have been different approaches to stall recovery training in the past, the important response when confronted with a stall or a stall warning is to immediately reduce angle of attack. The United States Federal Aviation Administration (FAA) advises all pilots and operators to use evaluation criteria for stall recovery that do not mandate a predetermined value for altitude loss, and instead consider the multitude of external and internal variables that can affect the recovery altitude. This approach will also be recommended by the European Aviation Safety Authority (EASA). In a recent Advisory Circular (AC 120-109)[10], the FAA also identified the importance of simulated stall recovery training for pilots. Training should include stall recovery with the autopilot engaged, stick pusher response, and an emphasis on treating all stall warnings as if a full stall has occurred (FAA, 2012).

Higher risk events

The ATSB assesses the probable level of safety risk associated with each reported occurrence, considering the circumstances of the occurrence at the time it happened.[11] The safety risk of occurrences is assessed using a modified version of the Aviation Risk Management Solutions (ARMS) event risk classification framework.[12] This framework bases the event risk on the most credible potential accident outcome that could have eventuated, and the effectiveness of the remaining defences that stood between the occurrence and that outcome. The intention of this assessment is to determine if there was a credible risk of injury to passengers, crew, the public, and/or aircraft damage.

Occurrences that are identified as medium, high, or very high risk are targeted for investigations, but the ATSB also focuses investigation effort on occurrences where a systemic safety issue is likely to have allowed that occurrence to happen. There were four ATSB investigations of stall warnings between 2008 and 2012 that involved high capacity air transport aircraft. There was also an investigation into the Qantas Airbus A380 uncontained engine failure accident, in which there was a stall warning on landing.

As stall warnings are a warning only, and are a defence provided to ensure flight crew take corrective action to prevent a stall developing and a recoverable loss of control, they are generally low risk events. In some situations, they indicate a possibility for a more serious outcome because the aircraft is flying at a speed that is lower than it should be for the flight condition and configuration it is in. Many stall warnings, such as those that occur in turbulence during cruise, are not likely to indicate a loss of control will occur (even if the aircraft stalls), and are low risk. (However, as was shown by the Air France 447 accident in 2009, a stall is still possible.) Some stall warnings, such as those that occur on final approach at a high angle of attack and at a low airspeed, are high risk because of insufficient altitude to recover from a stall if it was to develop and the subsequent likelihood of a terrain collision.

Figure 7 shows that despite more of these types of reports to the ATSB in recent years (particularly since mid–2011), there continued to be only a small number of stall warnings involving high capacity air transport aircraft that were managed in such a way that there was an increased risk of a stall, a temporary control loss, or injury. The increase in stall warning reports with no accident risk in Figure 7 strongly suggests that the overall increasing trend is due to better reporting of stall warnings to the ATSB, with some seasonal spikes over summer months due to increased turbulence.

The very high risk occurrence shown in the October to December 2010 quarter was the Qantas A380 accident described earlier. There were two stall warnings occurrences assessed by the ATSB as representing a high accident risk. Both involved Boeing 717 aircraft, and both were

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[10] This Advisory Circular provides FAA recommended practices for stall and stick pusher training, and can be found at www.faa.gov/documentLibrary/media/Advisory_Circular/AC%20120-109.pdf.

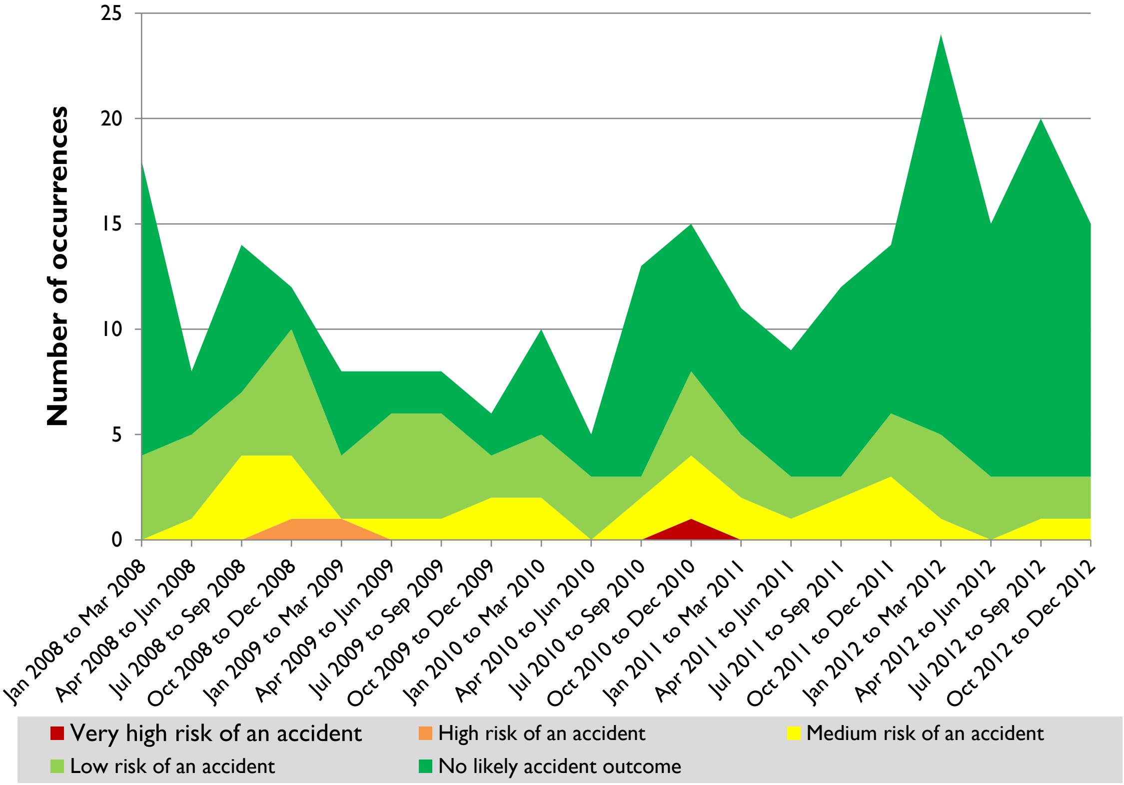
[11] The Event Risk Classification (ERC) methodology is used by the ATSB to make assessments of the safety risk associated with occurrences. For more information on how the ATSB uses occurrence and investigation data to drive proactive safety improvements, see Godley (2012).

[12] The methodology is from the report *The ARMS Methodology for Operational Risk Assessment in Aviation Organisations* (version 4.1, March 2010). ARMS is an industry working group set up 2007 in order to develop a new and better methodology for Operational Risk Assessments. It is a non-political, non-profit working group, with a mission to produce a good risk assessment methodology for the industry. The results are freely available to the whole industry and to anyone else interested in the concept.

associated with a temporary loss of control after encountering severe turbulence during cruise. A summary o fthese occurrences are as follows:

- After turning to avoid severe weather showing on the aircraft radar, the aircraft encountered severe turbulence and was lifted 1,000 ft above its cleared level. The stick shaker operated twice momentarily. After about 15 seconds the crew were able to return the aircraft to its cleared level. (See case study *Large altitude excursion* on page 23.)
- The aircraft encountered severe turbulence for a period of approximately 30 seconds. The crew received several stickshaker warnings. The crew declared a PAN, diverted the aircraft from the cleared track and commenced a descent. (See case study on page 11.)

Figure 7: Assessed risk of stall warning occurrences reported to the ATSB, 2008 to 2012



Between 2008 and 2012, there were 30 stall warnings reported where the ATSB assessed that there was a medium risk of an unsafe outcome due to the conditions that existed at the time (severe turbulence at low altitudes, such as on initial climb, where the aircraft is travelling close to V_{Ref} and at a high angle of attack). In these cases, the worst credible outcomes were considered to be a temporary but recoverable loss of control of the aircraft, and minor injuries to cabin crew and unrestrained passengers.

The most commonly involved aircraft types in these medium risk events were Boeing 747-400 (nine occurrences), Boeing 767 (eight occurrences), and Boeing 717 aircraft (three occurrences).

The majority of these occurrences were brief stick shaker activations, and were associated with moderate or severe turbulence. Some were also associated with:

- additional warnings associated with the stall warning (excessive bank angle and undershoot GPWS alerts, flap overspeed)
- large bank angle and altitude deviations (often associated with unexpected turbulence)
- overspeeds followed by underspeeds

- minor passenger and crew injuries from loose objects, or due to being unrestrained during sudden changes in aircraft motion (generally due to associated turbulence).

Many of these stall warnings occurred while the aircraft was manoeuvring in areas of thunderstorm activity and encountered severe turbulence, and the stick shaker probably activated due to significant airspeed fluctuations and a higher than normal V_{SW} because of a greater wing loading (g) factor when the aircraft was banking. Most of the serious stall warnings reported to the ATSB happened on approach to land, when aircraft were in a low speed, high angle of attack configuration, and in several cases the stall warning speed was higher than normal (due to a higher wing loading (g) factor in a turn, or an incorrect reference speed switch setting). In these cases, the risk of a stall developing was increased by:

- a lack of awareness of decreasing airspeed and increasing angle of attack prior to the stall warning, particularly when the aircraft was being controlled by the autopilot, and flight crew were taken by surprise by a stall warning (stick shaker activation)
- an approach where the flight crew were focused on trying to correct the approach prior to the stabilised approach height instead of conducting a missed approach or go-around. In these cases, there was either little margin between the approach speed and the stall warning speed for the configuration and attitude of the aircraft, or control inputs to correct the approach or reintercept the glideslope were made without consideration of the aircraft’s airspeed, load factor, and angle of attack.

Stall warnings are more likely to occur in these situations due to confusion, or due to the crew trying to diagnose the situation ahead of taking precautionary action to address the stall warning (decrease angle of attack, and increasing engine power).

Bombardier DHC-8 unstable approach into Sydney Airport

ATSB investigation AO–2009–001

In December 2008, a Bombardier DHC–8–300 was on an instrument landing system (ILS) approach to Sydney Airport. The flight crew levelled the aircraft off at 2,000 ft AGL, with the intention of intercepting the glideslope from below. At the point when the aircraft intercepted the glideslope, the crew had not yet configured the aircraft for landing, resulting in a higher than normal airspeed during at the start of the descent. To reduce the aircraft's speed and continue the approach, the flight crew attempted to use high propeller RPM on a low power setting to create additional drag, however, the speed decreased more rapidly than the flight crew expected. The autopilot attempted to maintain the glidepath, resulting in a high angle of attack, low airspeed condition that caused the stick shaker to activate. The flight crew initiated a missed approach in response to the stick shaker, but the pilot flying made a brief attempt to continue the approach before abandoning this plan and conducted a missed approach.

As a result of this particular occurrence, the operator proactively made changes to its DHC–8 training syllabus, highlighted to its crews the destabilising effects of changes to an aircraft's configuration during an approach, and emphasised to crews the importance of good communication in a multi–crew environment. In other stall warning occurrences reported to the ATSB where a stall warning took the flight crew by surprise, changes in aircraft configuration, system operation, airspeed and angle of attack were not noticed over a relatively long period of time, similar to this occurrence.

Worldwide, stall warnings have resulted in accidents or near accidents only in cases where the pilot did not respond appropriately to the initial stall warning (usually a stick shaker) by treating the warning as if a full stall had occurred, and taking recovery action to reduce angle of attack and apply power. The worst-case outcome of inappropriate stall warning response was shown by the crash of a Bombardier Q400 in the United States in 2009, where the flight crew had not considered how close the aircraft was operating to the flight envelope limit for the combination of flight profile and environmental conditions. This accident, and its investigation by the National Transportation Safety Board (NTSB), is discussed further in Appendix A. When a stall warning occurred, the flight crew did not respond effectively to regain positive control by reducing angle of attack, and when the stick pusher activated to intervene, the pilot in command actively worked against this last line of defence for a stall. While this was an unusual situation, the short period of time between activation of the stick shaker and stick pusher illustrates that a failure to respond to a stall warning promptly in all instances (by reducing angle of attack and increasing power) can place the aircraft in a high risk situation.

In Australia, despite the growth in the number of occurrences reported to the ATSB in recent years, only four stall warning occurrences were identified where there was a credible potential for a situation where control of the aircraft was temporarily lost (significant deviations in altitude or airspeed due to severe turbulence, especially while on approach, climb, or during a turn, repeated stick shaker activations, or stick shaker events lasting for several seconds), or for injuries to crew or passengers. These included the serious incident involving a Boeing 717 near Perenjori, WA (discussed on page 11). The remaining three stall warning occurrences are described below.

Low speed climb at maximum weight with gusts and turbulence

On departure from Sydney Airport in September 2012 at close to maximum take-off weight, the crew of a Boeing 747-400 received a stick shaker warning. A strong westerly wind was blowing causing moderate turbulence and gusty conditions. When the flaps were being retracted, the flight crew needed to apply pitch control to keep the airspeed within the manoeuvring and flap limit speeds. When the flaps were selected to up, a strong gust was encountered which caused the indicated airspeed to increase rapidly approaching the flap/speed limit. To contain the speed, the flight crew applied continuous elevator control to increase the aircraft’s angle of attack to 14°, which was followed by stick shaker activation for a few seconds. The elevator back pressure was immediately reduced, reducing angle of attack and the stick shaker stopped. No speed limits were exceeded, and the aircraft continued to climb normally.

Data entry errors affecting stall warning speeds

ATSB investigation AO–2010–081

In October 2010, while a Boeing 717 aircraft was on approach to land at Kalgoorlie Airport, the aircraft’s stick shaker activated. The pilot flying reduced the aircraft’s pitch angle and continued the turn onto the final approach. About a minute later, the approach was no longer stabilised, and the flight crew conducted a go-around. On the second approach to land and after turning onto final, the co-pilot noted that the aircraft was below the required profile. As the co-pilot increased the aircraft’s pitch attitude, the stick shaker activated again for about 2 seconds. Following recovery actions, a go–around was conducted. The third approach and landing was conducted at an airspeed that was about 15 kts higher than the previous approaches. The investigation found that the stick shaker activations were primarily a result of an incorrect approach speed, which had been calculated on an incorrect landing weight that the flight crew had inadvertently entered into the aircraft’s flight management system (FMS) prior to departure. The approach speed generated by the FMS was based on a landing weight that was 9,415 kg less than the aircraft’s actual weight. The data entry error also influenced the aircraft’s take-off weight in the FMS. The error went unnoticed and did not manifest as an operational problem until the approach into Kalgoorlie.

This serious incident highlights the importance of conducting a gross-error check of aircraft performance figures calculated by the aircraft’s FMS, as they are easily influenced by data entry errors prior to take-off. Data entry errors are not always picked up by the FMS verification logic, and their effect may not be detected until a critical phase of the flight when the aircraft is operating close to its stall speed.

As a result of this occurrence, the operator made a number of enhancements to the format of the Boeing 717 load sheet, the FMS weight data entry and verification procedures, the weight validation checks, and the 717 simulator training involving recovery from stick shaker activation.

Large altitude excursion

In February 2009, while in cruise at FL350 in IMC and experiencing light turbulence, the flight crew of the Boeing 717 identified areas of moderate and heavy turbulence on the weather radar about 20 nm ahead. After clearance was received by ATC, the flight crew commenced a turn to avoid the suspected turbulence. During the turn, the weather radar suddenly showed heavy turbulence areas ahead on the intended flight path. The aircraft encountered severe turbulence, which caused the autopilot to disconnect, and the flight crew reported that the aircraft was pushed up 1,000 ft from the cruising altitude in a few seconds. The flight crew noticed that during this excursion, the aircraft's V_{Max} indication reduced to the current airspeed, while the V_{Min} indication increased to the same speed. The stick shaker activated briefly, and a few seconds later activated again for 3 seconds. The aircraft stabilised after about 15 seconds, and the flight crew descended to their original cleared altitude after reporting the altitude excursion to ATC. All passengers and cabin crew were seated with seat belts on, and there were no injuries.

Summary

Stall warnings sometimes occur in normal operations, are normally low risk events, and are frequently reported to the ATSB by a range of operators. From a review of reported occurrences from 2008 to 2012, they occurred in a range of flight conditions, but were most often associated with unexpected or severe turbulence.

In Australia, even the most serious events have not resulted in a loss of control, and were generally well managed by flight crew. About 70 per cent of stall warnings reported to the ATSB were genuine indications that the aircraft was approaching the point of stall if the flight crew did not reduce the aircraft's angle of attack. The remaining 30 per cent of occurrences were related to stall warning system problems, although very few of those reported resulted in false stick shaker activation. Most of the 169 stall warnings reported to the ATSB in the last 5 years that resulted in genuine stall warning events (usually stick shaker activations) were momentary in duration (lasting for 2 seconds or less). There were no occurrences reported in this period where a stall occurred, and no occurrences where the stick pusher activated to prevent a stall occurring. As might be expected, stall warnings happened in situations where the stall speed increased (due to a particular (and often unexpected) combination of environmental conditions and flight profile), and the buffer between the stall speed and the aircraft's airspeed reduced. The majority of reported stall warnings (81 per cent) were associated with aircraft tracks in the vicinity of thunderstorms or other turbulent regions of air, and the greatest proportion of these occurred when the aircraft was operating at an airspeed close to (or below) the minimum for the current configuration (V_{Ref}), at a bank angle greater than 20°, or when there were sudden and rapid changes in pitch angle or airspeed.

More than half of genuine stall warnings on high capacity air transport aircraft happened in visual meteorological conditions (VMC), though the most likely situation for a stall warning to occur was during cruise in instrument meteorological conditions (IMC) where turbulence and wind changes were likely. At typical cruise operating altitudes and weights there is often a narrow band (about 20 knots) between the maximum operating speed and the stall warning speed (which is generally 20 per cent higher than the aircraft's stall speed, V_s). The difference between the aircraft's optimum cruise speed and the stall warning speed is even less, and turbulence can cause airspeed variations of more than 10 kts. In about one-fifth of these occurrences, the stall warning system was activated when the autopilot tried to correct the aircraft's speed or flight path due to a disturbance. Stall warnings that occurred in VMC were more likely to occur on approach and landing than in cruise, and were also associated with turbulence and airspeed fluctuations. However, there were more than a few cases identified where the flight crew allowed the airspeed to bleed off too much on approach and fall below the stall warning activation speed. Sometimes, this was due to a wind change in turbulent conditions, but in other cases it was due to increased workload on approach or task distraction (such as monitoring for traffic).

Very few stall warnings reported to the ATSB involving high capacity air transport aircraft indicated a credible risk of a stall, loss of control or an accident. There were some common themes identified in investigations of genuine stall warning incidents by the ATSB that increased safety risk — stall warnings that happened on approach, when aircraft were in a low speed, high angle of attack configuration, and situations where the aircraft's stall warning speed was higher than normal (due to a higher wing loading (g) factor in a turn, or an incorrect reference speed switch setting).

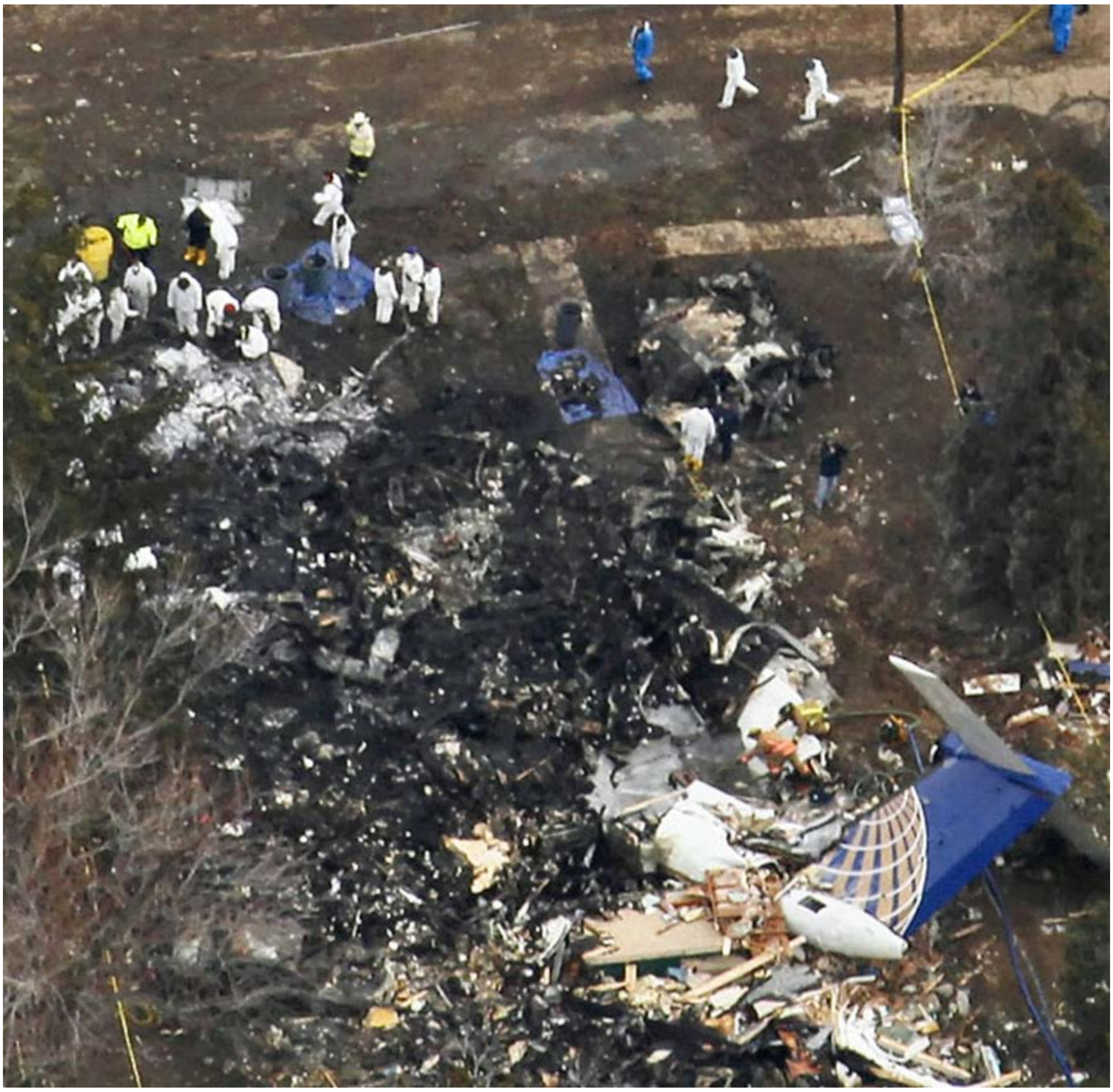
Appendix A

Worst case scenario – loss of control on approach after inappropriate stall management

The occurrence

In February 2009, a Bombardier Q400 aircraft experienced a loss of control on an instrument landing system (ILS) approach to Buffalo-Niagara International Airport in the United States, and collided with terrain in a residential area 5 nm northeast of the airport (Figure 8). The two pilots, two cabin crew, and 45 passengers aboard the aircraft were killed, one person on the ground was killed, and the aircraft was destroyed by impact forces and a post-impact fire.

Figure 8: Accident site following collision with terrain, Clarence Center, New York



Source: All Things Aviation.com

Following a typical flight, a night-time descent into Buffalo was conducted under night visual meteorological conditions (night VMC) in icing conditions with reported snow at Buffalo. The aircraft was configured for a planned ‘flaps 15’ landing (15° flap angle) following the ILS approach. The planned reference landing speed (V_{Ref}), however, was not calculated for an aircraft configured for flight in icing conditions, resulting in a V_{Ref} that was 20 kts lower than appropriate for the icing conditions. As the aircraft descended through 10,000 ft under autopilot control, the pilots were required to maintain sterile cockpit conditions.[13]

During the descent, the pilots began several conversations unrelated to their flying duties, one of which indicated that the first officer had little experience flying in icing conditions. Although the aircraft's propeller, pitot–static, and airframe de-icing systems were turned on throughout the flight, the captain and first officer observed noticeable ice accretion on the windshield and on the leading edge of the wing.

The aircraft reached a pre-selected altitude of 2,300 ft and was travelling at 180 kts, at which point the pilot selected 5° of flaps, and air traffic control provided manoeuvring instructions to establish the aircraft on the localiser for the ILS approach. The captain began to slow the aeroplane down to establish the appropriate approach speed, reducing engine power, deploying the landing gear, and adjusting propeller pitch. The autopilot also set the pitch trim to nose-up, slowing the aircraft to 145 kts.

As the aircraft's speed decreased, the autopilot added more nose-up pitch trim, and an 'ice detected' warning message appeared on the engine display in the cockpit. The flaps were then set to 10°, and the 'before landing checklist' was carried out. At this point, the aircraft was in a nose-up attitude, and the airspeed was about 135 kts. A few seconds later, the aircraft's stick shaker activated, and the autopilot disconnected. The flight crew applied power, but as power was increasing, the aeroplane pitched up, rolled 45° to the left, and then rolled to the right.

As the aeroplane rolled to the right through wings level, the stick pusher system activated to decrease angle of attack. The first officer retracted the flaps, and the aircraft continued to roll to the right, reaching an angle of 105° right wing down before the aircraft rolled back to the left. The stick pusher activated a second time. The aircraft's airspeed had reduced to about 100 kts.

The aircraft continued to roll to the left and right, and was in an attitude of 25° nose down and 100° right wing down when the aircraft entered a steep descent. The stick pusher activated for a third time, before the aircraft collided with terrain.

The investigation

The investigation into this accident by the US National Transportation Safety Board (NTSB) found that a series of aspects contributed to the accident. While not explored here, these included pilot fatigue, crew rostering and rest arrangements, and observation of the sterile cockpit rule when in critical, high workload phases of flight. One aspect of the NTSB investigation was a review of the pilot's training for flying in icing conditions and in situations where a stall could have developed.

A post-accident survey was also conducted by the NTSB of pilots operating into Buffalo at the time of the accident. The survey results indicated that most pilots were not surprised by the icing conditions and did not consider them to be significant.

Analysis of the accident sequence and flight data recorders suggested that when the stick shaker activated for the first time, the aircraft was not close to stalling. Because the flight crew had set the aircraft's stall reference speeds switch to the increase (icing conditions) position, the stall warning occurred at an indicated airspeed 15 kts higher than would be expected for a Q400 aircraft in a clean (non-icing) configuration. As a result of the stall reference speed switch, the flight crew had a 20 to 22 kt warning of a potential stall.

In addition, the NTSB found that the Q400 aircraft had other stall warning systems that gave both pilots several indications that a stall was likely to occur, and provided adequate time to respond with corrective action. These included a low-speed cue, an airspeed trend indicator, and numbers that changed colour on the indicated airspeed display, though a supplementary aural warning of

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[13] Sterile cockpit conditions refer to procedures that limit all flight crew activities, including conversations, to be strictly confined with the operation of the aircraft.

imminent stick shaker activation was not a feature of the aircraft. The investigation could not determine why neither the captain nor first officer responded to the presence of these cues.

When the stick shaker activated and the autopilot disconnected, the captain responded inappropriately by pulling back on the control column, which resulted in the aeroplane nose pitching upwards, and the angle of attack increasing to 13°. The airspeed slowed to 125 kts, but the nose-up attitude of the aircraft meant that the speed at which a stall would occur increased. The airflow over the wing separated as the aircraft's angle of attack exceeded the critical angle, and the aircraft entered a left-wing-down roll despite opposing control inputs. During each subsequent activation of the stick pusher, the flight data recorder showed that the captain pulled back on the control column. This prevented the stick pusher system from lowering the aircraft's nose, compounding the stall and causing a loss of control.

The NTSB concluded that there was minimal aircraft performance degradation due to the icing conditions, and that the captain's inappropriate aft control column inputs in response to the stick pusher caused the aeroplane's wing to stall, and made subsequent actions ineffective at regaining control of the aircraft. Several actions by both the captain and the first officer, such as the raising of the flaps and application of increased engine power, were not conducted as required by the operator's procedures for responding to a stall warning.

The pilots had previously conducted simulated stall recovery training with the operator, and the operator had also provided training for winter operations (including the effects of icing on aircraft stability and control).

Prior to the accident, the operator had shown a training video that was presented in the operator's winter operations training. The purpose of the video was to review icing fundamentals, and to enhance pilot knowledge on the effects of icing on aircraft stability and control, and both the captain and the first officer had seen this video during initial and recurrent ground school. This video indicated that the technique for recovering from wing stalls was to lower the nose by pushing forward on the control column, add power, and maintain flap setting. The video also discussed the possibility of a tailplane stall, which can result from ice accretion on the horizontal stabiliser. Warning signs of a tailplane stall included light-feeling controls, pitch excursions and difficulty in trimming pitch, buffeting, and sudden nose-down pitching. It indicated that the technique for recovering from a tailplane stall was to raise the nose by pulling back on the control column, reduce flap setting, and in some aircraft to reduce power.

This video suggested that the differences between a wing stall and a tailplane stall were subtle, and that pilots needed to properly diagnose the icing problem because application of the wrong recovery technique could compound the stall. While the NTSB investigation found (through evidence provided from aircraft flight testing) that the Q400 aircraft was not susceptible to tailplane stalls, the operator did not have a procedure for tailplane stalls or provide tailplane stall training for the Q400. Post-accident interviews with other Q400 pilots at the operator about tailplane stalls produced varying responses, with some pilots indicating that the video had had a 'big impact' on their thoughts about stall recovery techniques. Other pilots were uncertain about the susceptibility of the Q400 to tailplane stalls, and others stated that it would be difficult to differentiate between a wing stall and a tailplane stall.

While the investigation found that the captain's actions to respond to the stick shaker were unlikely to have been a misdiagnosis that a tailplane stall had occurred, and it was unlikely that he was trying to perform a tailplane stall recovery, it was possible that the first officer's action to retract the flaps may have been a misinterpretation of the event as a tailplane stall. The first officer had seen the training video less than one month before the accident. Other possibilities for the first officer's actions, such as her general aviation experience in which stall recoveries were not crew-coordinated manoeuvres, were considered in the investigation, but it could not be conclusively determined why the first officer retracted the flaps after the first stick shaker warning.

If the captain had not overridden the stick pusher’s action to decrease the angle of attack, then the pusher would have forced the nose of the aeroplane downward. In addition, had the captain responded appropriately to this nose-down input, the aeroplane might have recovered flying speed in sufficient time to avoid the impact. However, the raising of the flaps, in addition to the vertical loading at the time, increased the stall speed. This reduced the potential of the wings to produce lift, and would have made it more difficult for the pilot to recover from the loss of control at a time when the aeroplane was already stalled (NTSB, 2010).

Sources and submissions

Sources of information

The sources of information during the investigation included:

- the ATSB aviation occurrence database
- ATSB investigation reports
- Aircraft accident investigation reports from the following international agencies:
  - National Transportation Safety Board of the United States (NTSB)

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Australian Transport Safety Bureau

The Australian Transport Safety Bureau (ATSB) is an independent Commonwealth Government statutory agency. The Bureau 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 fare-paying passenger operations.

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 safety factors related to the transport safety matter being investigated. The terms the ATSB uses to refer to key safety and risk concepts are set out in the next section: Terminology Used in this Report.

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.

Reference speed: also referred to as V_{Ref}, the landing or final approach speed of an aircraft. It is often used operationally as the minimum airspeed of an aircraft in other phases of flight in a particular configuration. It is generally 30 per cent higher than the aircraft's stall speed.

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.

Stall speed: also referred to as V_S, the minimum steady flight speed in specific conditions and in specific aircraft configurations at which an aircraft is still controllable.

Stick shaker: part of the stall warning that involves the pilots' control columns vibrating.

Stall warning: the activation of an aircraft's automated stall warning system, usually comprising of an aural tone and control column/stick shaker activating on air transport aircraft.

Stall warning speed: also referred to as V_{sw}, the activation speed for an aircraft's automated stall warning system, usually comprising of an aural tone and control column/stick shaker activating on air transport aircraft. It is below the reference speed (V_{Ref}) in normal flight profiles, aircraft configurations and environmental conditions, but is always above the stall speed (V_S).

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Research

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