Erroneous takeoff performance:

Why the past is still highly relevant today

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Introduction

On the 21st July 2017, a Boeing 737-800 with 179 passengers and 6 crew onboard took off from Belfast for Corfu with the incorrect thrust set and struck an approach light for the reciprocal runway (1). The damaged light was 36 centimetres high and situated 29 metres beyond the end of the takeoff runway, itself 2.6 kilometres long, and ample for operation of the Boeing.

Figure 1 – The damaged approach light

The crew realised as the aircraft's speed approached V_r during the takeoff roll that they were not accelerating as expected but did not recognise the reason for the shortfall in aircraft performance. After the aircraft became airborne it climbed away very slowly and it was only when 4 kilometres from the end of the runway that full thrust was applied by the crew.

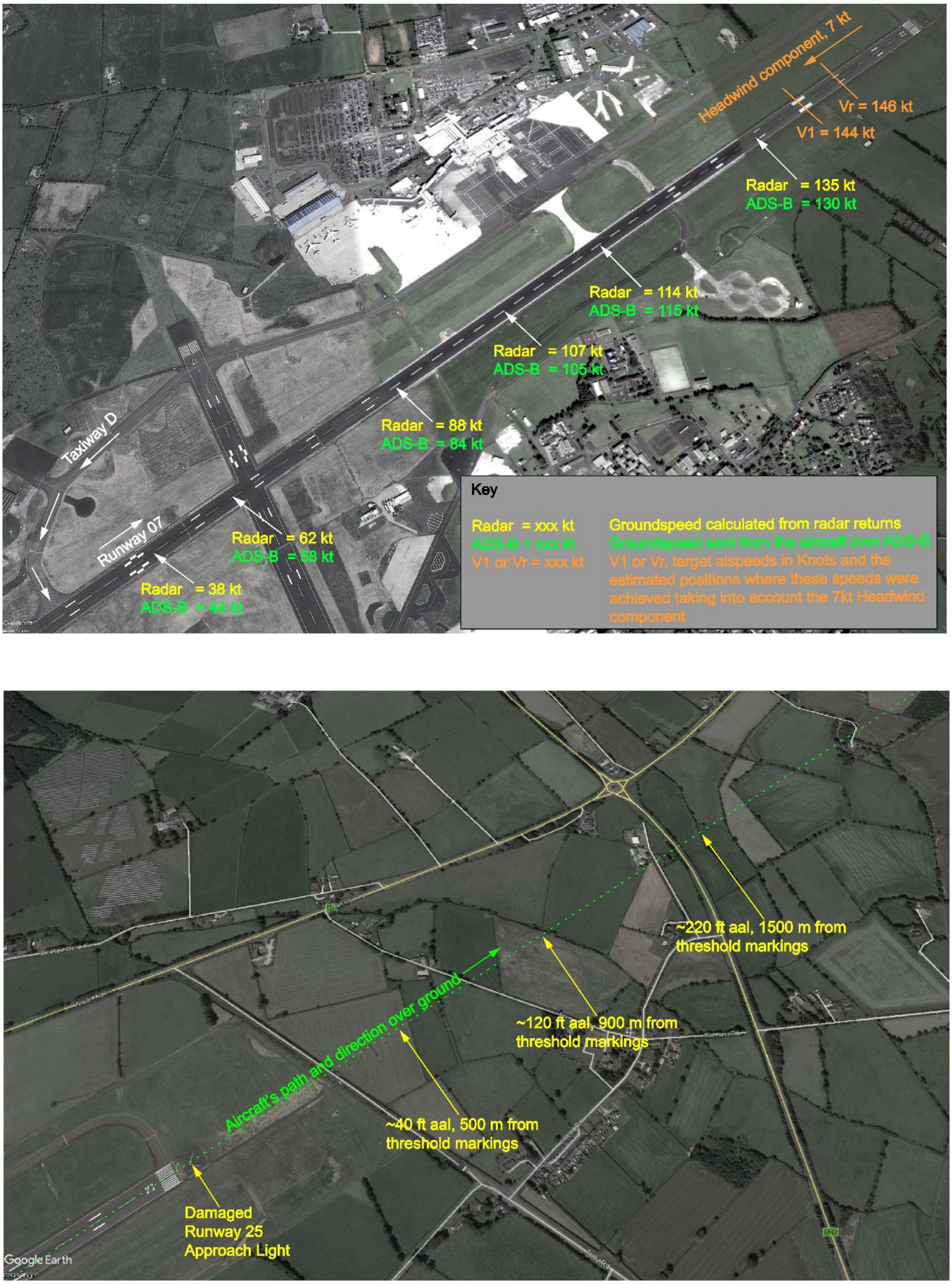

Figure 2 - The takeoff roll, showing groundspeeds and the estimated point where V_1 and V_r were attained, and initial climb

Although there was no damage to the aircraft, it was the benign nature of the runway clearway, a lack of obstacles in the climb-out path and the absence of significant terrain surrounding the airport that allowed the aircraft to climb away without further collision after it had struck the light. Had an engine failed beyond V_1 the consequences would certainly have been catastrophic with the manufacturer's own modelling confirming a negative climb gradient in this condition.

However, despite the severity and potential consequences of these occurrences, these events continue to occur. A review of notifications received by the AAIB since 2018, representing just one state investigation agency within Europe, includes 6 reports from commercial carriers where erroneous data had been used for takeoff; 3 of these events have happened in the first half of 2019.

It is likely that these numbers underestimate the true scale of the issue, especially when the performance degradation is subtle, or when erroneous data leads to an increase in performance because the occurrence may go unnoticed and, even if it is noted, not all cases are reported.

In the July 2017 occurrence, there were multiple barriers intended to prevent erroneous data from being used at takeoff - such as Standard Operating Procedures (SOPs) which included the cross-checking of data - but these were procedural, human-based, barriers which ultimately proved ineffective.

Past takeoff performance events, such as the loss of MK Airlines flight 1602 (2), provide further evidence of the fragility of human performed cross-checks and SOPs. These events prove "Why the past is still highly relevant today" because, despite rapid advancements in technology and an idea, which was first contemplated in the 1970s, for a technological solution to monitor takeoff acceleration we are still predominantly reliant on humans to identify data entry errors.

Figure 3 - The remains of the main fuselage and number 4 engine from MK Airlines flight 1602

However, as technology has evolved in recent years, the AAIB has repeatedly called for a technological solution to monitor takeoff acceleration.

This paper therefore briefly explores the cause of the July 2017 event, discusses the barriers that were intended to pick up on the erroneous data entry, and covers other events where similar barriers have failed to detect erroneous entries, before summarising a basic takeoff acceleration monitoring system and the effect this would have had on the July 2017 event.

The 21st July 2017 event

The AAIB investigation found that a thrust setting of approximately 81.5% N_1 was used for takeoff instead of the correct setting of 92.7% N_1.

This was because an extremely low outside air temperature had been entered into the Flight Management Computer (FMC) instead of the actual OAT of 16°C. Another entry used by the FMC, to optimise the flight profile, is the ambient temperature at the top of climb and it is this figure which the investigation believes was mistakenly entered from the flight plan.

The FMC uses the OAT to calculate the value of N_1 which will produce the engine's rated thrust. Given a lower OAT, the engine will require a lower value of N_1 to achieve the engine's rated thrust. Therefore, by entering an incorrect and abnormally low OAT, the FMC calculated a value of N_1 that was significantly below that expected for the environmental conditions on the 21st July 2017.

A company engineer, who was travelling with the aircraft on the flightdeck jumpseat, took the photo prior to the aircraft leaving the stand at Belfast.

Figure 4 - The cockpit before first leaving the stand

This shows a target N_1 of 88.2% (in green text at the top of the engine gauges), prior to the application of any engine derate, which could only be achieved by the OAT entry shown in the FMC photo below.

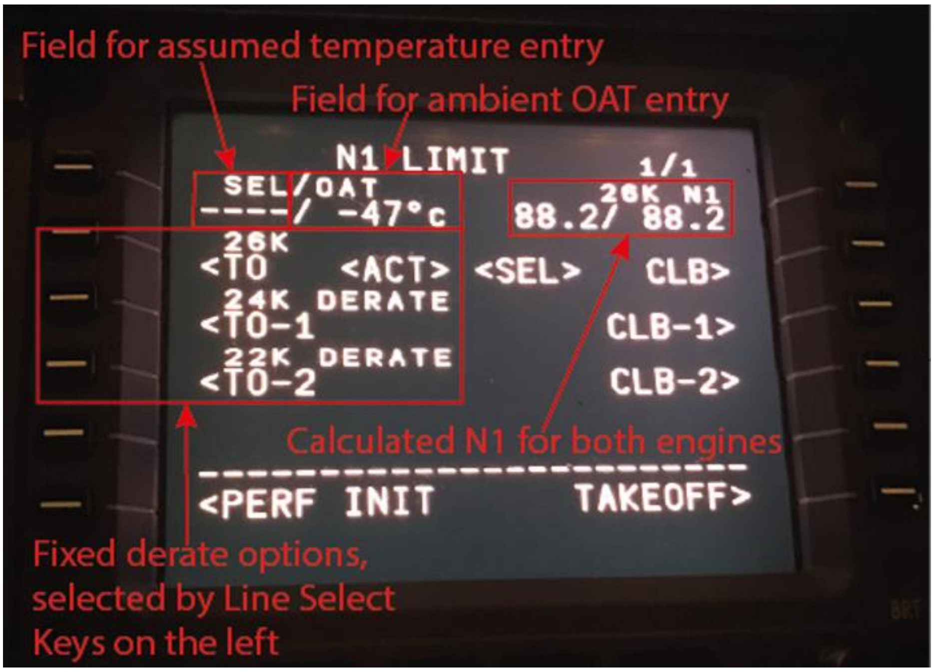

Figure 5 - The FMC engine derate page

However, this doesn't fully explain how an N_1 of 81.5% was used for the takeoff. One way on the Boeing 737-800 of reducing the takeoff thrust to the minimum required for takeoff, which is common airline practice used to conserve engine life and reduce maintenance costs, is by entering a higher than ambient temperature called an assumed temperature into the 'SEL' (for SELected temperature) field of the FMC. The assumed temperature method, as it is known was regularly used by this airline, and the crew having correctly calculated this temperature entered it into the FMC, which resulted in the target N_1 changing to 81.5% for the takeoff.

SOPs and Cross-checks as barriers?

The crew, who had both been off-duty the day before the flight, said that they were well rested and had only completed 2 hours and 26 minutes of duty time at the time of departure. Both pilots had also worked together before and knew each other.

The pilots were required to use their own Electronic Flight Bag (EFB), having obtained the latest airport weather, to calculate takeoff reference speeds and the assumed temperature for setting the engine derate. This required the crew to enter an OAT, along with aircraft and other environmental data.

This was performed twice, as the aircraft returned to stand for a nosewheel change as damage was noticed during the first pushback, and during this time the OAT had changed, however, a review of the crew's EFBs showed that both sets of calculations were completed correctly.

It is worth stating here that the calculation performed after the nosewheel had been changed was because of a 1°C change in OAT, which had a negligible effect on the aircraft's performance, but nevertheless increased the opportunity to make an error. In aviation, the use of SOPs which lay down the exact procedure, and even the phraseology to be used, are designed to reduce the chance of making errors but they cannot cover for all eventualities as this example shows.

The EFB values were then transposed into the FMC and cross-checked, a process embedded within a SOP designed to trap errors that have already been made, but neither crew noticed that the OAT was incorrect either the first time that the aircraft left the stand nor the second time after the nosewheel change. This is possibly because the Canadian crew, who regularly operated in the cold Canadian winters, were used to seeing low OATs and low N_1 targets on the FMC and engine gauges.

Another serious incident recently investigated by the Japanese Transport Safety Board illustrates a case where predisposition also played a part. This example involved the crew of a Boeing 747-800 freighter who were expecting a departure from Runway 16R at Tokyo (3). This was largely because of the much shorter taxi route from where the aircraft was positioned to Runway 16R, than to Runway 16L, but also because of an airport operational policy that stipulated Runway 16R would normally be in use at the time of departure. In this incident, the commander thought that, even if clearance was given to depart from Runway 16L, the lengthy taxi route would give the crew time to reprogramming the FMC correctly. However, when the clearance to depart from Runway 16L was given, the lengthy taxi which was also somewhat more complicated than anticipated meant that the crew performed their cross-checks but both pilots failed to notice that, although the departure runway was changed in the FMC, the original engine derate remained selected. The result was that the aircraft passed the end of the runway at 16ft and the aircraft's jet blast disabled an airport intrusion detection sensor situated some 450m south of the airport. An N_1 of 89.1% had been used rather than the required N_1 of 97.2%.

Another event reported to the AAIB in 2019 relates to the incorrect selection of departure runway in the FMC but in this case the incorrect selection was also used for performance planning purposes. However, the selection of FMC departure runway was for a shorter runway than actually used for the departure which resulted in an increase in takeoff performance. Another operator had also reported a comparable error that had been made, involving the same aircraft type, only a few months earlier. In both cases, SOPs and cross-checks designed to detect such anomalies failed to mitigate the error.

A factor which hinders the cross-checking process is significant differences between the presentation of information, whether these are on computer displays, or on paper such as a loadsheet. In the AAIB investigation into the July 2017 event, it was established that the layout of the entry page for engine derate information on the FMC (see Figure 5) bears little similarity to the layout of the EFB calculation results page shown below. Not only does this hinder any cross-check but also the transposition of data from one presentation to another.

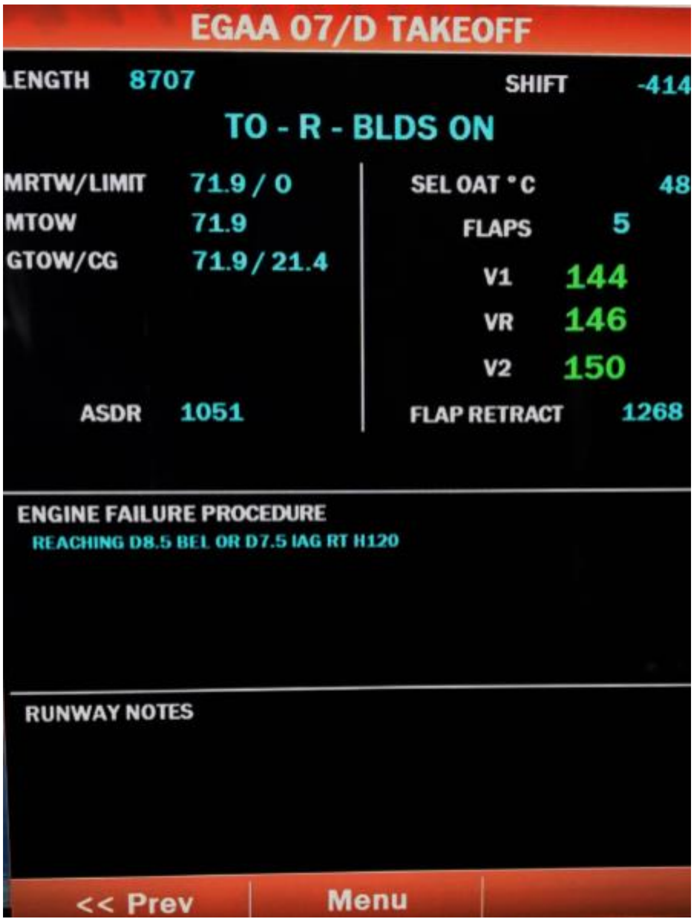

Figure 6 - EFB Calculation results page

For instance, the OAT, pertinent information on which the engines' thrust is based and a required entry on the FMC page, is absent from the EFB results page but instead is entered on a previous screen no longer visible to the crew. The nomenclature used on the EFB also differs with the assumed temperature on the EFB labelled 'SEL OAT' whereas on the FMC there are separate fields for the two, distinctly different, variables 'SEL' and 'OAT'. As all FMC derate data leads to a thrust setting, expressed as an N_1 value and shown on the FMC, you might think that this vital information should be displayed on the EFB, but this is also absent on the results page.

EFBs are not regulated instead approval of an EFB is typically undertaken by the regulator's Flight Operations department who, as was the case, with the AAIB's investigation, review the EFB and the installed applications against their own Acceptable Means of Compliance or Advisory Circulars; guidance documents not standards (4). This document did not define the content or layout of the displayed information, other than that the use of colour and entry methods should be consistent, even for safety critical applications such as weight and balance or performance computations but rather talked about the mounting of an EFB, connections to the aircraft and the need not to interfere with other aircraft systems.

From all the examples discussed above, SOPs and cross-checks as barriers to a takeoff performance event, though generally effective, are often weakened by poor equipment design and rely upon well-rested crews and the highest level of attention, even though such checks are carried out many times during a typical duty day.

A technological solution

The loss of a McDonnell Douglas DC-8 at Anchorage in 1970 (5), an accident attributed to braking pressure being applied to the wheels during takeoff, and shortly after a takeoff accident to a Boeing 747 at San Francisco in 1971 (6) that used incorrect takeoff reference speeds significantly raised industry awareness of takeoff performance issues.

During 1971, these events led to the Flight Operations Committee of the Air Transport Association of America to consider the use of existing onboard equipment to assist pilots in judging aircraft acceleration towards V_1. This rational, incorporating the use of technology, followed on from the DC-8 crash when the National Transportation Safety Board made a safety recommendation which suggested that: ‘The Federal Aviation Administration determine and implement takeoff procedures that will provide the Flightcrew with time of distance reference to appraise the aircraft’s acceleration to the V_1 speed’.

Fearing the reliability of such a system and the risk of an increased number of high speed aborted takeoffs this idea was subsequently discounted until 1982 when a McDonnell Douglas DC-10 crashed at Boston (7). The FAA was then requested to: ‘Convene an industry-government group which includes the National Aeronautics and Space Administration to define a program for the development of a reliable takeoff acceleration monitoring system’.

This was done, resulting in the publication of a technical standard, and several academic and government institutions carried out active research in the area until around 2009. Several promising ideas were trialled during this time and generally were met with promising feedback. However, despite first contemplating using technology to solve erroneous takeoff performance in 1971, no certified product – other than for some Airbus aircraft - is available today. Yet still several state investigation agencies continue to investigate occurrences that have involved severely compromised takeoff performance, including the crash of MK Airlines flight 1602.

During the AAIB's investigation into the July 2017 event an online article was discovered from 2014 that discussed a simple takeoff acceleration monitoring system. The premise of the system was simple; to monitor the aircraft's longitudinal acceleration, once thrust had been set and as the aircraft accelerated, but to warn the crew at a speed well below V_1, where the risk in stopping is low, if the acceleration was less than a predetermined value.

This took advantage of the fact that derated thrust takeoffs have a normalising effect on the rate of acceleration on takeoff. This is illustrated in the histogram below which shows approximately 73,500 departures for a Boeing 737-800, across a weight range that covers 93% of the aircraft's operating weight range, and a wide range of climatic conditions.

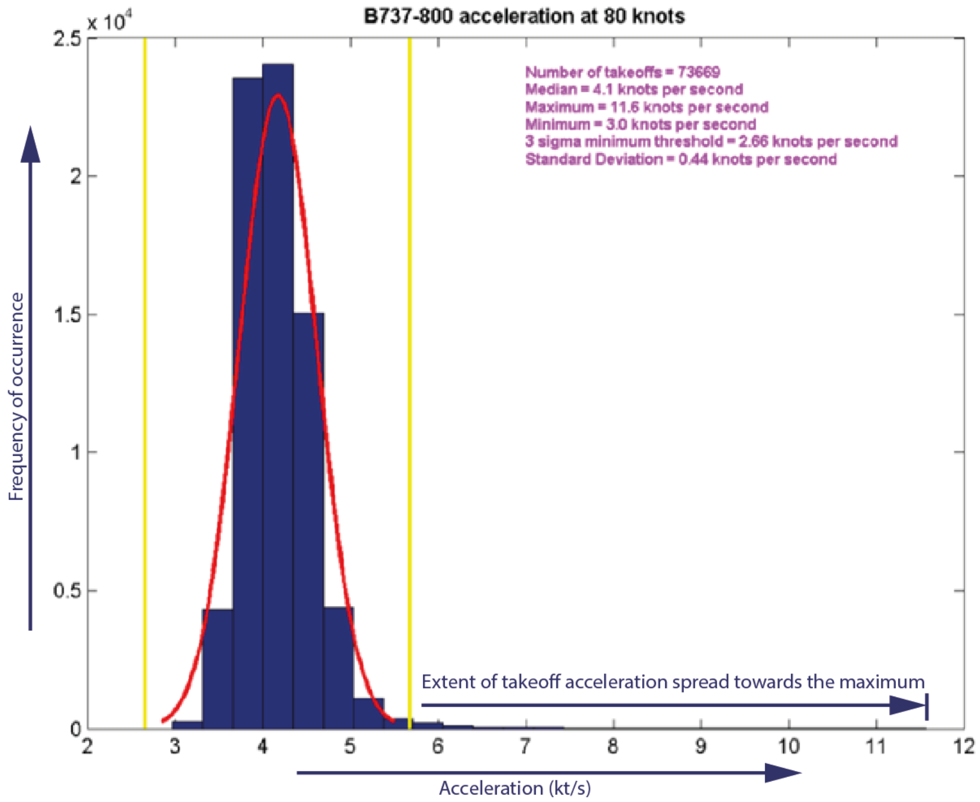

Figure 7 - Acceleration histogram of 73,669 Boeing 737-800 departures

Across all departures, the data showed a Standard Deviation in acceleration of only 0.44 knots per second with the median acceleration being 4.1 knots per second. Any skew in acceleration also tended to be in favour of higher accelerations, rather than lower values, meaning any system proposed to detect cases of poor acceleration would benefit. Plotting the same data set but this time against runway length, shown below, also shows this skew and that a 'best fit' line of minimum acceleration required for takeoff could be drawn.

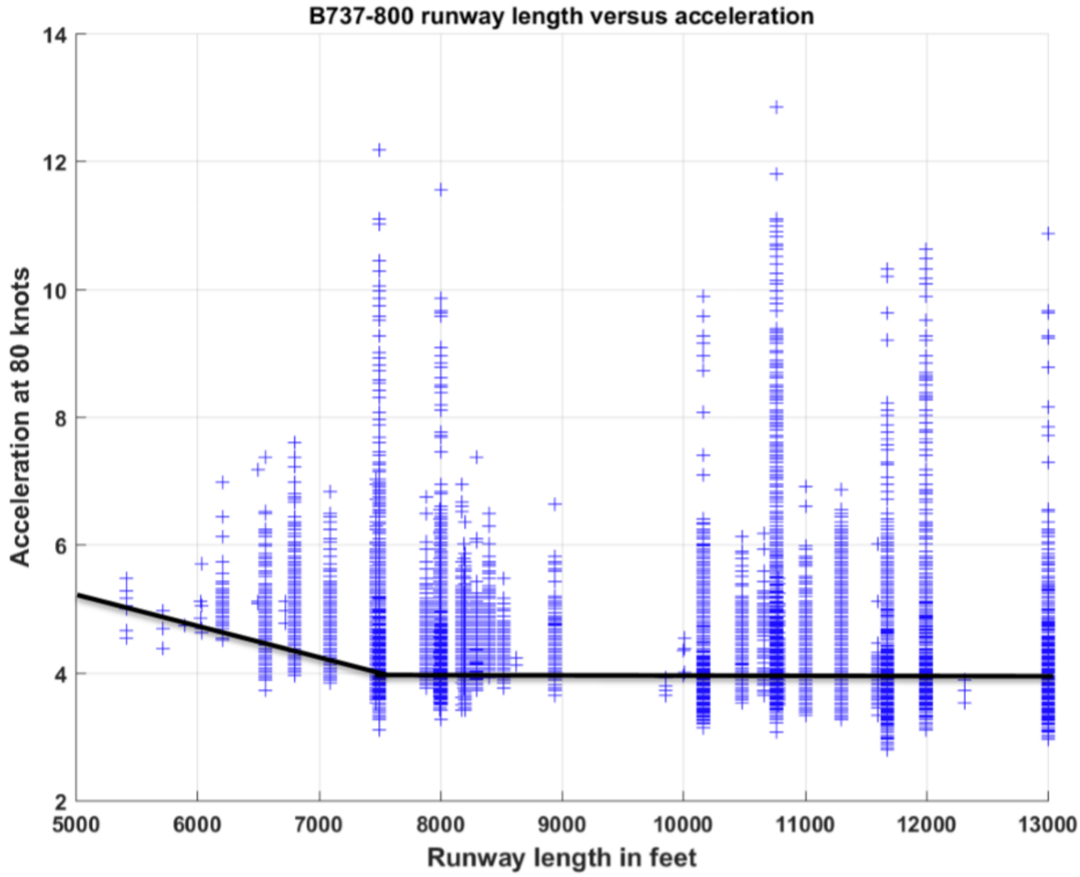

Figure 8 - Acceleration rate against runway length for 73,669 Boeing 737-800 departures

This confirmed that the minimum acceleration required remained constant for most runway lengths, but an increase was noted as the runway length becomes the limiting factor.

The manufacturer compared the Boeing 737 data with a dataset for the Boeing 777 covering 60,445 departures from 87 worldwide airports to see if these findings would remain true. This data covered airport elevations between sea level and 5,600ft above sea level, as well as ambient temperatures on takeoff of between -27 and 49°C. The results mirrored the Boeing 737 data, with very low Standard Deviations in acceleration, further confirming the normalising effect of derated takeoffs and a second study on Boeing 747 aircraft also reached the same conclusion.

One main advantage of this system is the lack of reliance on any crew entered data removing the human fallibility concern regarding SOPs and cross-checks which were noted above. However, the biggest advantage of this system is that the software required to perform the acceleration check can be embedded in the aircraft's Terrain Awareness and Warning System – a system that is required to be fitted to all large commercial aircraft.

To prove the effect this system would have had on the July 2017 event the AAIB used a simulator set-up with the correct loading, aircraft configuration and environmental parameters and set an N_1 of 81.5% to reflect the actual takeoff conditions. At 75kt the system identified that the acceleration was falling below the level of acceleration needed for the length of runway, established from the 737-800 dataset above, and issued an alert. <u>The takeoff was rejected and after the simulator had come to a stop a further 1,670 metres of runway remained ahead – a very different outcome to the same event.</u>

A similar technological solution has also been developed by Airbus, called Takeoff Monitoring, and this is available on later A380s and is under development for the A350. However, the AAIB is not aware of any other aircraft manufacturer that has either developed, or is developing, a comparable system.

In conclusion

Takeoff performance events continue to occur, as the numbers of notifications to the AAIB alone for this year to date shows, however, the true scale of the problem is hard to establish as cases are not always noticed nor reported. It is likely that these numbers therefore reflect only the "tip of the iceberg".

Barriers performed by humans, such as SOPs and cross-checks, are reliant on well rested crews and the highest level of attention to detail. Often, these barriers are weakened by poor equipment design and a lack of guidance, however, technological solutions already exist or are in active development that could be installed. Further, as this technology can be retrofitted within systems that are already mandated on large commercial aircraft, a greater benefit in safety could be realised.

This is especially true as past events have shown that takeoff performance events are not new and that any strengthening of procedural checks will not necessarily stop these events from occurring again. A technological solution reliant on minimal, or no, manual data entry could offer a realistic way to identify erroneous takeoff performance and lower this risk.

References

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