AIRCRAFT ACCIDENT REPORT 6/2007

Air Accidents Investigation Branch

Department for Transport

Report on the accident to Airbus A320-211, registration JY-JAR at Leeds Bradford Airport on 18 May 2005

This investigation was carried out in accordance with
The Civil Aviation (Investigation of Air Accidents and Incidents) Regulations 1996

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Department for Transport
Air Accidents Investigation Branch
Farnborough House
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November 2007

The Right Honourable Ruth Kelly
Secretary of State for Transport

Dear Secretary of State

I have the honour to submit the report by Mr A P Simmons, an Inspector of Air Accidents, on the circumstances of the accident to Airbus A320-211, registration JY-JAR at Leeds Bradford Airport on 18 May 2005.

Yours sincerely

David King
Chief Inspector of Air Accidents

Contents

Appendices

GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB	Air Accidents Investigation Branch
ABCU	Alternate Brake Control Unit
ADIRU	Air Data and Inertial Reference Unit
aal	above aerodrome level
agl	above ground level
AIP	Aeronautical Information Publication (or Package)
amsl	above mean sea level
A/SKID	Anti-skid
BDDV	Brake Dual Distribution Valve
BITE	Built-In Test Equipment
BSCU	Brake and Steering Control Unit
CAA	Civil Aviation Authority
CG	Centre of Gravity
CIAIAC	Comisión de Investigatión de Accidentes e Incidentes de Aviaçion Civil
COM	Command
CVR	Cockpit Voice Recorder
DGAC	Direction Générale de l'Aviation Civile
dt	Time Increment
EASA	European Aviation Safety Agency
ECAM	Electronic Centralised Aircraft Monitor
EM^2	Enhanced Maintenance and Manufacturability
FCOM	Flight Crew Operating Manual
FDR	Flight Data Recorder
FMEA	Failure Modes and Effects Analysis
ft	feet
g	normal acceleration
hPA	hectopascal
hr(s)	hour(s)
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
JAR	Joint Aviation Requirements
kg	kilogram(s)
KIAS	Knots Indicated Airspeed
km	kilometre
kt	knot(s)
LBA	Leeds Bradford Airport
LO	Low
m	metre(s)
mA	milliampere
LDA	Landing Distance Available
MAX	Maximum
MED	Medium
MLG	Main Landing Gear
mm	millimetre
MMEL	Master Minimum Equipment List
MON	Monitoring
m/s	metre/second
MSN	Manufacturer's Serial Number
N_1	Engine low pressure spool rotational speed
NLG	Nose Landing Gear
nm	nautical miles
N/W STRG	Nosewheel Steering
OBRM	On-Board Replaceable Module
psig	pounds per square inch (gauge)
QNH	pressure setting to indicate elevation above mean sea level
TDZ	Touchdown Zone
TPIS	Tyre Pressure Indicating System
VAP	visual aids panel
V_{cons}	$V_{consigne}$, ie Command Speed
V_r	V_{roue}, ie Filtered Wheel Speed
V_{ref}	Reference Speed
V_x	Computed Groundspeed
ºC	Degrees celsius
ºM	Degrees magnetic

Air Accidents Investigation Branch

Aircraft Accident Report No: 6/2007 (EW/C2005/05/03)

Registered Owner and Operator:	Jordan Aviation, Hashemite Kingdom of Jordan
Aircraft Type:	Airbus A320-211
Nationality:	Jordanian
Registration:	JY-JAR
Place of Accident:	Leeds Bradford International Airport, UK
Date and Time:	18 May 2005 at 1143 hrs All times in this report are UTC unless otherwise stated

Synopsis

The accident was notified to the Air Accidents Investigation Branch (AAIB) by Air Traffic Control at Leeds Bradford International Airport at 1155 hrs on 18 May 2005. The following Inspectors participated in the investigation:

Mr J J Barnett	Investigator-in-Charge (until 30 April 2007)
Mr A P Simmons	Investigator-in-Charge (from 30 April 2007)
Mr J M Firth	Operations
Mr A N Cable	Engineering
Mr J R James	Flight Recorders

While landing on Runway 14 at Leeds Bradford Airport the aircraft touched down just beyond the end of the marked touchdown zone with low autobrake selected. Manual wheel braking commenced shortly after mainwheel touchdown. At a groundspeed of around 70 kt the brakes ceased operating, for about 17 seconds. A pronounced dip in the runway surface initially prevented the pilots from seeing the runway end. When it became apparent to the commander that it would not be possible to stop before the end of the runway, he deliberately did not select alternate braking, as this would have caused loss of nosewheel steering, but instead used nosewheel steering to turn the aircraft sharply to the right. The aircraft skidded sideways and came to a halt with its nosewheels off the runway, shortly before the end of the paved surface and the start of a steep down slope.

The cause of the braking loss could not be positively established but it was consistent with the effects of excessive noise in the electrical signals from the mainwheel tachometers used to sense groundspeed. Two of the tachometer driveshafts were found bent and it was known that this encouraged a resonant condition that could cause tachometer signal errors above the groundspeed at which they would be detected by the aircraft's monitoring systems. Should the condition affect both main landing gears simultaneously, the brake control system logic could generate an erroneous aircraft reference speed, which could activate the anti-skid system and release the brakes. Fluctuation in the signal errors would prevent the system from detecting and correcting the braking loss or providing a warning to the crew.

It was found that there were a number of other known anomalies with the brake control and monitoring system that could cause either brake failure or locking of the wheels, some of which had resulted in previous incidents and accidents. The aircraft manufacturer and the Airworthiness Authority had defined and implemented corrective actions, and redesigned tachometer driveshafts and updated software intended to correct some of the faults were available, but had not been incorporated on a substantial number of aircraft, including JY-JAR. The findings raised concerns about the aircraft manufacturer's procedures intended to ensure design quality and continued airworthiness.

The investigation identified the following causal factors:

1. Excessive wheel tachometer signal noise, caused by a bent tachometer driveshaft on each main landing gear assembly, resulted in loss of braking using the Normal system.

2. Inadequate fault tolerance within the brake control system led to the sustained loss of Normal braking during the landing ground roll.

3. There was no flight deck indication of brake system malfunction, and this delayed the crew's recognition of the loss of braking.

4. There was a lack of effective action to fully rectify brake system anomalies apparent from previous incidents and accidents.

Seven Safety Recommendations were made.

1. Factual Information

1.1 History of the flight

The Jordanian registered aircraft was operating on behalf of a Spanish charter airline, carrying mostly British passengers who were returning to the UK from Fuerteventura in Spain. The aircraft had last flown two days before the accident, and its crew were adequately rested.

On the morning of the accident the aircraft departed Fuerteventura at 0735 hrs and was flown by the co-pilot on the four-hour flight to Leeds Bradford International Airport (LBA). The aircraft was radar vectored for an Instrument Landing System (ILS) approach to Runway 14. Before commencing the final approach, the flight crew selected low autobrake and briefed that idle reverse thrust would be used during the landing run in order to comply with a published noise abatement procedure requesting the use of minimum reverse on landing. The commander took control of the aircraft after it was established on final approach to Runway 14 at LBA, stating later that he did so only because neither of the pilots had landed at this airport before. The statements of the pilots plus information provided by the Flight Data Recorder (FDR) indicated that the approach was stable and that the aircraft crossed the displaced threshold at the target speed of approximately 140 KIAS.

At 1143 hrs the aircraft touched down just beyond the end of the marked Touchdown Zone (TDZ), approximately 700 m beyond the touchdown threshold and 400 m beyond the Aiming Point (Figure 1, page 5). The pilots stated that they observed normal indications of ground spoiler deployment and the selection of idle reverse thrust. The commander commenced manual (pedal) braking shortly after touchdown. A few seconds later, he considered the rate of deceleration was inadequate so he applied increased brake pedal displacement and then maximum reverse thrust. Adequate retardation was not restored. The co-pilot shared the commander's perception and firmly depressed his own brake pedals. Judging that deceleration was still inadequate, the commander ordered the co-pilot to release his brake pedals whilst he continued to apply his own. As the aircraft crested a hump in the runway about 600 m before the end of the paved surface, the commander saw the end of the runway, which hitherto had been hidden from his view, and judged that the aircraft would not stop before the end. At that point he considered selecting the alternate braking system, but knew that this would cause loss of nosewheel steering. Because of the limited runway distance remaining, he considered that the only course of action available to avoid overrunning the end of the paved surface was to turn the aircraft on to a level grassed area beside the right-hand edge of the runway. Using nosewheel steering he accomplished this manoeuvre successfully, causing the aircraft to skid sideways before it came to rest with its nosewheels on the grass.

The airfield fire and rescue service attended shortly after the aircraft came to rest. There were no indications of fire and the commander did not order an evacuation. External steps were brought to the right rear door of the aircraft and passengers began to disembark approximately 20 minutes after the aircraft had stopped. There were no injuries to the passengers or crew.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	-	-	-
Serious	-	-	-
Minor/None	7	171	

1.3 Damage to aircraft

Nose landing gear deformed.

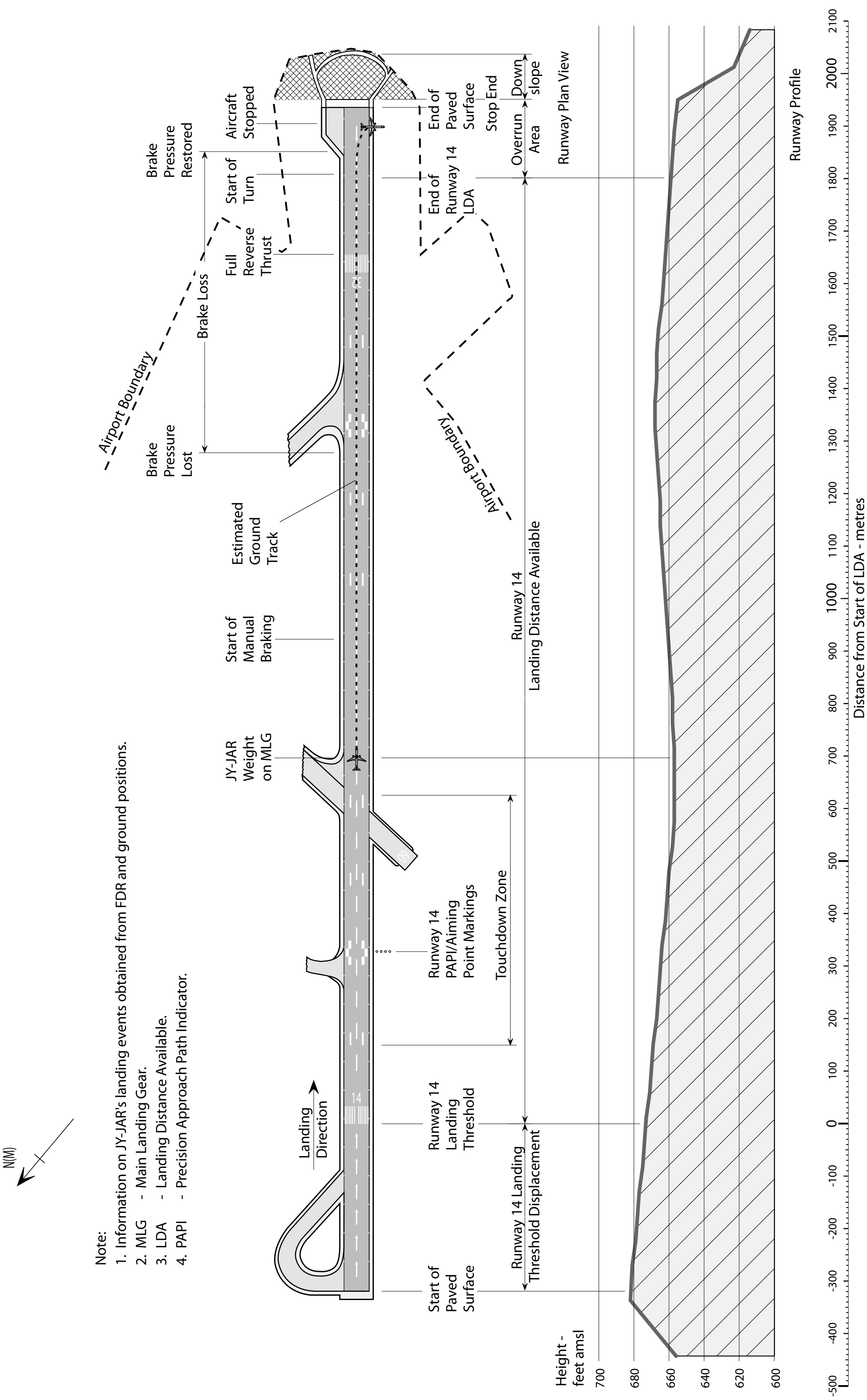
1.4 Other damage

There was minor damage to the grassed runway margin area.

1.5 Personnel information

1.5.1 Commander

Male:	Aged 43 years	
Licence:	Airline Transport Pilot’s Licence (Jordanian)	
LPC/OPC renewed:	12 February 2005	
Line check renewed:	1 December 2004	
Medical certificate:	Class 1, issued 7 February 2005 Requiring holder to wear lenses for distant vision	
Flying experience:	Total all types	12,500 hours
	Total on type	4,500 hours
	Last 90 days	190 hours
	Last 28 days	65 hours
Previous rest period:	14 hours	



Note:
1. Information on JY-JAR's landing events obtained from FDR and ground positions.
2. MLG - Main Landing Gear.
3. LDA - Landing Distance Available.
4. PAPI - Precision Approach Path Indicator.

Figure 1

Runway and Aircraft Ground Run

1.5.2 Co-pilot

Male:	Aged 28 years	
Licence:	Commercial Pilot's Licence (Jordanian)	
LPC/OPC renewed:	10 February 2005	
Line check renewed:	1 January 2005	
Medical certificate:	Class 1, issued 9 November 2004	
	Requiring holder to wear lenses for distant vision	
Flying experience:	Total all types	450 hours
	Total on type	110 hours
	Last 90 days	70 hours
	Last 28 days	25 hours
Previous rest period:	24 hours	

1.6 Aircraft information

1.6.1 General information

Manufacturer:	Airbus
Type:	A320-211
Aircraft Serial No:	234
Year of manufacture:	1991
Certificate of Registration:	Issued by the Hashemite Kingdom of Jordan on 13 January 2004
Certificate of Airworthiness:	Issued by the Hashemite Kingdom of Jordan on 13 January 2004, valid until 12 January 2006
Engines:	2 CFM56-5A3 turbofans
Total airframe hours:	28,957 hours
Total airframe cycles:	16,321 flight cycles

1.6.2 Aircraft description

The A320 is a twin-engined aircraft of conventional layout with a tricycle landing gear. The mainwheels are numbered from 1-4, from left to right across the aircraft. The systems used for retardation during the landing ground roll are ground spoilers fitted to the wings, engine thrust reversers and wheel brakes. The ground spoilers are normally set to deploy automatically on landing in order to reduce residual lift from the wings during the subsequent ground roll and thus improve the effectiveness of the wheel brakes. Thrust reversers are selected manually and wheel brake control is as described below. The A320 Type Certificate was issued by the French Direction Générale de l'Aviation Civile (DGAC).

1.6.2.1 Wheel brake and steering system

Each main landing gear (MLG) has two wheels ('mainwheels'), each fitted with a multi-disc brake. JY-JAR was fitted with radial type tyres at the time of the accident. The brakes can operate in Normal, Alternate With Anti-Skid, Alternate Without Anti-Skid, or Park Brake modes. The brakes are applied by hydraulically pressurising a number of cylinder/piston callipers on each brake unit, using the aircraft's 'green' hydraulic system in Normal mode and the 'yellow' hydraulic system, backed up by an accumulator, in Alternate and Park modes. Maximum brake pressure is 2,538 psig[1] (175 bar).

In Normal mode the pressure applied to each brake is regulated by a dual servo-valve which responds to electrical current signals. The signals are determined by a digital electronic computer, known as the Brake and Steering Control Unit (BSCU), installed in an equipment bay beneath the flight deck. For brake system operation, the BSCU responds to commands from the pilots' brake pedals or from an autobrake system, attenuated as necessary by an anti-skid function. The unit has two channels, one active and the other passive at any moment, and each channel has two lanes, one in command (COM) and the other monitoring (MON). Disagreement and fault conditions detected by the BSCU cause the channels to interchange or to deactivate. A number of different standards of BSCU software have been used (see paragraph 1.18.1); JY-JAR had Standard 9 installed.

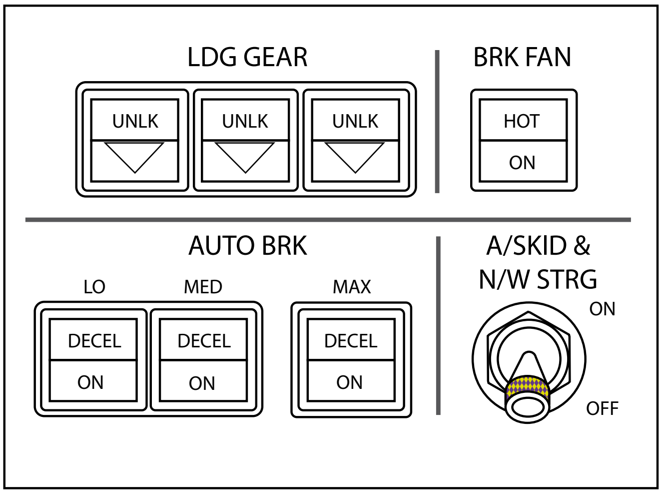


Figure 2

AutoBrake Selection and A/SKID & N/W STRG Switches

Flight deck controls consist of left and right brake pedals for each pilot, an autobrake control panel and an A/SKID & N/W STRG (Anti-skid and Nosewheel Steering) On/Off switch (Figure 2) on the forward panel and a parking brake switch on the centre console. The flight deck brake pedals drive resolvers (with a left and a right channel) that convert pedal displacement into four parallel electrical signals. In Normal braking mode these pass to the BSCU as the pilots' manual braking commands.

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[1] Pounds per square inch, gauge, ie above ambient pressure.

The autobrake system can be armed in one of three modes, LO, MED OR MAX (low, medium or maximum), by pushbuttons on the autobrake control panel. When Normal braking is active, each mode provides a target aircraft longitudinal deceleration rate on the ground without brake pedal operation. The MAX mode is not used for landing; it is armed only for takeoff to apply maximum braking automatically in the event of a rejected takeoff. LO or MED can be used for landing. In each case the mode is initiated by ground spoiler deployment and, after a certain time delay, wheel brakes are automatically and progressively applied with the aim of producing a target deceleration rate, as follows:

Autobrake Mode for Landing	**Delay seconds**	**Deceleration**		
		metre/second^2	**kt/second**	**g***
LO	4	1.7	3.3	0.17
MED	2	3.0	5.8	0.31

* g – gravitational acceleration

A green DECEL caption in the mode button illuminates when the actual deceleration rate is at or above 80% of the selected rate. All autobrake modes are deactivated if brake pedals are displaced.

In Alternate braking modes the brake pedal demands are transmitted via a hydro-mechanical system and the brakes are pressurised by the yellow hydraulic system. The detection of a fault in Normal braking causes the system to revert to the 'Alternate With Anti-skid' mode, and in this situation the BSCU continues to regulate anti-skid. If the A/SKID & N/W STRG switch is selected off, or a BSCU failure is detected, the 'Alternate Without Anti- Skid' mode becomes active and brake calliper pressure is directly proportional to brake pedal angle.

A triple gauge adjacent to the brake and steering control panel indicates the yellow accumulator pressure and, when the yellow hydraulic system is providing brake pressure, the hydraulic pressure at the left and right brake callipers. Brake pressures are not indicated in Normal mode.

Operation of the parking brake switch applies an unmodulated 2,031 psig (140 bar) pressure to the brakes for parking or emergency braking.

The nosewheel steering is also operated by the green hydraulic system and controlled by the BSCU in response to demands from each pilot's steering tiller, the rudder pedals and the autopilot. Tiller operation provides maximum nosewheel steering angles of ±75°. Switching off the A/SKID & N/W STRG switch deactivates the nosewheel steering system. The aircraft manufacturer's Master Minimum Equipment List (MMEL) permits dispatch with the nosewheel steering system inoperative.

1.6.2.2 Anti-skid system

The anti-skid system is intended to prevent the mainwheels locking by individually reducing brake pressures should tyre adhesion to the runway become marginal. The system deactivates when the aircraft's groundspeed is below 20 kt.

Groundspeed information for the BSCU is derived from four tachometers, one driven by each mainwheel, and from the aircraft's three Air Data and Inertial Reference Units (ADIRUs). The BSCU repeatedly computes a minimum allowable wheel speed (V_{cons}, the target speed) and compares this with each of the four tachometer signals. Whenever the measured speed of a wheel is below V_{cons}, an anti-skid electrical current is generated, which is subtracted from the brake demand current (see paragraph 1.6.2.1) to provide a progressive, filtered brake release signal to the respective servo-valve. If autobrake is in use, the autobrake current is fixed and the anti-skid current is subtracted.

V_{cons} is computed by the BSCU from a reference speed (V_{ref}), intended to closely approximate to the aircraft's actual groundspeed (see paragraph 1.6.2.4). The available braking effort is maximised by allowing a degree of slippage of the wheel (ie wheel groundspeed less than aircraft groundspeed). Thus it is arranged for V_{cons} to be less than V_{ref} by a small percentage, varying as a function of groundspeed.

1.6.2.3 Brake system monitoring

The aircraft incorporates Built-In Test Equipment (BITE) that automatically checks many system signals for faults and passes information on any faults found to a Central Fault Display System for recording. Faults are classified as:

Class 1 - Generally indicated to the crew during flight (but some fault indications are inhibited during certain flight phases).

Class 2 - Available to the crew on request on the ground.

Class 3 - Available for maintenance personnel on request on the ground.

The Flight Crew Operating Manual (FCOM) specifies a number of Class 1 messages as '*For Crew Awareness only*' with no action required.

The monitoring system checks the braking system tachometer circuits for continuity. It also checks tachometer signals during each takeoff run by comparing each of the signals with a filtered wheel speed, V_r (see paragraph 1.6.2.4), at groundspeeds of 15-20 m/s (29-39 kt) and 20-25 m/s (39-49 kt).

The monitoring system is intended to record a '*Total Loss of Braking*' event if all anti-skid currents exceed a threshold value and all brake pressures are below a threshold value for more than a certain period while a braking command is present. The monitoring is arranged in three steps. For the BSCU Standard 9 software the thresholds are 23 milliamperes (mA) anti-skid current and 21 bar brake pressure, effectively corresponding to all brakes fully released, for more than 2 seconds. This event, known as a 'Failure 87', is categorised as Class 3 and therefore, initially (Step 1) not indicated to the flight crew, because it was intended that automatic action would recover the braking.

The system response is for the BSCU, after 0.2 seconds, to set V_{ref} to the current filtered wheel speed V_r. It was intended that this reset should occur only once and that, if a Failure 87 persisted for a further 2 seconds after the reset (Step 2), a Class 1 fault should be generated. This should be accompanied by the Electronic Centralised Aircraft Monitor (ECAM) message 'BRAKES SYSTEM 1(2) FAULT'. If the fault was re-confirmed at a groundspeed of less than 30 kt (Step 3) a 'BRAKES A/SKID NWS FAULT' ECAM message should be displayed.

1.6.2.4 Reference speed computation

Before touchdown, V_{ref} is set at a nominal speed in the order of 100 kt (the aircraft manufacturer considered the actual value to be proprietary data). After a wheel spin-up phase following MLG touchdown, V_{ref} is computed by the BSCU every 0.2 seconds using either mainwheel tachometer signals or an inertial deceleration value determined from the ADIRUs.

Tachometer signals, indicating wheel rotation rate, are converted to a groundspeed via multiplication by a nominal tyre rolling radius. The maximum groundspeed signal from the pair of wheels on each MLG is determined (Figure 3), to give a V_{left} and a V_{right} value, and the minimum of these two values is taken as the filtered wheel speed, V_r. This logic would prevent V_r from being affected by a single erroneous tachometer signal.

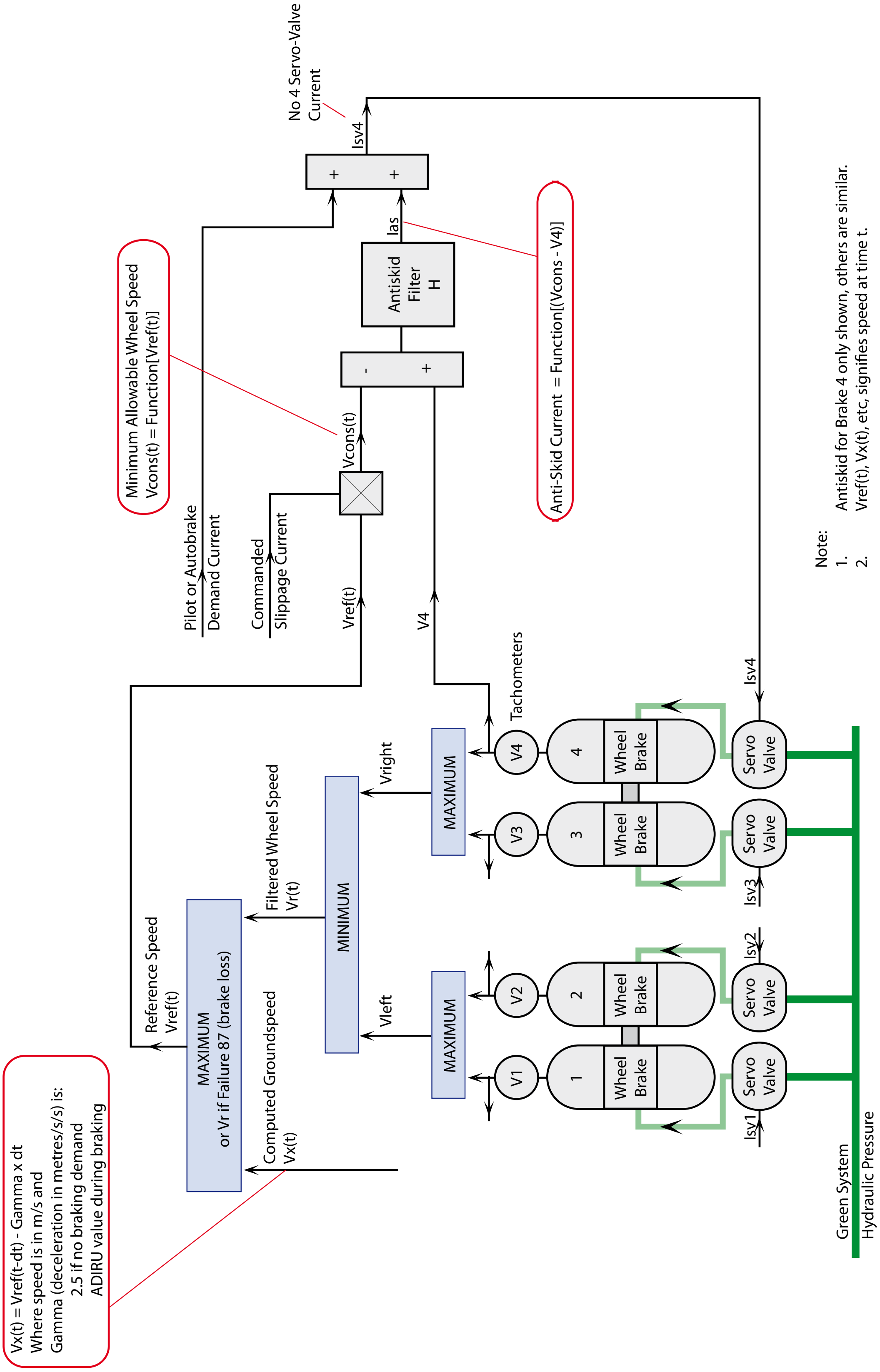


Figure 3

A320 Wheel Braking System Schematic

A computed groundspeed, V_x, is calculated by subtracting from the value of V_{ref} determined at the previous time step, a deceleration value (gamma) multiplied by the time increment (dt), and a constant. Gamma is set at a constant value (referred to as 'C' in this report) while no braking is commanded, corresponding to a deceleration between the LO and MED autobrake settings. When a braking command is present, from either the autobrake system or the pedals, gamma is set at the value determined from the ADIRUs. The BSCU then takes the maximum of V_r and V_x as the new value of V_{ref} and from this calculates a new value of V_{cons} for comparison with individual tachometer derived wheel speeds.

In summary, $V_r(t)$ and $V_{ref}(t)$ (the filtered wheel speed and the reference speed at time t) are intended to be set as follows, where dt is the time interval in seconds between calculation steps:

Situation	**Vr(t)**	**$V_{ref}(t)$**
No braking command	$\mathrm{Min}[\mathrm{Max}(V_1,V_2), \mathrm{Max}(V_3,V_4)]$	$\mathrm{Max}[V_r(t), \{V_{ref}(t\text{-}dt) - C \times dt\}]$
With braking command	Ditto	$\mathrm{Max}[V_r(t), \{V_{ref}(t\text{-}dt) - \mathrm{Gamma} \times dt\}]$
0.2 secs after Failure 87	Ditto	$V_r(t)$ (intended to be once only reset)

1.6.2.5 Tachometer driveshafts

The tachometer for each mainwheel is located in the respective wheel stub axle (see Figure 4) and connected to the wheel by a driveshaft and the wheel cap (sometimes called the 'debris guard').

JY-JAR was fitted with carbon brake packs, each with an optional brake cooling fan system and an optional Tyre Pressure Indicating System (TPIS). The brake fan is driven by an electric motor fitted in the wheel axle and a TPIS slip-ring unit is mounted on the outer end of the motor. The tachometer is mounted on the inner end of the motor. With this configuration the tachometer driveshaft passes through the fan and the TPIS units and is required to be longer than for an installation where a brake fan is not fitted.

The driveshafts fitted to JY-JAR were of the original type, referred to as the 'long hollow titanium driveshaft'. This consists of a hollow shaft, 0.22 inches (5.5 mm) in diameter, with a fitting at either end, forming an assembly 12.9 inches (329 mm) long (Figure 5). The outer fitting is formed into a male spline that mates with a female spline in the wheel cap and the inner

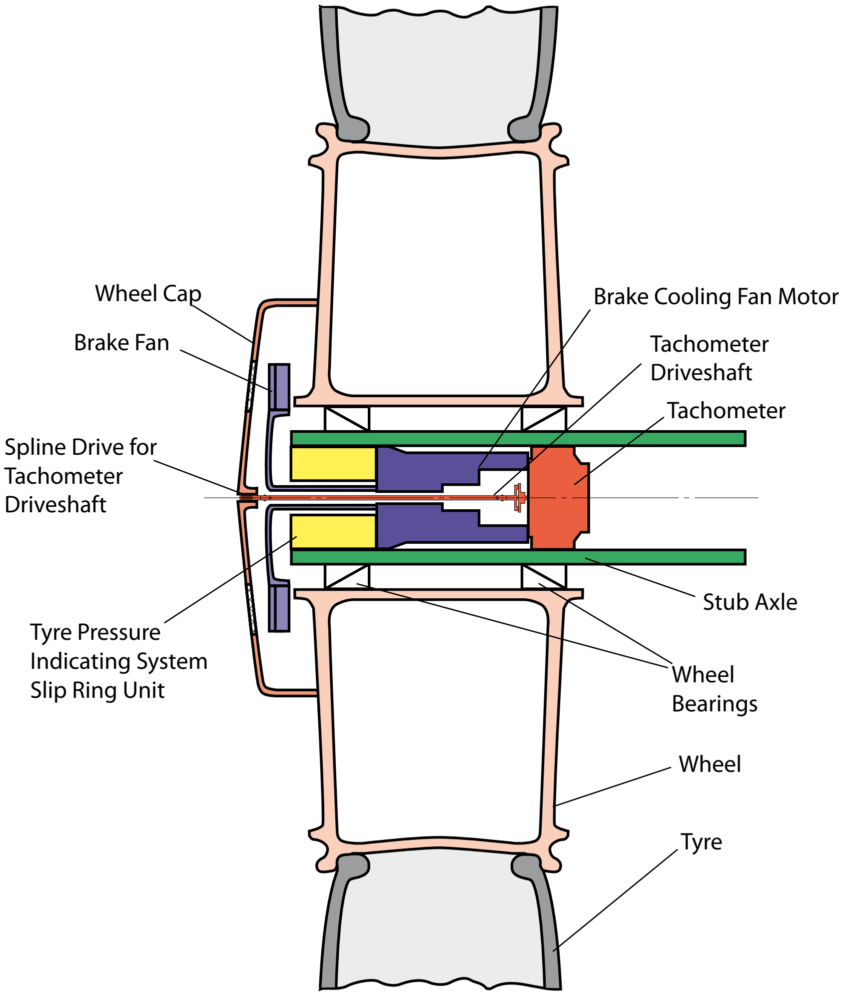


Figure 4

Mainwheel Assembly

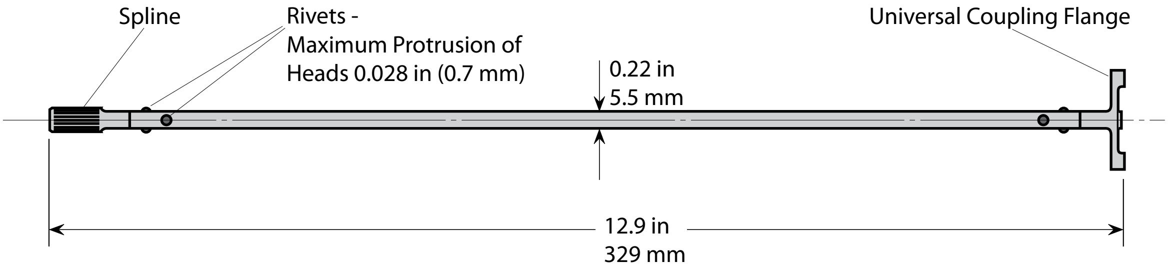


Figure 5

Tachometer Driveshaft

fitting carries a cross-piece that forms part of a universal coupling bolted to the tachometer rotor. Each fitting is connected to the shaft by two orthogonal rivets. The specified maximum protrusion of the rivet heads above the fitting surface was 0.7 mm. Only a small radial clearance is present between the shaft and the fan and TPIS units.

In its installed position the driveshaft protrudes approximately 1.5 inches (38 mm) beyond the outer end of the axle. A procedure is given in the A318/A319/A320/A321 Trouble Shooting Manual for investigating the cause of '*Loss of Normal Braking without Warning Indication*' (Task 32-42-00-810-919). Part of the procedure specifies checking that '*There is no deformation (twisting) and/or signs of friction on the drive shaft*'. The aircraft manufacturer has confirmed that the procedure should have required a check for bending, not twisting, of the shafts and plans to correct the wording. No limits for the allowable level of shaft bending distortion or the required concentricity of the tachometer and the associated wheel cap were specified in the relevant maintenance or overhaul manuals or available from the aircraft manufacturer.

1.6.3 Aircraft weight

Before the flight the crew received details of the passenger load; it comprised 153 adults, 9 children, 9 infants and 171 bags. The commander signed a trim sheet indicating that the aircraft was loaded so as to operate at all times within its approved Centre of Gravity (CG) envelope. He also signed a loadsheet which indicated that the landing weight of the aircraft would be 61,250 kg. This itemised the total passenger weight as 12,000 kg and total baggage weight as 2,200 kg. The correct figures, using International Civil Aviation Organization (ICAO) standard notional weights for a charter operation, were in fact 11,943 kg and 2,223 kg respectively. Thus, the calculated total load value presented to the commander was not significantly different to the figure based on standard values. When the bags were weighed individually after offloading it was found that their total weight was 2,919 kg. The distribution of passengers and baggage was such that the difference between notional and actual aircraft weight and CG position would not have had a significant effect on aircraft performance. The investigation used the actual landing weight of approximately 62,000 kg in assessing the landing performance of the aircraft.

1.6.4 Landing performance

The A320 FCOM, a copy of which was kept on the flight deck of JY-JAR, contains advice on the selection of retardation devices to achieve adequate stopping performance. Tables are provided showing approximate actual landing distance to be expected under various conditions. The FCOM defines Actual Landing Distance as:

> *'the distance measured between a point 50 feet above the runway threshold and the point where the complete stop of the aircraft is achieved.'*

The published tables assume that the approach speed is on target at the threshold and that the anti-skid system and ground spoilers are operating. Not all of the tables consider the effects of using reverse thrust but a correction factor of 2% may be applied if LO autobrake is used together with two engines in reverse thrust. The table does not specify whether idle or maximum reverse thrust is intended.

The tables show that in standard atmospheric conditions at sea level, the actual landing distance of an A320 weighing 62,000 kg at touchdown on a dry runway, with LO autobrake selected, would be 1,886 m without the use of reverse thrust. However, the tables state that landing distance is increased by 4% per 1,000 ft above sea level on a dry runway, but without specifying whether elevation or density altitude should be used. If the appropriate density altitude in the prevailing conditions (305 ft amsl) were used, the corrected landing distance would be 1,909 m. The tables indicate that the use of reverse thrust would reduce this landing distance by 39 m, to 1,870 m.

The tables show that the predicted landing distance using MED autobrake would have been 1,230 m, but in this case no increment is allowed for the use of reverse thrust. The correction for density altitude would increase the predicted landing distance to 1,245 m. There is no factor for headwind component in either case. The actual headwind component was insignificant.

In determining the landing ground run required, the aircraft is assumed to cross the landing threshold at a height of 50 ft and touch down, after travelling approximately a further 300 m, at the painted Aiming Point (Figure 1, page 5). This distance will vary with piloting technique, but is unlikely to be less than 300 m if the aircraft crosses the landing threshold at 50 ft. Therefore, the landing ground run required may be assumed to be the predicted Actual Landing Distance minus approximately 300 m; therefore the predicted ground roll will be approximately 1,570 m using LO autobrake and reverse thrust, or approximately 945 m using MED autobrake and reverse thrust.

Assuming normal operation of all systems, with LO autobrake selected, idle reverse and no manual intervention by the pilots, the published figures indicate that JY-JAR would not have come to a complete stop before the end of the paved runway surface, even if it had touched down at the Aiming Point. In fact, the aircraft touched down just beyond the end of the marked TDZ, approximately 360 m beyond the aiming point, with approximately 1,100 m of runway remaining in which to stop (see paragraph 1.10). Consequently, the application of MED autobrake should have been adequate, even in the absence of manual intervention by the pilots.

The FCOM also contains a table showing actual landing distances resulting from maximum application of manual braking, with an operating anti-skid system, uncorrected for runway slope. This indicates an actual landing distance of 845 m for the subject aircraft in the prevailing conditions. Consequently, although touchdown occurred slightly beyond the TDZ, had the brakes not malfunctioned it should have been possible to stop the aircraft within the remaining runway using manual braking.

Noise abatement procedures promulgated by LBA do not prohibit the use of reverse thrust, but they discourage it. The text of the relevant document reads:

> *'To minimise disturbance in areas adjacent to the airport, captains are requested to avoid/reduce the use of reverse thrust after landing, consistent with safe operation of the aircraft, wherever possible.'*

1.6.5 Flight Crew Operating Manual (FCOM)

1.6.5.1 Selection of autobrake

The FCOM, produced by the aircraft manufacturer, describes standard operating procedures and provides information about aircraft performance in various phases of flight. In relation to the selection of autobrake it states:

> *'Use of autobrake is recommended. On short or contaminated runways, use MED mode. On long and dry runways, LO mode is recommended.'*

In the section describing standard operating procedures for landing, it states:

> *'Select MAX REV immediately after main landing gear touches down. If the airport regulations restrict the use of reversers, select and maintain reverse idle until taxi speed is reached.'*
>
> *'Monitor autobrake, if it is on. When required, brake with the pedals.'*

However, the commander believed that the operator's standard procedure was always to use LO autobrake. Other operators of the type advise the use of MED autobrake except on very long, dry, runways where the pilot's own experience has shown that LO mode is always sufficient.

1.6.5.2 Brakes system fault

The Abnormal and Emergency section of the FCOM states that the ECAM message BRAKES SYS 1(2) FAULT is provided for crew awareness only; no action is required.

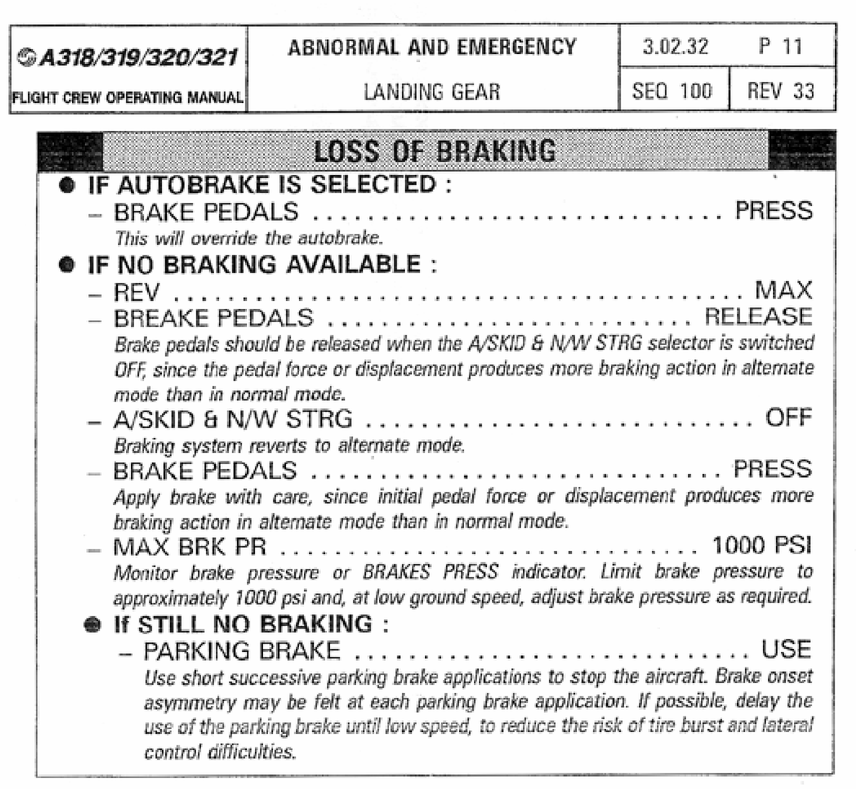
1.6.5.3 Loss of braking

There is no ECAM annunciation of loss of braking. If the flight crew perceive a loss of braking, the FCOM Abnormal and Emergency section specifies the procedure shown at Figure 6, page 18).

The black edges on the title bar indicate that this procedure is not displayed on the ECAM and so, when needed, it must completed from memory by the flight crew. Switching off the A/SKID & N/W STRG switch selects Alternate braking without anti-skid protection but it also deactivates the nosewheel steering system. The aircraft manufacturer has demonstrated that the aircraft is controllable for taxi, takeoff and landing with the nosewheel steering deactivated, and the aircraft is certified for dispatch with the nosewheel steering system inoperative.

1.7 Meteorological information

Meteorological conditions at the time of the accident were recorded by the Aerodrome Controller. The surface wind was from 190° at 7 kt. Surface visibility was 30 km with scattered cloud at 3,000 ft aal. Local QNH was 1,018 hPa, temperature was 11°C and dew point 3°C. The runway surface was dry.



A318/319/320/321 FLIGHT CREW OPERATING MANUAL	ABNORMAL AND EMERGENCY LANDING GEAR	3.02.32	P 11
		SEQ 100	REV 33

LOSS OF BRAKING

● **IF AUTOBRAKE IS SELECTED :**
- BRAKE PEDALS .... PRESS
  This will override the autobrake.

● **IF NO BRAKING AVAILABLE :**
- REV .... MAX
- BREAKE PEDALS .... RELEASE
  Brake pedals should be released when the A/SKID & N/W STRG selector is switched OFF, since the pedal force or displacement produces more braking action in alternate mode than in normal mode.
- A/SKID & N/W STRG .... OFF
  Braking system reverts to alternate mode.
- BRAKE PEDALS .... PRESS
  Apply brake with care, since initial pedal force or displacement produces more braking action in alternate mode than in normal mode.
- MAX BRK PR .... 1000 PSI
  Monitor brake pressure or BRAKES PRESS indicator. Limit brake pressure to approximately 1000 psi and, at low ground speed, adjust brake pressure as required.

● **If STILL NO BRAKING :**
- PARKING BRAKE .... USE
  Use short successive parking brake applications to stop the aircraft. Brake onset asymmetry may be felt at each parking brake application. If possible, delay the use of the parking brake until low speed, to reduce the risk of tire burst and lateral control difficulties.

Figure 6

Loss of Braking Procedure

1.8 Aids to navigation

Not applicable.

1.9 Communications

Statements received by the AAIB from a number of passengers on board the accident flight expressed concern that, immediately after the aircraft stopped, they were not given any information about the nature of the problem or the proposed course of action. Some noticed that smoke was briefly visible outside the aircraft, probably as a result of heating of the tyres during the final skidding manoeuvre. They were also surprised that disembarkation did not commence immediately.

The pilots were Jordanians whose first language was Arabic. They used Arabic for all internal cockpit communications, except where the use of English aviation terminology precluded this. The cabin crew, who were all employees of the Spanish charter airline, used Spanish for all communications among themselves.

English was used by the pilots and cabin crew for all communications between the cockpit and cabin and for passenger announcements. When interviewed by the AAIB, all of the crew demonstrated a good command of the English language and appeared to have no difficulty communicating as a group.

1.10 Aerodrome information

Leeds Bradford International Airport is located 6 nm north-west of Leeds city, at an elevation of 682 ft above mean sea level. There are two paved runways: Runway 09/27 (used primarily by general aviation) and the main instrument Runway 14/32. Runway 14 is 46 metres wide; it has a grooved concrete surface and a 7 metre wide asphalt shoulder on either side; its total length is 2,250 metres but a displaced touchdown threshold and overrun area reduce the landing distance available (LDA) to 1,802 metres (see Figure 1, page 5). At the end of Runway 14 is a 152 metre long flat overrun area (137 metre paved followed by 15 metres grassed), at the end of which the ground slopes downwards at around 10º to the horizontal, over a distance of 85 metres, to the airport boundary fence. Approach lights for Runway 32, mounted on pylons, together with a substantial ILS localiser aerial are located on the slope, on the runway extended centreline.

Runway 14 slopes down from a landing threshold elevation of 673 ft to a minimum of 657 ft at a point approximately 700 m from the start of the LDA. For the next 700 m the runway slopes upwards, to a peak at 668 ft, before falling once more to 659 ft at the end of the LDA. This profile results in an average down slope of approximately 0.25% from the start of the LDA to the stop end. The combination of up and down slopes means that pilots of aircraft rolling on Runway 14 are not able to see the stop end until shortly before the aircraft reaches the highest point after the TDZ, less than 500 m from the end of the LDA. Consequently, the adequacy or otherwise of the retardation effort may not become apparent until late in the landing roll.

CAP 168 – '*Licensing of Aerodromes*', published by the Civil Aviation Authority, describes the physical characteristics that are to be taken into account when an aerodrome is licensed. The extracts relevant to this investigation are:

1. *Sight distance*

> *Where slope changes cannot be avoided they should be such that there will be an unobstructed line of sight from any point 3 m above the runway within a distance of at least half the length of the runway or 1,200 m whichever is less.*

2. *Distance between slope changes*

> *The distance in metres between the points of intersection of two successive slope changes should not be less than the sum of the two slope changes in absolute terms multiplied by 300.*

The profile of Runway 14 was assessed on behalf of the AAIB, and found to comply with the second standard but not the first. Where runways do not conform to the provisions of CAP 168, they may, nevertheless, be licensed if the variation from these provisions is deemed by the Civil Aviation Authority (CAA) to be acceptable. Any such variations should be published in the entry for that aerodrome in the Aeronautical Information Publication (AIP, now called the Air Information Package). There was no information to this effect in the edition of the AIP current at the time of the accident.

Furthermore, the CAA may, at its own discretion, publish in the AIP any other information regarding runway characteristics which may affect aircraft operations, even if the aerodrome meets all licensing criteria. Operators are required to make aerodrome information available to the aircraft operating crew in flight, but need not furnish the AIP itself. Instead, almost all operators use one of the commercially available flight guides. Information provided in the AIP is not necessarily reproduced in these flight guides.

The CAA advised the investigation that there are several other runways in the United Kingdom which, while complying with the technical provisions of CAP 168, have profiles that reduce the ability of pilots to assess landing performance visually. In each case, the CAA intends to review the information provided in the AIP with the aim of ensuring, where necessary, any anomalies regarding runway profiles and lines of sight are identified and appropriately notified.

Within the United Kingdom there are runways with special characteristics at which non-standard signs are used to provide additional information on runway length remaining. These signs take the form of lights set in the runway, painted distance-to-run markings and, in the case of government aerodromes, frangible distance-to-run placards beside the runway.

The possibility of erecting ‘distance to go markers’ at airports was discussed at the 13th Meeting of the ICAO Visual Aids Panel (VAP) held in Montreal in 1997. The VAP concluded that there was no operational requirement for such markers and some practical difficulties were envisaged with their installation. The VAP failed to find a suitable single solution.

The ILS and visual approach slope indicators for Runway 14 at LBA are set to indicate an approach angle of 3.5°, steeper than the conventional 3º because of rising terrain along the approach path. The landing flare from such an approach often results in touchdown at a point beyond the aiming point at the start of the TDZ, indicated by the painted Aiming Point markers centred 300 m beyond the landing threshold.

Observations on the day after the accident confirmed that most large aircraft touched down towards the end of the marked TDZ, 600 m beyond the touchdown threshold. The point at which JY-JAR touched down was estimated by eyewitnesses to be at or just beyond the intersection of the main runway and the shorter Runway 09/27, approximately 700 m from the start of the LDA. This position was confirmed by FDR data.

1.11 Flight recorders

The 30-minute tape CVR and the solid state FDR were removed from the aircraft and replayed; both had retained information recorded during the event.

1.11.1 Cockpit Voice Recorder

The Cockpit Voice Recorder (CVR) installation was of the 'hot microphone' type[2] but only the microphone of the commander was recorded. His speech was often masked by higher signal levels of radio communications also recorded on his CVR channel. Speech from the co-pilot could only be discerned from the area microphone recording. As a result of these two issues the overall intelligibility of flight crew speech throughout the recording was poor. The absence of a good quality audio recording did not impede this investigation, given the circumstances of the event and the fact that pertinent recorded evidence was provided by the FDR.

1.11.2 Flight Data Recorder

The recorded data indicated that the cruise, descent and approach were uneventful. The aircraft was configured for landing with full flap, ground spoilers armed and low autobrake selected. The crew flew an ILS approach to Runway 14, with the autopilot remaining engaged until 540 ft agl. Airspeed at 50 ft agl was 144 kt and the auto-thrust system remained engaged, with a selected speed of 140 kt, until 20 ft agl, by which time the flare had been initiated. The thrust levers were retarded to flight idle at approximately 10 ft.

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[2] In a 'hot microphone' installation the crew microphones are always live and provide a more intelligible recording than the alternative installation type in which crew speech is only recorded from the cockpit area microphone, together with any ambient noise.

Touchdown occurred at 1143:34 hrs at an airspeed of 134 kt. Analysis of recorded positional data indicated that the touchdown point was just past the intersection of the two runways at LBA. During de-rotation, the thrust levers were momentarily brought back to maximum reverse thrust before being returned to idle reverse. Ground spoilers deployed automatically. Pertinent parameters recorded during the touchdown and rollout are shown at Appendix A.

About 4 seconds after touchdown, before any brake pressure had been applied by the autobrake system, the left and right brake pedals were depressed to just under half travel and auto-braking was disengaged; at that point the retardation increased to 0.2g. Ten seconds after touchdown, with airspeed having reduced to 93 kt, both left and right brake pedals were depressed further, to just beyond half travel. The recorded values of longitudinal deceleration increased from 0.2g to 0.3g. Throughout this period of manual braking, the brake pressures recorded for each of the wheels showed values consistent with the changes in brake pedal angle.

Five seconds later, at 73 kt airspeed, both brake pedals were depressed slightly further and a large, momentary retardation 'spike' was recorded on longitudinal acceleration. Recorded deceleration values changed from 0.28g to 0.46g and back to 0.27g over a period of half a second. The brake pressures recorded for all four wheels then reduced to near zero and the overall rate of retardation reduced significantly. The left and right brake pedals were then depressed to full deflection but there was no effect on the retardation of the aircraft and only small values of brake pressure were recorded for all four wheels. The CVR recording revealed that the crew recognised that they had a braking problem and selected full reverse thrust. Both engines achieved 70% N_1 within 4 seconds of the selection.

One second after the selection of full reverse, another momentary longitudinal acceleration 'spike' was recorded, after which a small increase in overall retardation (0.2g) was evident for a further 4 seconds. During this period, although both brake pedals were depressed to nearly full travel, brake pressures on the right mainwheels remained at zero whilst for those on the left only 700 psig was recorded (the maximum is 2,538 psig). A maximum of 4° of left rudder was recorded at this time. As a result the aircraft yawed left by 6° during this 4 second period.

With airspeed having reduced to approximately 40 kt, but still with no appreciable retardation under the application of full brake pedal and reverse thrust, the aircraft began a progressive turn to the right with right rudder also being applied. During the turn, both brake pedals were backed off to 70% of full deflection before being reapplied in full.

Just before the nosewheels departed the paved surface[3] at 22 kt[4], with no appreciable change in brake pedal deflection, a sudden increase in retardation was recorded[5] and large brake pressures of over 2,000 psig were recorded at each of the mainwheels. The aircraft came to a halt within a further 5 seconds on a heading of 230°M (90° right of runway heading). The flight crew cancelled reverse thrust and advised ATC that they had lost their brakes but were "OK". Both engines were then shut down, terminating the FDR and CVR recordings.

1.11.3 Additional brake system parameters

In addition to brake pedal deflections and brake pressures, the FDR recorded a number of discrete parameters[6] relating to the braking system. No faults with the autobrake, anti-skid or Normal brake system were recorded by the FDR during the event. Autobrake had been selected to LO prior to the landing and was automatically cancelled upon the application of manual braking. The recording of the parameter 'autobrake off' reflected this change correctly. The A/SKID & N/W STRG switch remained ON during the entire landing sequence and the FDR recording indicated that the alternate braking system did not become active.

1.11.4 CVR maintenance

Following the incident the CVR was inspected by an approved maintenance organisation. Their inspection revealed a number of shortcomings in the maintenance history of the CVR. It was confirmed that the co-pilot's audio channel was not working, due to a combination of debris on the heads and worn pole pieces on the heads. Additionally, one of the tape transport bearings was seized and, more importantly, the thermal insulation protection had not been maintained in accordance with the requirements of the manufacturer for many years. Had this recorder been involved in a fire, the poorly maintained thermal insulation would have afforded little protection to the tape within.

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[3] Pitch attitude of the aircraft reduced by 1.5 degrees as the nosewheels left the paved surface.

[4] As recorded airspeed indications can be unreliable below 50 kt, this approximate groundspeed has been calculated using the recorded values of longitudinal acceleration.

[5] A rapid increase to 0.46g was recorded.

[6] A discrete parameter has only two states; '0' or '1' which equate to on/off, pass/fail etc.

1.12 Aircraft and site examination

1.12.1 Site examination

Examination showed that the aircraft had come to rest close to the end of Runway 14, turned 90° right of the runway heading with the nosewheels on the grassed area surrounding the runway. The nosewheel tyres had created a furrow in the ground approximately 1 foot deep. The mainwheels had stopped approximately 2 feet from the outer edge of the runway shoulder, just short of the grass.

Tyre tracks could be traced from the aircraft back along the runway for around 200 m. The tracks, in the direction of aircraft travel, were initially very faint but became progressively more defined and with intermittent short lengths of heavy black deposition and, at other points, with a lighter-coloured regular pulsing pattern, before beginning to turn right. All six tyre tracks became markedly heavier during the turn and the nosewheel tracks crossed over the right mainwheel tracks.

The markings indicated that over the latter part of its ground run the aircraft had initially been close to the runway centreline and that all four tyres had suffered intermittent momentary incipient skidding at times, probably interspersed with periods of anti-skid controlled braking. A right turn had commenced approximately 10 m beyond the end of Runway 14, around 140 m from the end of the overrun area. During the turn the MLG tyres had begun to skid to the left and at the point where they came to rest had been travelling around 90º left of the aircraft's heading. The left MLG had halted around 35 m from the end of the overrun area and the start of the downward sloping ground.

1.12.2 Aircraft examination

A detailed examination by an aircraft manufacturer's repair team revealed no signs of structural damage to the aircraft, except for excessive out-of-roundness of the nose landing gear (NLG) oleo piston. This was consistent with the effects of overload applied by the nosewheels during their excursion off the runway. Additionally, all four mainwheel tyres had suffered appreciable tread abrasion damage, consistent with skidding sideways to the left while rotating.

Reports provided by the aircraft maintenance fault monitoring system included reports for BSCU Channel 1 of "TOTAL BRK LOSS 1" (total loss of braking) and for BSCU Channel 2 "BRK ALTN SERVOVALVE 41GG" (brake alternate servo-valve) faults (both Class 3) occurring at around the time of the landing. The exact point at which these faults were registered was not known, as the time was recorded in hours and minutes only. The aircraft manufacturer believed that the alternate servo-valve fault had occurred after the aircraft had stopped, and had possibly resulted from vibration during the latter part of the ground run.

Additionally, a number of TPIS messages were recorded. Most appeared to be repeats, related to damage to a wiring loom caused during the aircraft recovery, but one message, "CHECK TIRE 1 PRESS" (Check Tyre 1 pressure), appeared to have been recorded before this point. No connection between this message and the accident events could be established, although the aircraft manufacturer considered that it could have been caused by the sideways skidding that occurred.

Return-to-Service bench testing of the BSCU at the component manufacturer and the landing gear manufacturer revealed no evidence of anomalies.

Examination of the mainwheel tachometer systems after removal from the aircraft showed no signs of excessive wear or looseness in the drive splines or universal joint. Each tachometer driveshaft had sustained local indentation damage to the surface of the spline fittings, consistent with moderate impact by hard objects, and moderate fretting damage to the mating faces of the universal joint had occurred. Both effects were rather more severe for No 2 and No 4 driveshafts than for the No 1 or No 3 driveshafts.

It was apparent that the No 2 and No 4 driveshafts were slightly bent and showed evidence of heavy rotational rubbing over their central portions. In both cases the bend was located approximately 1.8 inches (45 mm) from the outer end of the shaft and resulted in a radial displacement of the spline of approximately 0.04 inches (1 mm) relative to the axis of the unbent part of the shaft. In addition, the heads of the rivets securing the spline fitting to the shaft had suffered 'machining' damage in a number of cases, indicative of contact with surrounding static components while the driveshafts had been rotating. This was particularly severe for No 2 and No 4 driveshafts, where some of the rivet heads had been worn almost flush with the shaft surface.

During checks at the aircraft manufacturer's facilities, each tachometer was operated on a test bench, driven by its respective driveshaft. Each produced normal output signals over a range of rotational speeds; however, it was apparent that the test could not accurately simulate installed operating conditions.

No other anomalies with any aspect of the braking system were identified. The aircraft re-entered service 10 days after the accident, following replacement of the BSCU, the tachometers, the tachometer driveshafts and the NLG. No further braking problems have been reported.

1.13 Medical and pathological information

Not applicable.

1.14 Fire

There was no fire.

1.15 Survival aspects

Not applicable.

1.16 Tests and research

1.16.1 Braking performance without anti-skid protection

The aircraft manufacturer calculated the minimum distance required to stop JY-JAR after the commander determined that the brakes had failed. Two assumptions were made: firstly, the ground speed at the time was 54 kt and secondly, a period of 3 seconds was considered to represent the minimum time required to release the brake pedals, move the A/SKID & N/W STRG switch to OFF and then increase brake pedal displacement so as to achieve a maximum of 1,000 psi brake pressure. For the conditions pertinent to this accident, the total distance required was calculated to be 252 m and the elapsed time required to stop the aircraft was 15 seconds.

1.17 Organisational and management information

Not applicable.

1.18 Additional information

1.18.1 BSCU Software

The type of brake system used on the A320 is also fitted to A319 and A321 aircraft, in each case with a number of different options available. Other Airbus types have different systems, some of which have features similar to that for the A320 family (A319/320/321). In some cases this includes a similar logic for reference speed computation.

A considerable number of BSCU software upgrades have been developed for the system used on the A320 family since the fleet's entry into service. Standard 7 was released in November 1994, with the aim of preventing loss of braking due to V_{ref} over-estimation (see paragraph 1.18.3) by improving tachometer signal filtering. The 'Loss of Braking' monitoring function was introduced with Standard 8 in February 2000, on a trial basis, and made generally available in May 2001 with Standard 9. A further upgrade in 2002, to Standard 9.1, had aimed to improve this function following a further case of undetected loss of braking due to V_{ref} over-estimation. Standard 9.1 also corrected a software error, introduced at Standard 9, that incorrectly reset V_{ref} to V_r repeatedly, rather than just once (see paragraph 1.18.4.2). The manufacturer advised that tachometer signal noise filtering was much improved with software Standard 9.1, enabling the system to monitor and recover braking when there are bent or noisy tachometer shafts.

JY-JAR's BSCU software at the time of the accident was at Standard 9. Updating to Standard 9.1 could be accomplished by incorporating a Messier-Bugatti Service Bulletin (No C20216-32-3229, dated 23 August 2002, revised 3 February 2003). This required the replacement of On-Board Replaceable Modules (OBRM), supplied free of charge by the manufacturer and requiring 0.2 man-hours to accomplish with the BSCU installed. The Bulletin was categorised as "*Recommended*", with the stated purpose being '*to improve in service operation*'; no indication was given that the change was intended to eliminate faults and reduce the possibility of a loss of braking. At the time of the accident slightly less than half of the A318/319/320/321 fleet had been upgraded to Standard 9.1.

1.18.2 Tachometer driveshaft resonance

The brake system on the A320 aircraft family had a number of different options available. The tachometer driveshaft used for aircraft without brake fans was a short solid steel shaft. Where brake fans were fitted, a long solid steel shaft was used for the A321 and originally the long hollow titanium shaft was used for A319 and A320 aircraft.

It was reported by the aircraft and brake system manufacturers that a natural vibration mode of the long hollow titanium shaft assembly is at a frequency that is close to a tyre resonant frequency, at approximately 60 Hz. This resonance tends to be excited at a groundspeed of around 70 kt. For some years, the aircraft and braking system manufacturers had been aware that tyre resonance could amplify the driveshaft vibration, causing excessive electrical noise in the tachometer signal. In certain circumstances this noise could result in an excessive reference speed, causing erroneous operation of the anti-skid system and consequent loss of braking (see paragraph 1.18.3).

The aircraft manufacturer has had a programme in place for some years to replace the titanium shaft with an upgraded, tapering, solid steel shaft. This has a resonant frequency of 130 Hz, which is outside the aircraft's normal groundspeed range. Data from the manufacturer indicated that this upgrading of the fleet slowed almost to a halt in mid-2004, and that this programme applied to new build and replacement on an attrition basis; it was not a retro-fit programme.

1.18.3 Tachometer signal noise

It was reported that the electrical noise that could be generated in the tachometer signal by driveshaft resonance (see paragraph 1.18.2) tended to have a significantly asymmetric nature. This asymmetry could prevent it from being adequately suppressed by BSCU electrical filters intended to limit noise transmission. It appeared that the resultant excessive electrical noise passing into the BSCU could be interpreted as a higher individual wheel speed (V_1, V_2, V_3 or V_4, see Figure 3) than was in fact the case.

An erroneously high signal from one MLG only would not affect the filtered wheel speed V_r because it would be blocked by the input logic ($\mathrm{Min}[\mathrm{Max}(V_1,V_2),\mathrm{Max}(V_3,V_4)]$); therefore, it could have no effect on the reference speed V_{ref}. However, the incorrect signal would not be identified as a fault, because the two groundspeed ranges at which the monitoring system checked the tachometer signals were below the speed at which driveshaft resonance was likely to occur.

In the event of a second erroneously high signal, from the other MLG, the filtering logic would cause an erroneously high V_r to be generated. As the computed groundspeed V_x would initially remain close to the aircraft's actual groundspeed and the system logic selected the highest of V_x or V_r, an erroneously high V_{ref} value would result. This in turn would generate an erroneously high V_{cons} value. If the incorrect V_{cons} exceeded any of the individual measured wheel speeds, the BSCU anti-skid function would operate to release the brakes on those wheels. Therefore, the twin driveshaft resonance condition could cause release of the brakes on wheels not suffering from driveshaft resonance.

In the above situation, fluctuation in the tachometer signal error was likely, as it could be expected that the resonant vibration responsible for the condition would be intermittent. It could therefore be expected that at some stage V_r would revert to the correct value, when one or both of the excessively noisy tachometer signals returned to normal. However, by this point V_x would have become erroneously high, because it is calculated using the V_{ref} value determined at the previous computation cycle, and would exceed V_r. In this case the filtering logic would set the new V_{ref} as equal to V_x, therefore initially retaining the error in V_{ref}. The BSCU's method of updating V_x would cause it to decrease at the actual deceleration rate as the aircraft's groundspeed reduced, if the braking demand were maintained, thereby maintaining the incremental error in V_x constant.

Thus, once V_{ref} had been set at an erroneously high level, the computation method used would effectively latch V_{ref} at a constant offset above the true groundspeed. If the offset were sufficient, as a proportion of the true groundspeed, the effect of the resultant excessive V_{cons} would be to continue the release of the brakes on all wheels with a correct tachometer signal. With both erroneous tachometer signals reverted to normal, all four brakes would be affected. As the aircraft's groundspeed reduced, the offset would become an increasing proportion of the groundspeed and the effect would therefore increase as the aircraft slowed.

In the event that all brakes were erroneously released, the resultant Failure 87 detection could terminate the situation after 2.2 seconds by setting V_{ref} equal to V_r. In this case, the Standard 9 software error that incorrectly reset V_{ref} to V_r repeatedly, rather than just once, would cause loss of anti-skid. However, the process could be interrupted by fluctuations in the tachometer signal errors and hence in V_r. The resultant intermittent recovery of some brake pressures would prevent Failure 87 detection and the generation of a Class 1 fault. Consequently, braking would not be recovered and no warning of the loss of braking would be annunciated to the crew.

The situation would affect both the Normal and Alternate With Anti-Skid braking modes. Furthermore, a V_{ref} offset occurring during autobraking would be retained if manual braking commenced. To recover braking it would be necessary to cancel autobrake or release the brake pedals for a period after the twin driveshaft resonance condition had ceased. This would effectively select the default deceleration rate (C) for the BSCU and cause V_x, and hence V_{ref}, to progressively decrease to the correct value.

1.18.4 Previous braking loss events

1.18.4.1 A320, G-UKLL, 21 May 1998

G-UKLL, a UK registered aircraft (Manufacturer's Serial Number (MSN) 189) with 187 occupants, was landing at Ibiza, in the Spanish Balearic Islands. A BSCU Channel 2 fault was annunciated when LO autobrake was selected during the approach but FCOM drills required no further action.

The brakes failed during the ground roll and the aircraft ran off the end of the runway at 55 kt. The flight crew did not fully appreciate that the wheel brakes had failed until 19 seconds after touchdown. They avoided colliding with an airfield boundary wall and an overrun into the sea by steering the aircraft into an embankment, causing the nose landing gear to collapse. The accident was investigated by the Spanish Air Accidents Investigation Commission (Comisión de Investigatión de Accidentes e Incidentes de Aviaçion Civil (CIAIAC)) with participation from the UK AAIB.

It was determined that there had probably been a problem of 'Momentary Autobrake Acquisition' on both BSCU channels. This was a situation where a short-duration depression of an autobrake selector push-button was detected by one of the two lanes in each channel but not the other. Such an anomaly could occur because the lanes, which function on a cyclic basis, would be capable of detecting a switch signal over only part of the cycle and because the cycling of the two lanes was not synchronised.

The active channel would interpret the disagreement between its COM and MON lanes as a fault and deactivate, and the passive channel would take command. The second channel would remain in command until braking commenced, in spite of it too having a disagreement between the COM and MON lanes, as the design logic prevented a channel that was active but non-functioning from quitting if the other channel had already failed. However, when the brake servo-valves started to open, the monitor failed the channel. At this point the system should have switched to alternate braking but a latent fault in a brake hydraulic distribution valve prevented the alternate system from functioning.

The evidence that this type of incomplete engagement of the BSCU could occur suggested that the provisions for ensuring that both lanes detected a selection were inadequate. G-UKLL's BSCU was fitted with Standard 7 software. Standard 9 reportedly corrected the momentary acquisition problem, but not a broadly similar anomaly of 'Multiple Autobrake Acquisition' that could result from multiple depressions of an autobrake selector push-button. With either of these discrepancies, a '5E' fault message should have been generated. A similar case of brake loss had occurred on another aircraft in July 2003. The aircraft manufacturer had attributed the problem to '*bad management of the COM/MON function synchronisation due to a lack of software robustness.*'

The Spanish CIAIAC report into the accident (No A-19/98) made nine recommendations relating to the brake system. These included improved status indications, improved crew guidance and training, A/SKID & N/W STRG switch re-labelling to reflect its BSCU reset function, parking brake switch re-labelling to reflect its emergency brake function and consideration of mandatory updating of the BSCU to Standard 9. In responding to these recommendations, the aircraft manufacturer also modified the Brake Dual Distribution Valve (BDDV), which it considered was the appropriate corrective action arising from this accident.

1.18.4.2 A320, 26 December 2001

The aircraft (MSN 191) was fitted with Standard 9 BSCU software. On landing with the autobrake system armed, braking effect was initially reported as normal but a loss of deceleration was felt as the speed reduced. The handling pilot immediately commenced manual (pedal) braking but this produced no significant retardation. The aircraft was halted using the parking brake. Two other similar episodes of braking loss were experienced on the aircraft in December 2001; in these cases braking effect was restored after the release and re-application of the brake pedals.

The recorded flight data for the 26 December incident was consistent with the flight crew reports. It showed that at a groundspeed of just above 70 kt, with autobrake engaged, all four brake pressures decreased. After the brake pedals were depressed, all four brake pressures remained at zero for 4 seconds and then intermittent pressure was present on Brakes 1 and 3 during the remainder of the ground roll. The data included the four mainwheel tachometer signals and V_{ref} (parameters not available for JY-JAR's accident) and showed that V_{ref} increased to around 10 kt above the actual groundspeed just before the braking loss. The offset was maintained as the aircraft slowed.

Such an error would be interpreted by the BSCU as indicating that wheel speeds were excessively low and cause the anti-skid system to release the brakes (see paragraph 1.18.3). The aircraft manufacturer concluded that the incorrect V_{ref} value resulted from an erroneously high signal from two wheel tachometers simultaneously, one on each MLG, due to excessive noise caused by driveshaft vibration (see paragraph 1.18.2).

The aircraft manufacturer noted that the BSCU Standard 9 software should have detected, and corrected for, the total braking loss. However, it was concluded that the logic lacked robustness and that the threshold values for the parameters used by the BSCU to confirm the condition were inappropriate. Accordingly, as a corrective action, the manufacturer introduced software Standard 9.1 for the BSCU.

In addition, a Standard 9 software error was found whereby, following a Failure 87 detection, V_{ref} was repeatedly reset to V_r every 0.2 seconds until the next BSCU reset (Off then On selection), instead of once only, as intended. The repeated resetting could cause loss of anti-skid and allow the wheels to lock during braking. The anomaly reportedly resulted from deletion of a 'Partial Brake Loss' monitoring function that had been present in the Standard 8 software.

1.18.4.3 A320, C-FTDF, 3 August 2003

The aircraft was making a night landing at Cardiff, Wales, with 170 occupants. On final approach with LO autobrake selected the ECAM display indicated a 'STEERING' anomaly. Cycling the A/SKID & N/W STRG switch eliminated the caution and automatically de-selected autobrake, but possibly the autobrake system was not subsequently re-armed.

After touchdown the aircraft did not decelerate normally and the commander pressed the brake pedals, but without effect. He did not determine that the brakes had malfunctioned until some 10 to 13 seconds after touchdown, whereupon maximum reverse thrust was selected and the A/SKID & N/W STRG switch was cycled, but manual braking was not restored. The A/SKID & N/W STRG switch was selected OFF and alternate braking became effective. The aircraft was stopped 40 m from the end of the runway, with three burst MLG tyres. There were no injuries. The commander noted that when manual braking had failed, he had been reluctant to switch off the A/SKID & N/W STRG switch in accordance with the crew drills as he wished to retain steering capability on the runway.

The incident was investigated by the AAIB (reported in AAIB Bulletin 2/2005). It appeared that the loss of braking had been caused by abnormal behaviour of the BSCU. The abnormality could not be fully explained but was possibly related to hardware faults in the electrical power supply module for both channels. It was concluded that a major contributory factor to the incident was the lack of warning of the BSCU system problem. Recommendations were made for Airbus to improve both the crew warnings and the crew drills related to loss of braking.

1.18.4.4 Other braking loss cases

A number of instances of brake fade had been reported on two other A320 aircraft, apparently because the rolling radius of the tyre when compressed by the ground reaction was smaller than the nominal radius used by the BSCU. This would cause an over-estimation of V_{ref} by a constant increment that would become increasingly significant as the aircraft speed decreased, leading to erroneous anti-skid activation and a progressive loss of braking. Generally the aircraft were fitted with bias tyres, short tachometer driveshafts and either Standard 9 or 9.1 BSCU software; the problem occurred with both autobrake and manual braking. The aircraft manufacturer concluded that the occurrences '*revealed a lack of robustness for the computation of Vref*'.

Further information suggested that a similar problem had also caused braking loss on an A320 aircraft fitted with a recent updated standard of braking system, known as the 'EM^2 System' (Enhanced Maintenance and Manufacturability System, further described in Paragraph 1.18.6). In this case, nosewheel steering was supplied from the yellow hydraulic system and alternate braking was controlled electronically. The aircraft manufacturer issued a Temporary Revision (No 924-2) to the relevant A319, A320 and A321 FCOMs in August 2005, entitled "*DEGRADED BRAKING EFFICIENCY DURING LANDING*". It was applicable to aircraft with certain types of MLG bias tyres and noted:

> *'A few cases of degraded braking efficiency occurred during landing, while at low speed (approx. 60 knots), in AUTOBRAKE mode. In order to help prevent the recurrence of such cases, the Temporary Revision recommends using manual braking rather than AUTOBRAKE. However, if AUTOBRAKE is used during landing, increase the Actual Landing Distance (ALD) in MED or LOW autobrake modes by 160 meters, regardless of the runway condition.'*

The aircraft manufacturer advised that the issues of V_{ref} over-estimation due to the tyre rolling radius were addressed with the introduction of Standard 10 and EM^2 std 4.9 software.

1.18.4.5 Total number of cases

Information from the aircraft manufacturer during JY-JAR's investigation indicated that a total of 23 cases of braking loss had been reported on the single-aisle Airbus fleets. These were attributed to:

14 cases of erroneous (excessive) reference speed
4 cases of a jamming brake valve or erroneous electronic memory code
5 cases with the cause not identified

It was noted that the 14 cases resulting from an erroneous V_{ref}, together with the 5 cases where the cause was unidentified, had all occurred on A319 and A320 aircraft with long hollow titanium tachometer driveshafts. At the time, around 50% of the A319 and A320 fleets were fitted with this type of shaft. It had apparently been concluded that the failure in these cases had probably resulted from V_{ref} over-estimation due to electrical noise in the tachometer signals as the result of driveshaft resonance and excessive vibration.

The investigation found one other, unreported, case of brake failure on an A320 family aircraft. It is possible that there are other unreported cases.

1.18.5 Brake system safety assessment

An assessment of the risk and hazard of brake failure was made by the aircraft manufacturer after the 2001 brake failure case (see paragraph 1.18.4.2). In order to take a conservative approach, the 5 cases where the cause remained unidentified were assumed to have been due to V_{ref} over-estimation, giving a total of 19 cases from this cause (see paragraph 1.18.4.5). On this basis, it was determined that the in-service rate of brake failure due to V_{ref} overestimation was in the 'Remote' probability range defined by the contemporary airworthiness code (see paragraph 1.18.7). It was concluded that the severity of the hazard should be classed as 'Catastrophic' for failure during a high-energy rejected takeoff and 'Major' for failure during landing. This was based on the assumed likelihood that such an event during landing would only occur close to or below 70 kt and on the assumption that FCOM procedures would ensure the recovery of braking. The analysis results were accepted by the DGAC, the certification authority responsible.

Documentation and subsequent discussions with the aircraft and brake system manufacturers showed that they considered that if Normal braking were lost, pilots would in all cases act in accordance with FCOM procedures and braking would be restored. Thus the penalty would be limited to a relatively modest increase in stopping distance. It was evident that there was generally a strong reluctance by the manufacturers to accept that, on encountering sudden Normal braking system failure, such action might be precluded by excessive workload or by concerns about retaining directional control.

It was also considered notable that the manufacturers, in both internal and published documents, generally referred to instances where brakes had failed to function as cases of '*loss of braking efficiency*' or '*degraded braking efficiency*'.

1.18.6 Further brake system improvements

The aircraft manufacture anticipated that a further BSCU software upgrade, to Standard 10, intended to improve a number of aspects of the system, would be made mandatory by the certification authority. Preliminary estimates were that retrofit would commence in 2007 and take approximately two to three years to accomplish across the relevant fleet. The retrofit has not been mandated by EASA.

Additionally, a common 'Brake and Steering Control System' (BSCS), known as the 'EM^2 System' was developed for certification of the A318 aircraft. This uses different hardware and software from the BSCU, partially because of BSCU obsolescence, but employs similar logic. Like some earlier standards of BSCU software, it includes a facility to monitor tachometer signal noise. Additionally, the system replaces the hydro-mechanical control of the alternate braking system with an electronic control system, known as the Alternate Brake Control Unit (ABCU). The system can be retrofitted to A318/319/320/321 aircraft, with the aim of enhancing system reliability and system operation. As noted, the system can be affected by the tyre rolling radius problem (see paragraph 1.18.4.4). Notably, the system segregates the Normal braking and nosewheel steering hydraulic systems by transferring the steering from the green to the yellow hydraulic system. However, both systems remain controlled by a single switch.

1.18.7 Airworthiness requirements for system design and analysis

For aircraft type-certification, the acceptability of a system design would normally be determined by a Failure Modes and Effects Analysis (FMEA). The intention is to consider the probability of each reasonably possible failure, or combination of failures, in order to determine the overall probability of failure of the system. It is then aimed to establish that the failure probability is at an acceptable level commensurate with the predicted potential consequences of failure.

The Airbus A320 was certificated to JAR 25. This has now been superseded by the current Airworthiness Code applicable to turbine-powered Large Aeroplanes, EASA CS-25, which is essentially similar. The section of EASA CS-25 which specifies the requirements for equipment, systems and installations is CS 25.1309. The specified requirements are shown in Appendix B.

Guidance on the methods of achieving the requirements of CS 25.1309 is contained in a separate document known as CS-25- AMC (Acceptable Means of Compliance). Relevant extracts of the guidance provided under the section AMC 25.1309 *System Design and Analysis* are presented at Appendix C. The guidance in AMC 25.1309 is expansive but does not actually specify that an FMEA must be conducted.

With regard to failure warning indication, the requirements of CS-25.1309(c) state:

> *'Information concerning unsafe system operating conditions must be provided to the crew to enable them to take appropriate corrective action. A warning indication must be provided if immediate corrective action is required. Systems and controls, including indications and annunciations must be designed to minimise crew errors, which could create additional hazards'.*

2. Analysis

2.1 Flight recorders

Although it is the responsibility of the operator to ensure that his aircraft and associated equipment are maintained to the standards required, the operator of this aircraft had only acquired it, with the appropriate paperwork, a few weeks prior to the accident. This would explain why the operator was not aware of the deficiencies in the maintenance of the CVR. However, it was expected that the deficiencies would be identified and corrected at the time of the first scheduled maintenance whilst the aircraft was under the operator's control.

The aircraft was acquired from an organisation operating under the oversight of the Jordanian Civil Aviation Authority and so it is to that regulator that the following recommendation is made:

> The Jordanian Civil Aviation Authority should ensure that aircraft operators under their jurisdiction have procedures in place to ensure the continued airworthiness of mandatory flight recorders. (Safety Recommendation 2007-012)

2.2 Landing roll

2.2.1 Landing Distance

Neither flight crew member had landed at Leeds Bradford Airport before, so they would have been unfamiliar with the line-of sight characteristics of Runway 14. The landing distance data showed that use of the LO autobrake setting selected would have been inappropriate for a runway of this length, especially for a landing weight of 62 tonnes with a light headwind component. However, the commander commenced manual braking approximately 4 seconds after main gear touchdown, before the autobrake system had activated.

The timing of the brake application, 2-3 seconds after nose gear touchdown, appears relaxed given that the aircraft touched down somewhat beyond the marked touchdown zone. However, the pilots were not able to make an early assessment of braking adequacy because the runway profile prevented them from seeing the end of the runway until late in the landing roll. The landing distance data showed that sufficient runway remained for the pilots to stop the aircraft before the end of the available landing distance, if the brakes had been working normally.

2.2.2 Loss of braking

The FDR data showed that the brakes had operated normally for around 10 seconds. The brake pressures had then suddenly decreased and remained essentially at zero over most of the next 17 seconds, although the brake pedals continued to be pushed, until about the time that the nose wheels ran off the runway. For much of the time there had intermittently been some brief pressure recovery, but without significant braking effect as a result; however within the period there had been a temporary restoration of some braking effect for a few seconds. The somewhat intermittent nature of the loss of braking effect would have made it difficult for the handling pilot to rapidly recognise that the brakes had essentially failed.

2.2.3 Crew actions

Having perceived that the aircraft could not be brought to rest on the remaining runway using Normal braking, the commander elected to steer the aircraft off to one side of the paved surface. Had he decided instead, after selecting MAX reverse thrust, to follow the remainder of the prescribed procedure and manually selected Alternate Braking Without Anti-Skid, it should have been possible to stop the aircraft on the paved surface. However, he could not have known this at the time. The aircraft would have used at least 252 m of the remaining 280 m of paved surface and this estimate assumes a near-perfect performance from the commander's application of the procedure. Consequently, there remains some doubt that the aircraft would have been stopped in time to prevent an overrun.

The commander did not know that the loss of braking was due to failure of the anti-skid system and consequently he may have lacked confidence that selecting Alternate braking would restore brake operation. He also knew that this selection would result in loss of nose wheel steering. Therefore, having judged that he would probably be unable to stop the aircraft on the paved surface, the commander decided to rely upon steering the aircraft to the right to avoid running off the end of the runway. If the commander had followed the procedure as soon as he saw the end of the paved surface, (which was before he perceived that the brakes had essentially failed) there would have been about 600 m remaining. In this case, stopping on the paved surface after switching off the anti-skid would have been assured. Therefore, a flight deck warning of anti-skid malfunction could have given the flight crew more time in which to deal with the brake problem. This is discussed further in section 2.3.6.

While it is intended that, after selecting the A/SKID& N/W STRG switch OFF, directional control could be maintained by use of the rudder and differential braking, this assumption could be compromised in the event of tyre skidding or deflation because of the loss of anti-skid. Moreover, nosewheel steering was likely to be particularly effective at low speed. Had it not been possible to stop the aircraft by skidding it sideways using nosewheel steering, it is possible that the aircraft would have continued off the end of the runway on to the steeply sloped overrun area. In this case, the aircraft would probably have sustained significant damage from fixed obstacles on the extended runway centreline. Use of the parking brake after loss of pedal braking, as recommended in the FCOM, may not be an instinctive reaction of the flight crew, and can result in additional control difficulties, particularly if applied at high speed. In the circumstances, the commander's actions resulted in an outcome with no injuries and minimal damage.

2.2.4 Runway profile

Runway 14 met the standard published in CAP 168 regarding slope change, but not that regarding line of sight. There was no information to this effect in the edition of the AIP current at the time of the accident. The CAA intends to review the information provided in the AIP with the aim of ensuring, where necessary, any anomalies regarding runway profiles and lines of sight are identified and appropriately notified for this and other UK airfields.

It is recognised that operators rely on commercially available flight guides, rather than the AIP itself, for information on specific aerodromes and that the publishers of these guides are under no obligation to reproduce such information. However, in practice, they tend to include any information that is contained in a warning within the AIP. In order to increase the likelihood that this information is available to pilots, it is recommended that:

> The Civil Aviation Authority should publish information within the Aeronautical Information Package relating to runways which do not comply with the provisions of CAP 168, or which have profiles that reduce the ability of pilots to assess landing performance distance remaining visually, in the form of a 'Warning'. within the 'Local Traffic Regulations' section or the 'Remarks' area of 'Runway Physical Characteristics' for all affected UK airports. (Safety Recommendation 2007-013)

Non-standard signs are sometimes used to provide additional information on runway length remaining. The crew's situational awareness may have been improved had there been distance markers located at regular intervals near the sides of the runway. The ICAO Visual Aids Panel has concluded that there is no operational requirement for such markers, but in view of the number of runway overruns in recent years, particularly those involving aircraft touching down significantly beyond the marked touchdown zone, it may be time for ICAO to again review this policy. Therefore it is recommended that:

> The International Civil Aviation Organization (ICAO) should re-assess the benefits and disadvantages to runway situational awareness of runway distance markers for any runway which has a profile that prevents the end of the paved surface from being in view continuously from the flight deck. If the re-assessment concludes that a net benefit is likely, the ICAO should encourage the installation of such markers at relevant civil airports. (Safety Recommendation 2007-014)

2.3 Braking system

2.3.1 JY-JAR's loss of braking

It was clear from the flight crew reports, FDR data and site evidence that JY-JAR had suffered an intermittent but essentially sustained loss of braking during the landing run. The lack of a flight deck indication of the brake failure very probably made it more difficult for the flight crew to assess the cause of the problem.

The anomalies known to be capable of leading to brake failure concerned momentary or multiple autobrake acquisition, faults in the BSCU power supplies, over-estimation of the tyre rolling radius and excessively noisy tachometer signals, in some cases combined with lack of robustness of the software. Each of these anomalies had apparently been responsible for previous brake failure events on aircraft in the A320 family. The aircraft manufacturer had acted with the intention of correcting these anomalies but the corrective actions had not been entirely successful.

In JY-JAR's case, although the over-estimation of V_{ref} was probable, positive evidence of a defect responsible for the braking loss was not found, both because the available testing was insufficiently representative of the installed situation and because the required parameters were not recorded. The absence of the 5E fault code in the fault monitoring record suggested that most of the possible scenarios could be dismissed, although the inability to positively explain the servo-valve fault message and the TPIS fault message recorded at about the time of the landing cast some doubt on the reliability of this analysis.

However, one tachometer driveshaft on each MLG was found bent and it appeared that this condition would encourage increased driveshaft vibration due to excitation by a tyre resonant condition at a groundspeed of around 70 kt. This was approximately the speed at which Normal braking had been lost. An indication that the two distorted shafts had suffered excessive vibration was provided by the greater rotational rubbing damage and the somewhat more extensive fretting damage to the mating surfaces of the universal joint on these shafts, although the evidence was not conclusive.

It had been known by the aircraft and brake system manufacturers for some years that driveshaft vibration could cause excessive electrical noise in the tachometer signal. Such noise, because of its asymmetric nature, would not be fully suppressed by the BSCU filters and could be interpreted as a higher wheel speed than was in fact the case (see paragraph 1.18.3). An erroneously high signal from one MLG only would not affect the reference speed because it would be blocked by the filtering logic. However, it would not be detected as a fault because the speeds at which the monitoring system checked the tachometer signals during the takeoff roll were below the speed at which resonance was likely to occur. In the event of a second erroneously high signal, from the other MLG, an error in the reference speed would result which, if sufficient, would erroneously activate the anti-skid system, leading to a loss of braking.

Initially, the brakes on the wheels with correctly indicating tachometers would be affected. Because the driveshaft resonant condition would probably be intermittent, it was likely that the tachometer signal errors would fluctuate, or disappear. However, the BSCU computation method would tend to lock in the reference speed error and, when driveshaft resonance ceased and tachometer signals reverted to normal, all four brakes would be released. The intermittent nature of the signal errors could prevent both automatic recovery of braking and flight deck warning of braking loss.

Thus it could be envisaged that a sustained loss of braking on all mainwheels, possibly with brief intermittent pressure recovery on some brakes, could result from noisy tachometer signals, without a crew warning being given. It would be expected that Normal braking (without anti-skid) would be restored when the anti-skid system automatically deactivated at 20 kt groundspeed. The available data from JY-JAR's FDR and the evidence from the runway markings were consistent with this scenario. Therefore, it was concluded that excessive tachometer signal noise, caused by the effects of a bent tachometer driveshaft on each MLG, had probably been responsible for the brake failure in this case.

2.3.2 Tachometer driveshaft damage

It could not be positively determined how the No 2 and No 4 driveshafts had become bent or when this had occurred. However, given the relatively slender hollow section of the main part of the shaft, it did not appear that much force would be necessary to cause the distortion. Additionally, the protrusion of the driveshafts beyond the end of the axle left them vulnerable to damage when the associated wheel was not fitted. Shaft damage due to contact by the wheel during its removal and installation appeared to be a particular possibility and both the No 2 and No 4 driveshafts showed signs of moderate local impact damage to the spline fitting. Consequently, it was concluded that the shaft bending had probably resulted from relatively minor strikes on the outer end of the shafts while the respective wheel had not been fitted, possibly during a wheel change.

2.3.3 Braking system fault tolerance

The logic by which V_r, and hence V_{ref}, were determined by the BSCU would eliminate single tachometer signal errors and dual tachometer signal errors on the same MLG. Furthermore, the monitoring system would detect certain other signal errors. However, an erroneously high signal caused by tachometer shaft vibration would only be likely to occur at a groundspeed above that at which the signals are monitored and therefore would probably not be detected. Thus, a single high signal would effectively remain a dormant fault until a second high signal occurred on the other MLG, leading to brake failure.

During the ground roll the brakes are essential controls. Brake failure clearly represents a substantial safety risk, particularly if the flight crew receive no timely and unambiguous warning of the failure, as in this case. It is unusual for an aircraft control system to be designed such that an undetectable fault and a single further fault would cause the normal mode to fail. It would have been expected that the situation would have been identified and rectified at the design stage by the FMEA exercise that typically would be conducted to qualify this type of system. This had evidently not been the case, but the reasons for this could not be established.

2.3.4 Eliminating potential causal factors

The two factors that, in combination, probably caused this accident were the use of BSCU Standard 9 software and long hollow titanium tachometer driveshafts. Some 19 cases of brake failure on Airbus A319 and A320 aircraft had been attributed to a combination of resonance-prone long hollow driveshafts and/or a lack of robustness in the software. Most of the cases might have been prevented if the driveshaft resonance condition had been eliminated.

2.3.4.1 Tachometer driveshaft replacement

JY-JAR's accident would probably have been prevented if a different type of tachometer driveshaft had been fitted. This action should eliminate the resonant condition responsible for excessive tachometer noise.

Improved driveshafts are fitted to new aircraft but their retrofit to in-service aircraft has not been mandated because BSCU software Standard 9.1 is considered sufficient to filter noisy signals and to monitor and recover braking when there is a bent or noisy tachometer shaft. The A321 aircraft equipped with brake fans were factory-fitted with solid steel tachometer driveshafts but about 50% of the A319 and A320 aircraft were equipped with long hollow titanium driveshafts. Many of these aircraft probably still have the long hollow, resonance-prone driveshafts. Thus a substantial number of aircraft remain in service with the original type of driveshaft and it appears that this number has stayed almost static for some time. In view of the potentially serious consequences of driveshaft resonance, it is recommended that:

> The European Aviation Safety Agency should require the expeditious replacement of the long hollow titanium tachometer driveshaft in the braking systems of the A320 family of aircraft with a driveshaft of improved design. (Safety Recommendation 2007-015)

2.3.4.2 Software replacement

Providing replacement solid steel driveshafts for all these aircraft may take some time so other interim measures to minimise the risk of brake failure induced by driveshaft resonance should be considered.

At the time of this accident slightly less than half of A320 family aircraft were operating with BSCU software Standard 9.1. BSCU Standard 9 software was known to contain an error which the aircraft manufacturer stated '*revealed a lack of robustness for the computation of Vref*'. The upgrading from Standard 9 to Standard 9.1, with the intention of introducing additional and improved fault monitoring logic, has not been a complete success in dealing with Normal brake system problems, perhaps because of tyre radius computation errors. However, service experience suggests that the vast majority of aircraft using software Standard 9.1 have not suffered brake failure problems, even though many of them must still have long hollow driveshafts.

The modification to 9.1 was categorised as 'recommended' by a BSCU manufacturer's Service Bulletin. In the circumstances it is considered that a 'mandatory' categorisation by means of an Airworthiness Directive would have been more appropriate. The upgraded components were available at no charge to the aircraft owner and required just 0.2 man-hours to embody. Consequently, there was no obvious reason why Standard 9.1 should not have been retrofitted to all aircraft with Standard 9 or earlier. However, while the aircraft manufacturer considered that it had actively promoted the change, the stated purpose of the Service Bulletin ('*to improve in service operation*') would not have conveyed its potential importance. If the upgrade had been made mandatory, this accident and at least one earlier serious incident may have been averted. The manufacturer advised that by mid 2007, 99.4% of the fleet had been modified to software Standard 9.1. Therefore it is recommended that:

> The European Aviation Safety Agency should ensure the replacement of software Standards 7 or 9 with Standard 9.1 or a proven later version, in those remaining Airbus A319 and A320 brake and steering control units not yet so modified. (Safety Recommendation 2007-16)

2.3.4.3 Brake system integrity

It became apparent during the investigation that the type of brake system used on JY-JAR suffered from a number of anomalies and that these had led to a number of cases of brake failure, commonly without warning to the pilots.

While a considerable number of modifications had been made over a period of some years, particularly to the BSCU software, cases of brake failure due to unintended system behaviour continued to occur. In particular, an erroneous reference speed, generated for a variety of reasons, appeared to be a known and continuing cause of brake failure, as in this case. The problem had even persisted with an updated type of brake system, due to tyre rolling radius anomalies, requiring the issue of a FCOM temporary revision in 2005 advising use of manual braking instead of autobrake for landing for aircraft with certain types of bias tyres.

A further recurring theme in the findings of the investigations of the previous cases was '*a lack of robustness*' in the software. The history of failures, in spite of the repeated changes aimed at resolving the deficiencies, raised concerns about the intrinsic reliability of the various standards of the system, including the most recent.

It was noted that the failures occurred during a very substantial number of operating hours by a large fleet of aircraft. Based on the estimated total flight hours, the aircraft manufacturer had assessed that the risk of catastrophic consequences due to a loss of Normal braking was acceptably low and, indeed, no catastrophic accidents had resulted. However, a number of the cases of loss of Normal braking had almost led to accidents. A small change in the circumstances could well have resulted in catastrophic aircraft damage and injury in the Ibiza overrun accident and quite possibly could have done so in the Cardiff case.

Similarly, while JY-JAR's accident did not result in injury or extensive aircraft damage, such a benign outcome would have been unlikely had the aircraft travelled a slightly greater distance before stopping. It was therefore judged that the potential for a serious accident was clearly apparent and needed to be addressed.

The delay, or omission, in carrying out the FCOM procedure in some cases may have been due to pilots not immediately recalling the procedure and acting rapidly during a brief period of high workload. Confusion created by the absence of a flight deck indication could make this more likely. It was also possible that sudden failure of Normal braking, without the expected automatic reversion to the Alternate braking mode, particularly if no flight deck indications were given, could reasonably reduce the confidence that manually selected Alternate braking would work. In other cases the procedure was not followed because of concerns about directional controllability, either because the manual selection of Alternate braking would cause nosewheel steering loss and possibly tyre deflation, or because of the likelihood of wheel locking if the parking brake were used.

In any event, the experience showed that the assumption within the aircraft manufacturer's risk assessment that pilot action would limit the consequence of loss of Normal braking to a modest increase in stopping distance was unreliable.

The Spanish CIAIAC had made a substantial number of recommendations in relation to the A320 braking system as a result of the findings from their investigation into the Ibiza accident in 1998. Further recommendations had been made after the Cardiff incident. However, it did not appear that effective action to address all of these recommendations had been taken.

2.3.5 Brake and steering systems independence

If Normal wheel braking fails, the manual selection of Alternate braking specified in FCOM procedures automatically causes loss of nosewheel steering. It is understandable that pilots may be reluctant to forfeit nosewheel steering, particularly when faced with an imminent runway over-run with obstacles directly ahead. Since both Alternate braking Without Anti-Skid and nosewheel steering systems can help to compensate for the loss of Normal braking, the inability to activate these two complementary aircraft control systems independently appears most unsatisfactory.

However, the deficiency could possibly be partially rectified, without the systems having separate hydraulic supplies, by modification that permitted independent selection of Alternate Braking Without Anti-Skid and nosewheel steering systems. It is judged that consideration of the feasibility of such a change is appropriate and that, if feasible, retrofitting of the change should be considered. It is also considered that some form of rectification should be incorporated on aircraft in the A320 family built in the future. It is therefore recommended that:

> The European Aviation Safety Agency should consider requiring, for aircraft in the A320 family and other aircraft with similar combined Brakes and Steering Control systems, changes that allow manual selection of Alternate braking without consequent loss of nosewheel steering. (Safety Recommendation 2007-018**)**

2.3.6 Flight deck indication

One particularly serious issue which arose in this accident and in earlier events is the lack of a flight deck warning if Normal braking is not achieved. There is not necessarily an ECAM annunciation of loss of braking, even though the loss may be caused by a detectable combination of system malfunctions. The absence of a reliable warning appears to be inconsistent with the design philosophy of an aircraft with otherwise extensive fault monitoring and indication.

The recall items for 'Total Brake Failure', as shown in paragraph 1.6.5.3, will always require immediate pilot action because the aircraft is being braked for a good reason. However, no warning of an internal BSCU power failure or, as was probably the case for JY-JAR, of anomalous tachometer signals that were likely to cause loss of braking action by both BSCU channels, was presented to the pilots. It would be difficult for monitoring systems to reliably detect a loss of braking by reference to anti-skid current and brake unit pressure in all cases, as the anti-skid system would necessarily command a major reduction in braking on a slippery runway. However, it would appear possible to detect anomalous brake system behaviour in many cases by monitoring other brake system parameters, for example by comparing tachometer signals.

For similar reasons it could be very difficult for the crew under some circumstances, such as a slippery or wet runway at night, to determine if a loss of retardation is caused by a braking system problem or by the condition of the runway surface. Also, at high groundspeeds, the retardation effect of spoiler extension can be similar to the target retardation of the autobrake LO setting and so a brake failure can be very difficult to detect, especially if there are other issues requiring immediate pilot reaction, such as a strong crosswind. Consequently, operating safety would be improved if the crew were warned of brake failure. Therefore it is recommended that:

> The European Aviation Safety Agency should require Airbus to take measures aimed at ensuring that anomalies in A318/319/320/321 aircraft braking systems that may lead to loss of Normal braking are clearly indicated to the flight crew. (**S**afety Recommendation 2007-019)

2.4 Airworthiness considerations

2.4.1 Braking system design

It was unexpected that an aircraft braking system would receive design approval if, during the ground roll, it had a failure mode whereby an undetectable fault and a single further fault would cause it to fail. Similar considerations applied to the momentary and multiple autobrake acquisition problems and to the BSCU Standard 9 software error (see paragraph 1.18.1) that could cause loss of anti-skid. In the same way, the potential loss of braking that could result from use of an incorrect tyre rolling radius by the BSCU should have been detected and corrected at the design stage.

Similar arguments apply to the inadequate robustness in the software and to the lack of independence of the manually selected Alternate braking and nosewheel steering systems. The inappropriate natural frequency of the tachometer driveshafts should have been detected and corrected at the design or qualification stages. As discussed above, there seems to be no good reason why failure of the brakes on an aircraft equipped with extensive fault monitoring and indication should not be communicated to the flight crew.

These anomalies in the braking system of the A320 aircraft family raise issues about the adequacy of the design systems aimed at eliminating such deficiencies.

2.4.2 Continued airworthiness action

Faults that could cause the failure of an essential aircraft control system such as the braking system, even if not detected and corrected at the design stage, should be rectified once they become apparent in service. Thus it appears that effective action had not been taken to eliminate some of the problems, particularly as, some years before, a number of relevant recommendations had resulted from the investigation of a serious accident.

A factor that had possibly inhibited full recognition of the potential seriousness of the problems may have been the aircraft and brake system manufacturers' shared assumption that crew action would limit the consequences of a normal brake system failure. While this was theoretically the case, in-service experience had shown that this assumption was unreliable and unjustified.

In spite of the in-service experience, the terminology generally used by the aircraft and brake system manufacturers in relation to instances of braking loss was euphemistic and consequently unlikely to fully convey the potential seriousness of the problem. The widespread use of terms such as '*loss of braking efficiency*' rather than 'brake failure' or 'loss of braking' appeared indicative of a reluctance to accept that such an event could have serious repercussions.

These considerations cast doubt on the effectiveness of the manufacturer's systems for assessing and acting on the potential flight safety implications revealed by in-service problems.

3. Conclusions

(a) Findings

1. The operating flight crew members were properly licensed and adequately rested to operate the flight.

2. The multi-lingual constitution of the crew did not adversely effect crew communications during the accident.

3 Neither flight crew member had landed at Leeds Bradford Airport before, so they were unfamiliar with the line-of sight characteristics of Runway 14.

4. The aircraft was below the maximum landing weight appropriate for the runway in the prevailing conditions and its centre of gravity was within permitted limits.

5. The speed of the aircraft over the landing threshold was consistent with the achievement of scheduled landing performance.

6. The aircraft touched down just beyond the end of the marked touchdown zone, approximately 400 m beyond the Aiming Point and 700 m beyond the displaced runway threshold.

7. The LO autobrake setting selected for landing was inappropriate for the conditions but manual braking was commenced about 4 seconds after touchdown and should have been adequate to stop the aircraft on the runway.

8. A pronounced dip in the runway prevented the pilots from seeing the end of the paved surface until late in the ground roll.

9. The Normal braking system malfunctioned at around 70 kt groundspeed causing the loss of almost all braking effect.

10. Automatic reversion to Alternate braking did not occur.

11. There was no flight deck warning of the brake malfunction.

12. The lack of a flight deck warning probably delayed the crew's recognition of the loss of braking.

13. The FCOM procedure for LOSS OF BRAKING was not completed.

14. If, after selecting MAX reverse thrust, the commander had followed the remaining actions of the LOSS OF BRAKING procedure, it should have been possible to stop the aircraft on the runway but it would have used at least 252 m of the remaining 280 m of paved surface.

15. The commander could not have known that the aircraft might have been stopped on the paved surface if he had persisted with the LOSS OF BRAKING procedure.

16. Alternate braking was not selected because of concerns that the consequent loss of nosewheel steering and anti-skid would severely reduce the directional control capability.

17. The aircraft was steered off the side of the runway overrun area using nosewheel steering.

18. The aircraft skidded sideways and came to rest with its nosewheels on a grassed area at the side of the runway overrun area shortly before a steep down slope.

19. Aircraft damage was limited to slight distortion of the nose landing gear caused by overload while running on the grassed area.

20. The driveshafts for two of the mainwheel tachometers used to sense wheel speed were found bent. This probably caused excessive noise in the tachometer electrical signals that resulted in an error in the groundspeed determined by the computerised brake control system and consequent release of the brakes by the anti-skid system.

21. Fluctuation in the tachometer signal noise probably prevented automatic correction of the Normal brake system loss and caused failure of the flight deck warning.

22. The aircraft monitoring systems were unable to detect the excessive tachometer signal noise as this occurred at a speed above the monitored speed range.

23. There were a number of other known anomalies with the brake control and monitoring system that could cause either brake failure or locking of the wheels, some of which had resulted in previous incidents and accidents.

24. The aircraft manufacturer had acted with the intention of correcting brake system anomalies identified during previous incident and accident investigations, but the corrective actions had not been entirely successful.

25. Redesigned tachometer driveshafts and updated software intended to correct some of the faults were available but had not been incorporated on a substantial number of aircraft, including JY-JAR.

(b) Causal factors

The investigation identified the following causal factors:

1. Excessive wheel tachometer signal noise, caused by a bent tachometer driveshaft on each main landing gear assembly, resulted in loss of braking using the Normal system.

2. Inadequate fault tolerance within the brake control system led to the sustained loss of Normal braking during the landing ground roll.

3. There was no flight deck indication of brake system malfunction, and this delayed the crew's recognition of the loss of braking.

4. There was a lack of effective action to fully rectify brake system anomalies apparent from previous incidents and accidents.

4. Safety Recommendations

The following safety recommendations were made:

4.1 **Safety Recommendation 2007-012**: The Jordanian Civil Aviation Authority should ensure that aircraft operators under their jurisdiction have procedures in place to ensure the continued airworthiness of mandatory flight recorders.

4.2 **Safety Recommendation 2007-013**: The Civil Aviation Authority should publish information within the Aeronautical Information Package relating to runways which do not comply with the provisions of CAP 168, or which have profiles that reduce the ability of pilots to assess landing performance distance remaining visually, in the form of a 'Warning'. within the 'Local Traffic Regulations' section or the 'Remarks' area of 'Runway Physical Characteristics' for all affected UK airports.

4.3 **Safety Recommendation 2007-014**: The International Civil Aviation Organization (ICAO) should re-assess the benefits and disadvantages to runway situational awareness of runway distance markers for any runway which has a profile that prevents the end of the paved surface from being in view continuously from the flight deck. If the re-assessment concludes that a net benefit is likely, the ICAO should encourage the installation of such markers at relevant civil airports.

4.4 **Safety Recommendation 2007-015**: The European Aviation Safety Agency should require the expeditious replacement of the long hollow titanium tachometer driveshaft in the braking systems of the A320 family of aircraft with a driveshaft of improved design.

4.5 **Safety Recommendation 2007-16**: The European Aviation Safety Agency should ensure the replacement of software Standards 7 or 9 with Standard 9.1 or a proven later version, in those remaining Airbus A319 and A320 brake and steering control units not yet so modified.

4.6 **Safety Recommendation 2007-018:** The European Aviation Safety Agency should consider requiring, for aircraft in the A320 family and other aircraft with similar combined Brakes and Steering Control systems, changes that allow manual selection of Alternate braking without consequent loss of nosewheel steering.

4.7 **Safety Recommendation 2007-019**: The European Aviation Safety Agency should require Airbus to take measures aimed at ensuring that anomalies in A318/319/320/321 aircraft braking systems that may lead to loss of Normal braking are clearly indicated to the flight crew.

5. Safety actions taken

5.1 Modification embodiment

At the time of the accident slightly less than half the fleet had been modified with BSCU software standard 9.1 (Modification No 32500P7810). By March 2007 only about 12 aircraft remained unmodified.

5.2 Tachometer drive shaft replacement

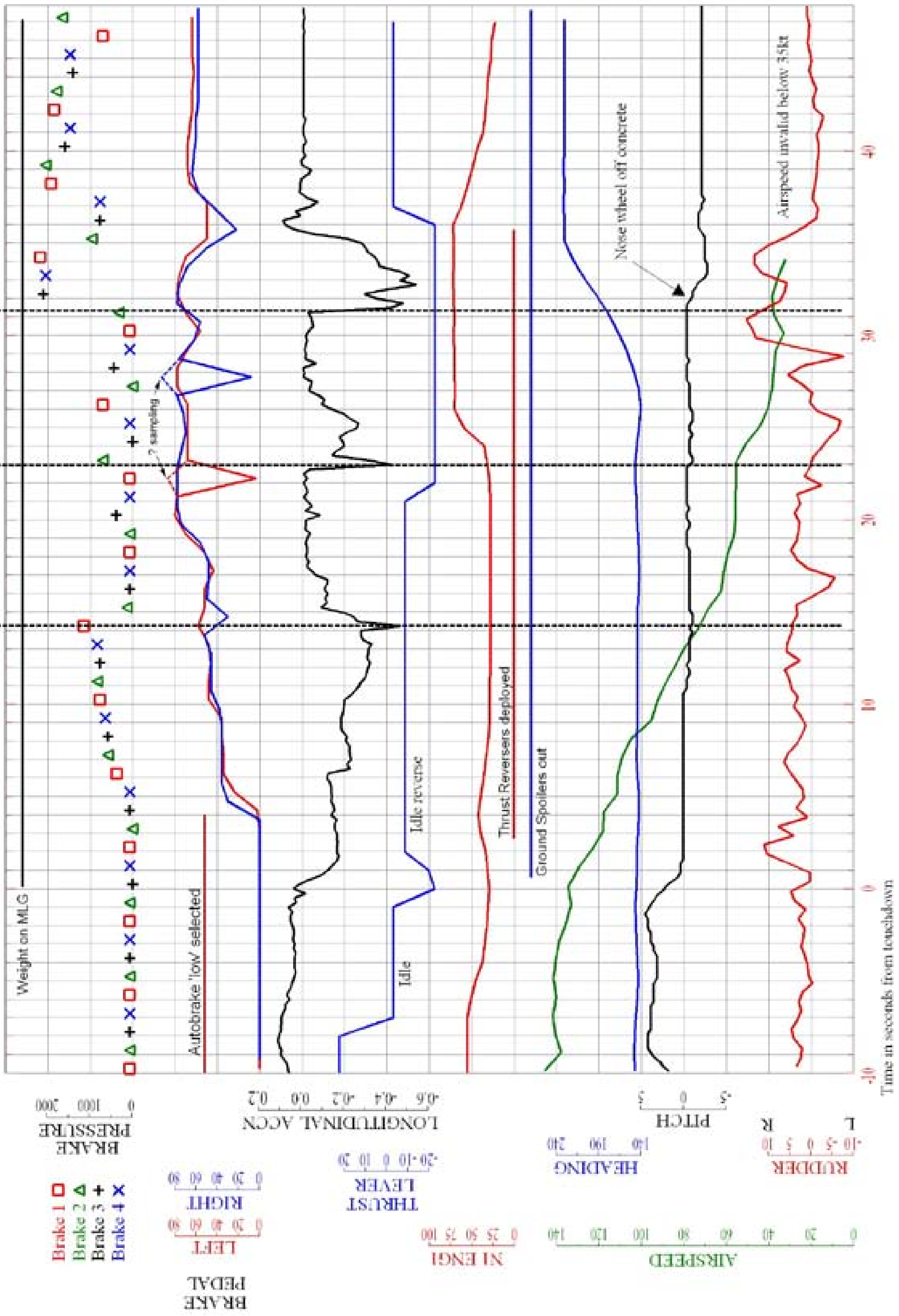
The production of replacement hollow tachometer drive shafts ceased and new aircraft are fitted with solid shafts. For in-service aircraft, hollow shafts are being replaced by solid shafts on an attrition basis.

5.3 AIP revision

In response to safety Recommendation 2007-13 The UK CAA has advised that information on the line of sight characteristics of Runway 14/32 is now published in the AIP in the 'Remarks' area of AD2.12, 'Runway Physical Characteristics'. This location within the AIP is considered by the CAA to be more appropriate than that suggested in the Safety Recommendation.

A P Simmons
Principal Inspector of Air Accidents
Air Accidents Investigation Branch
Department for Transport
November 2007

Appendix A



Plot of Pertinent Flight Data Parameters

Extracts from EASA CS-25 (Book 1)

(The Airworthiness Code applicable to turbine powered Large Aeroplanes)

CS 25.1309 Equipment, systems and installations

(See AMC 25.1309)

The requirements of this paragraph, except as identified below, are applicable, in addition to specific design requirements of CS-25, to any equipment or system as installed in the aeroplane. Although this paragraph does not apply to the performance and flight characteristic requirements of Subpart B and the structural requirements of Subparts C and D, it does apply to any system on which compliance with any of those requirements is dependent. Certain single failures or jams covered by CS 25.671(c)(1) and CS 25.671(c)(3) are excepted from the requirements of CS 25.1309(b)(1)(ii). Certain single failures covered by CS 25.735(b) are excepted from the requirements of CS 25.1309(b). The failure effects covered by CS 25.810(a)(1)(v) and CSCS 25.812 are excepted from the requirements of CS 25.1309(b). The requirements of CS 25.1309(b) apply to powerplant installations as specified in CS 25.901(c).

(a) The aeroplane equipment and systems must be designed and installed so that:

(1) Those required for type certification or by operating rules, or whose improper functioning would reduce safety, perform as intended under the aeroplane operating and environmental conditions.

(2) Other equipment and systems are not a source of danger in themselves and do not adversely affect the proper functioning of those covered by sub-paragraph (a)(1) of this paragraph.

(b) The aeroplane systems and associated components, considered separately and in relation to other systems, must be designed so that -

(1) Any catastrophic failure condition
(i) is extremely improbable; and
(ii) does not result from a single failure; and

(2) Any hazardous failure condition is extremely remote; and

(3) Any major failure condition is remote.

(c) Information concerning unsafe system operating conditions must be provided to the crew to enable them to take appropriate corrective action. A warning indication must be provided if immediate corrective action is required. Systems and controls, including indications and annunciations must be designed to minimise crew errors, which could create additional hazards.

Appendix C

Extracts from CS-25 (BOOK 2)

ACCEPTABLE MEANS OF COMPLIANCE – AMC

AMC 25.1309 System Design and Analysis

1. PURPOSE.

a. This AMC describes acceptable means for showing compliance with the requirements of CS 25.1309. These means are intended to provide guidance to supplement the engineering and operational judgement that must form the basis of any compliance demonstration.

b. The extent to which the more structured methods and guidelines contained in this AMC should be applied is a function of systems complexity and systems failure consequence. In general, the extent and structure of the analyses required to show compliance with CS 25.1309 will be greater when the system is more complex and the effects of the Failure Conditions are more severe. This AMC is not intended to require that the more structured techniques introduced in this revision be applied where traditional techniques have been shown to be acceptable for more traditional systems designs. The means described in this AMC are not mandatory. Other means may be used if they show compliance with CS 25.1309.

5. DEFINITIONS.

The following definitions apply to the system design and analysis requirements of CS 25.1309 and the guidance material provided in this AMC. They should not be assumed to apply to the same or similar terms used in other regulations or AMCs. Terms for which standard dictionary definitions apply are not defined herein.

a. Analysis. The terms “analysis” and “assessment” are used throughout. Each has a broad definition and the two terms are to some extent interchangeable. However, the term analysis generally implies a more specific, more detailed evaluation, while the term assessment may be a more general or broader evaluation but may include one or more types of analysis. In practice, the meaning comes from the specific application, e.g., fault tree analysis, Markov analysis, Preliminary System Safety Assessment, etc.

b. Assessment. See the definition of analysis above.

c. Average Probability Per Flight Hour. For the purpose of this AMC, is a representation of the number of times the subject Failure Condition is predicted to occur during the entire operating life of all aeroplanes of the type divided by the anticipated total operating hours of all aeroplanes of that type (Note: The Average Probability Per Flight Hour is normally calculated as the probability of a Failure Condition occurring during a typical flight of mean duration divided by that mean duration).

d. Candidate Certification Maintenance Requirements (CCMR). A periodic maintenance or flight crew check may be used in a safety analysis to help demonstrate compliance with CS 25.1309(b) for Hazardous and Catastrophic Failure Conditions. Where such checks cannot be accepted as basic servicing or airmanship they become Candidate Certification Maintenance Requirements (CCMRs). AMC 25.19 defines a method by which Certification Maintenance Requirements (CMRs) are identified from the candidates. A CMR becomes a required periodic maintenance check identified as an operating limitation of the type certificate for the aeroplane.

e. Check. An examination (e.g., an inspection or test) to determine the physical integrity and/or functional capability of an item.

f. Complex. A system is Complex when its operation, failure modes, or failure effects are difficult to comprehend without the aid of analytical methods.

g. Conventional. A system is considered to be Conventional if its functionality, the technological means used to implement its functionality, and its intended usage are all the same as, or closely similar to, that of previously approved systems that are commonly-used.

h. Design Appraisal. This is a qualitative appraisal of the integrity and safety of the system design.

i. Development Assurance. All those planned and systematic actions used to substantiate, to an adequate level of confidence, that errors in requirements, design, and implementation have been identified and corrected such that the system satisfies the applicable certification basis.

j. Error. An omission or incorrect action by a crewmember or maintenance personnel, or a mistake in requirements, design, or implementation.

k. Event. An occurrence which has its origin distinct from the aeroplane, such as atmospheric conditions (e.g. gusts, temperature variations, icing and lightning strikes), runway conditions, conditions of communication, navigation, and surveillance services, bird-strike, cabin and baggage fires. The term is not intended to cover sabotage.

l. Failure. An occurrence, which affects the operation of a component, part, or element such that it can no longer function as intended, (this includes both loss of function and malfunction). Note: Errors may cause Failures, but are not considered to be Failures.

m. Failure Condition. A condition having an effect on the aeroplane and/or its occupants, either direct or consequential, which is caused or contributed to by one or more failures or errors, considering flight phase and relevant adverse operational or environmental conditions, or external events.

n. Installation Appraisal. This is a qualitative appraisal of the integrity and safety of the installation. Any deviations from normal, industry-accepted installation practices, such as clearances or tolerances, should be evaluated, especially when appraising modifications made after entry into service.

o. Latent Failure. A failure is latent until it is made known to the flight crew or maintenance personnel. A significant latent failure is one, which would in combination with one or more specific failures, or events result in a Hazardous or Catastrophic Failure Condition.

p. Qualitative. Those analytical processes that assess system and aeroplane safety in an objective, non-numerical manner.

q. Quantitative. Those analytical processes that apply mathematical methods to assess system and aeroplane safety.

r. Redundancy. The presence of more than one independent means for accomplishing a given function or flight operation.

s. System. A combination of components, parts, and elements, which are inter-connected to perform one or more functions.

6. BACKGROUND

a. General.

For a number of years aeroplane systems were evaluated to specific requirements, to the "single fault" criterion, or to the fail-safe design concept. As later-generation aeroplanes developed, more safety-critical functions were required to be performed, which generally resulted in an increase in the complexity of the systems designed to perform these functions. The potential hazards to the aeroplane and its occupants which could arise in the event of loss of one or more functions provided by a system or that system's malfunction had to be considered, as also did the interaction between systems performing different functions. This has led to the general principle that an inverse relationship should exist between the probability of a Failure Condition and its effect on the aeroplane and/or its occupants (see Figure 1). In assessing the acceptability of a design it was recognised that rational probability values would have to be established. Historical evidence indicated that the probability of a serious accident due to operational and airframe-related causes was approximately one per million hours of flight. Furthermore, about 10 percent of the total were attributed to Failure Conditions caused by the aeroplane's systems. It seems reasonable that serious accidents caused by systems should not be allowed a higher probability than this in new aeroplane designs. It is reasonable to expect that the probability of a serious accident from all such Failure Conditions be not greater than one per ten million flight hours or 1×10^{-7} per flight hour for a newly designed aeroplane. The difficulty with this is that it is not possible to say whether the target has been met until all the systems on the aeroplane are collectively analysed numerically. For this reason it was assumed, arbitrarily, that there are about one hundred potential Failure Conditions in an aeroplane, which could be Catastrophic. The target allowable Average Probability per Flight Hour of 1×10^{-7} was thus apportioned equally among these Failure Conditions, resulting in an allocation of not greater than 1×10^{-9} to each. The upper limit for the Average Probability per Flight Hour for Catastrophic Failure Conditions would be 1×10^{-9}, which establishes an approximate probability value for the term "Extremely Improbable". Failure Conditions having less severe effects could be relatively more likely to occur.

b. Fail-Safe Design Concept.

The Part 25 airworthiness standards are based on, and incorporate, the objectives and principles or techniques of the fail-safe design concept, which considers the effects of failures and combinations of failures in defining a safe design.

(1) The following basic objectives pertaining to failures apply:

(i) In any system or subsystem, the failure of any single element, component, or connection during any one flight should be assumed, regardless of its probability. Such single failures should not be Catastrophic.

(ii) Subsequent failures during the same flight, whether detected or latent, and combinations thereof, should also be assumed, unless their joint probability with the first failure is shown to be extremely improbable.

(2) The fail-safe design concept uses the following design principles or techniques in order to ensure a safe design. The use of only one of these principles or techniques is seldom adequate. A combination of two or more is usually needed to provide a fail-safe design; i.e. to ensure that Major Failure Conditions are Remote, Hazardous Failure Conditions are Extremely Remote, and Catastrophic Failure Conditions are Extremely Improbable:

(i) Designed Integrity and Quality, including Life Limits, to ensure intended function and prevent failures.

(ii) Redundancy or Backup Systems to enable continued function after any single (or other defined number of) failure(s); e.g., two or more engines, hydraulic systems, flight control systems, etc.

(iii) Isolation and/or Segregation of Systems, Components, and Elements so that the failure of one does not cause the failure of another.

(iv) Proven Reliability so that multiple, independent failures are unlikely to occur during the same flight.

(v) Failure Warning or Indication to provide detection.

(vi) Flight crew Procedures specifying corrective action for use after failure detection.

(vii) Checkability: the capability to check a component's condition.

(viii) Designed Failure Effect Limits, including the capability to sustain damage, to limit the safety impact or effects of a failure.

(ix) Designed Failure Path to control and direct the effects of a failure in a way that limits its safety impact.

(x) Margins or Factors of Safety to allow for any undefined or unforeseeable adverse conditions.

(xi) Error-Tolerance that considers adverse effects of foreseeable errors during the aeroplane's design, test, manufacture, operation, and maintenance.

c. Highly Integrated Systems.

(1) A concern arose regarding the efficiency and coverage of the techniques used for assessing safety aspects of highly integrated systems that perform complex and interrelated functions, particularly through the use of electronic technology and software based techniques. The concern is that design and analysis techniques traditionally applied to deterministic risks or to conventional, non-complex systems may not provide adequate safety coverage for more complex systems. Thus, other assurance techniques, such as development assurance utilising a combination of process assurance and verification coverage criteria, or structured analysis or assessment techniques applied at the aeroplane level, if necessary, or at least across integrated or interacting systems, have been applied to these more complex systems. Their systematic use increases confidence that errors in requirements or design, and integration or interaction effects have been adequately identified and corrected.

(2) Considering the above developments, as well as revisions made to the CS 25.1309, this AMC was revised to include new approaches, both qualitative and quantitative, which may be used to assist in determining safety requirements and establishing compliance with these requirements, and to reflect revisions in the rule, considering the whole aeroplane and its systems. It also provides guidance for determining when, or if, particular analyses or development assurance actions should be conducted in the frame of the development and safety assessment processes. Numerical values are assigned to the probabilistic terms

included in the requirements for use in those cases where the impact of system failures is examined by quantitative methods of analysis. The analytical tools used in determining numerical values are intended to supplement, but not replace, qualitative methods based on engineering and operational judgement.

a. Classifications. Failure Conditions may be classified according to the severity of their effects as follows:

(1) No Safety Effect: Failure Conditions that would have no effect on safety; for example, Failure Conditions that would not affect the operational capability of the aeroplane or increase crew workload.

(2) Minor: Failure Conditions which would not significantly reduce aeroplane safety, and which involve crew actions that are well within their capabilities. Minor Failure Conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload, such as routine flight plan changes, or some physical discomfort to passengers or cabin crew.

(3) Major: Failure Conditions which would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to the flight crew, or physical distress to passengers or cabin crew, possibly including injuries.

(4) Hazardous: Failure Conditions, which would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating, conditions to the extent that there would be:

(i) A large reduction in safety margins or functional capabilities;

(ii) Physical distress or excessive workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; or

(iii) Serious or fatal injury to a relatively small number of the occupants other than the flight crew.

(5) Catastrophic: Failure Conditions, which would result in multiple fatalities, usually with the loss of the aeroplane. (Note: A “Catastrophic” Failure Condition was defined in previous versions of the rule and the advisory material as a Failure Condition which would prevent continued safe flight and landing.)

b. Qualitative Probability Terms.

When using qualitative analyses to determine compliance with CS 25.1309(b), the following descriptions of the probability terms used in CS 25.1309 and this AMC have become commonly accepted as aids to engineering judgement:

(1) Probable Failure Conditions are those anticipated to occur one or more times during the entire operational life of each aeroplane.

(2) Remote Failure Conditions are those unlikely to occur to each aeroplane during its total life,

but which may occur several times when considering the total operational life of a number of aeroplanes of the type.

(3) Extremely Remote Failure Conditions are those not anticipated to occur to each aeroplane during its total life but which may occur a few times when considering the total operational life of all aeroplanes of the type.

(4) Extremely Improbable Failure Conditions are those so unlikely that they are not anticipated to occur during the entire operational life of all aeroplanes of one type.

c. Quantitative Probability Terms.

When using quantitative analyses to help determine compliance with CS 25.1309(b), the following descriptions of the probability terms used in this requirement and this AMC have become commonly accepted as aids to engineering judgement. They are expressed in terms of acceptable ranges for the Average Probability Per Flight Hour.

(1) Probability Ranges.

(i) Probable Failure Conditions are those having an Average Probability Per Flight Hour greater than of the order of 1×10^{-5}.

(ii) Remote Failure Conditions are those having an Average Probability Per Flight Hour of the order of 1×10^{-5} or less, but greater than of the order of 1×10^{-7}.

(iii) Extremely Remote Failure Conditions are those having an Average Probability Per Flight Hour of the order of 1×10^{-7} or less, but greater than of the order of 1×10^{-9}.

(iv) Extremely Improbable Failure Conditions are those having an Average Probability Per Flight Hour of the order of 1×10^{-9} or less.

8. SAFETY OBJECTIVE.

a. The objective of CS 25.1309 is to ensure an acceptable safety level for equipment and systems as installed on the aeroplane. A logical and acceptable inverse relationship must exist between the Average Probability per Flight Hour and the severity of Failure Condition effects, as shown in Figure 1, such that:

(1) Failure Conditions with No Safety Effect have no probability requirement.

(2) Minor Failure Conditions may be Probable.

(3) Major Failure Conditions must be no more frequent than Remote.

(4) Hazardous Failure Conditions must be no more frequent than Extremely Remote.

(5) Catastrophic Failure Conditions must be Extremely Improbable.

b. The safety objectives associated with Failure Conditions are described in Figure 2.

Figure 1: Relationship between Probability and Severity of Failure Condition Effects

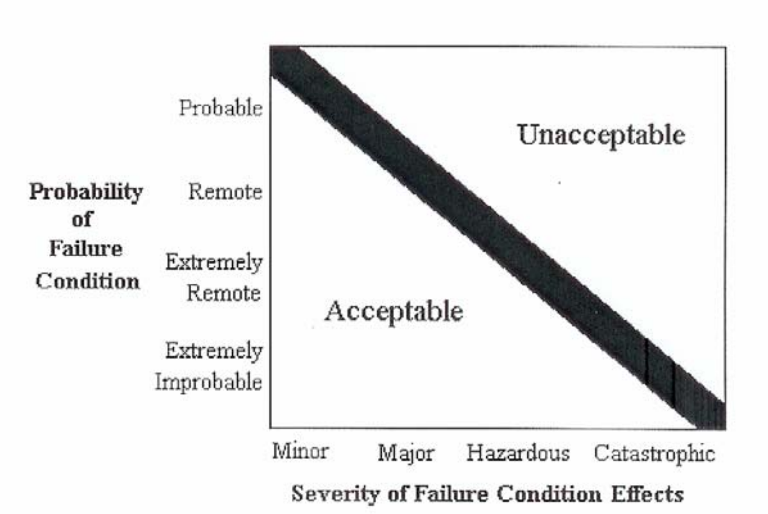


Figure 2: Relationship Between Probability and Severity of Failure Condition

Effect on Aeroplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants excluding Flight Crew	Inconvenience	Physical discomfort	Physical distress, possibly including injuries	Serious or fatal injury to a small number of passengers or cabin crew	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation
Allowable Qualitative Probability	No Probability Requirement	<---Probable---->	<----Remote---->	Extremely <------------------> Remote	Extremely Improbable
Allowable Quantitative Probability: Average Probability per Flight Hour on the Order of:	No Probability Requirement	<------------------> $<10^{-3}$ Note 1	<------------------> $<10^{-5}$	<------------------> $<10^{-7}$	$<10^{-9}$
Classification of Failure Conditions	No Safety Effect	<-----Minor------>	<-----Major------>	<--Hazardous-->	Catastrophic

Note 1: A numerical probability range is provided here as a reference. The applicant is not required to perform a quantitative analysis, nor substantiate by such an analysis, that this numerical criteria has been met for Minor Failure Conditions. Current transport category aeroplane products are regarded as meeting this standard simply by using current commonly-accepted industry practice.

Major Failure Conditions. Major Failure Conditions must be Remote:

(i) If the system is similar in its relevant attributes to those used in other aeroplanes and the effects of failure would be the same, then design and installation appraisals (as described in Appendix 1), and satisfactory service history of the equipment being analysed, or of similar design, will usually be acceptable for showing compliance.

(ii) For systems that are not complex, where similarity cannot be used as the basis for compliance, then compliance may be shown by means of a qualitative assessment which shows that the system level Major Failure Conditions, of the system as installed, are consistent with the FHA and are Remote, e.g., redundant systems.

(iii) For complex systems without redundancy, compliance may be shown as in paragraph 11d(3)(ii) of this AMC. To show that malfunctions are indeed Remote in systems of high complexity without redundancy (for example, a system with a self-monitoring microprocessor), it is sometimes necessary to conduct a qualitative functional Failure Modes and Effects Analysis (FMEA) supported by failure rate data and fault detection coverage analysis.

(iv) An analysis of a redundant system is usually complete if it shows isolation between redundant system channels and satisfactory reliability for each channel. For complex systems where functional redundancy is required, a qualitative FMEA and qualitative fault tree analysis may be necessary to determine that redundancy actually exists (e.g. no single failure affects all functional channels).

(4) Hazardous and Catastrophic Failure Conditions. Hazardous Failure Conditions must be Extremely Remote, and Catastrophic Failure Conditions must be Extremely Improbable:

(i) Except as specified in paragraph 11d(4)(ii) below a detailed safety analysis will be necessary for each Hazardous and Catastrophic Failure Condition identified by the functional hazard assessment. The analysis will usually be a combination of qualitative and quantitative assessment of the design.

(ii) For very simple and conventional installations, i.e. low complexity and similarity in relevant attributes, it may be possible to assess a Hazardous or Catastrophic Failure Condition as being Extremely Remote or Extremely Improbable, respectively, on the basis of experienced engineering judgement, using only qualitative analysis. The basis for the assessment will be the degree of redundancy, the established independence and isolation of the channels and the reliability record of the technology involved. Satisfactory service experience on similar systems commonly used in many aeroplanes may be sufficient when a close similarity is established in respect of both the system design and operating conditions.

(iii) For complex systems where true similarity in all relevant attributes, including installation attributes, can be rigorously established, it may be also possible to assess a Hazardous or Catastrophic Failure Condition as being Extremely Remote or Extremely Improbable, respectively, on the basis of experienced engineering judgement, using only qualitative analysis. A high degree of similarity in both design and application is required to be substantiated.