AIRCRAFT ACCIDENT REPORT 1/2009

Air Accidents Investigation Branch

Department for Transport

Report on the serious incidents to

Boeing 737-81Q, registration G-XLAC on 29 December 2006

Avions de Transport Regional ATR-72-202, registration G-BWDA on 29 December 2006

Embraer EMB-145EU, registration G-EMBO on 29 December 2006 and

Boeing 737-81Q, registration G-XLAC on 3 January 2007

at Runway 27, Bristol International Airport

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

The sole objective of the investigation of an accident or incident under these Regulations shall be the prevention of accidents and incidents. It shall not be the purpose of such an investigation to apportion blame or liablility.

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This report contains facts which have been determined up to the time of publication. This information is published to inform the aviation industry and the public of the general circumstances of accidents and serious incidents.

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2/2008	Airbus A319-131, G-EUOB during the climb after departure from London Heathrow Airport on 22 October 2005.	January 2008
3/2008	British Aerospace Jetstream 3202, G-BUVC at Wick Aerodrome, Caithness, Scotland on 3 October 2006.	February 2008
4/2008	Airbus A320-214, G-BXKD at Runway 09, Bristol Airport on 15 November 2006.	February 2008
5/2008	Boeing 737-300, OO-TND at Nottingham East Midlands Airport on 15 June 2006.	April 2008
6/2008	Hawker Siddeley HS 748 Series 2A, G-BVOV at Guernsey Airport, Channel Islands on 8 March 2006.	August 2008
7/2008	Aerospatiale SA365N, G-BLUN near the North Morecambe gas platform, Morecambe Bay on 27 December 2006.	October 2008

Department for Transport
Air Accidents Investigation Branch
Farnborough House
Berkshire Copse Road
Aldershot
Hampshire GU11 2HH

December 2008

The Right Honourable Geoff Hoon
Secretary of State for Transport

Dear Secretary of State

I have the honour to submit the report by Mr K Conradi, an Inspector of Air Accidents, on the circumstances of the serious incidents to Boeing 737-81Q, registration G-XLAC, Avions de Transport Regional ATR-72-202, registration G-BWDA and Embraer EMB-145EU, registration G-EMBO at Runway 27, Bristol International Airport on 29 December 2006 and 3 January 2007.

Yours sincerely

David King
Chief Inspector of Air Accidents

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Appendices

GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB	Air Accidents Investigation Branch
aal	above airfield level
AIC	Aeronautical Information Circular
AIP	Aeronautical Information Publication
amsl	above mean sea level
AOSWG	Aerodrome Operations and Services Working Group
ASU	Aerodrome Safety Unit
ATC	Air Traffic Control
ATIS	Automatic Terminal Information System
BIA	Bristol International Airport
CAA	Civil Aviation Authority
CAP	Civil air Publication
CFME	Continuous Friction Measuring Equipment
CVR	Cockpit Voice Recorder
°C	degrees Celsius
DOL	Design Objective Level
EASA	European Aviation Safety Agency
FCOM	Flight Crew Operating Manual
FDM	Flight Data Monitoring
FDR	Flight Data Recorder
FL	flight level
FMC	Flight Management Computer
FOD	Foreign Object Damage
FODCOM	Flight Operations Department Communication
ft	feet
ft/s^2	feet per second squared
g	normal acceleration
HDM	Heavy Duty Macadam
hrs	hours (clock time as in 12:00 hrs)
hz	hertz
ICAO	International Civil Aviation Organization
ILS	Instrument landing system
kg	kilogram(s)
KIAS	knots indicated airspeed
km	kilometre(s)
kN	kilonewton(s)
kt	knot(s)
LDA	Landing Distance Available
m	metre(s)
MATS	Manual of Air Traffic Services
METAR	a timed aerodrome meteorological report
MFL	Minimum Friction Level
MHz	megahertz
min(s)	minutes
mm	millimetre(s)
MOR	Mandatory Occurrence Report
NOTAL	Notice to Aerodrome Licence Holders
NOTAM	Notice to Airmen
PCU	Power Control Units
psi	pounds per square inch
psig	pounds per square inch gauge
PSV	Polished Stone Value
RFFS	Rescue and Fire Fighting Service
RHPS	Rudder Hardover Protection System
rpm	revolutions per minute
TAF	Terminal Aerodrome Forecast
UTC	Co-ordinated Universal Time (GMT)

Air Accidents Investigation Branch

Aircraft Incident Report No: 1/2009 (EW/C2006/12/05)

Three aircraft were involved in the principal events described in this report:

(i) Aircraft No 1 (This aircraft was involved in two events)

Registered Owner and Operator:	XL Airways UK Ltd
Aircraft Type and Model:	Boeing 737-81Q
Registration:	G-XLAC
Place of Incident:	Runway 27, Bristol International Airport Latitude: 51° 22' N Longitude: 002° 43' W
Date and Time:	(i) 29 December 2006 at 1150 hrs (ii) 3 January 2007 at 1832 hrs

(ii) Aircraft No 2

Registered Owner and Operator:	Aurigny Air Services Ltd
Aircraft Type and Model:	Avions de Transport Regional ATR-72-202
Registration:	G-BWDA
Place of Incident:	Runway 27, Bristol International Airport
Date and Time:	29 December 2006 at 1215 hrs

(iii) Aircraft No 3

Registered Owner and Operator:	British Airways CitiExpress PLC
Aircraft Type and Model:	Embraer EMB-145EU

Registration:	G-EMBO
Place of Incident:	Runway 27, Bristol International Airport
Date and Time:	29 December 2006 at 2133 hrs
	All times in this report are UTC unless otherwise stated.

Synopsis

The serious incidents involving G-BWDA and G-EMBO were notified to the Air Accidents Investigation Branch (AAIB) on 29 December 2006. An investigation into the two serious incidents began on 2 January 2007. During this investigation, the events involving G-XLAC, and others, were identified. All events took place during landings at Bristol International Airport, hereafter referred to as BIA.

The AAIB investigation team comprised:

Mr K Conradi	(Investigator-in-Charge)
Mr T J Atkinson	(Operations)
Mr S J Hawkins	(Engineering)
Mr C J Scott	(Flight Recorders)

Resurfacing and re-profiling work was taking place on parts of the runway at BIA as part of a major project to resurface the manoeuvring area pavements, and sections of the runway surface were ungrooved 'base course' asphalt. From 14 November 2006, there were reports from flight crew of a variety of problems related to the friction characteristics of the temporary runway surface, though no serious incidents occurred until 29 December 2006. On that day, the flight crew of G-XLAC experienced poor stopping performance during landing. Later that day, the flight crew of G-BWDA experienced stopping and lateral control difficulties during landing, and the aircraft departed the runway surface and came to rest on the grass area at the side of the runway. Later still, the flight crew of G-EMBO experienced lateral control difficulties during landing, and the aircraft partially left and then regained the runway. On 3 January 2007, another flight crew, also operating G-XLAC, experienced poor stopping performance. The airport was subsequently closed whilst grooves were cut in the base course. After it re-opened there were no further incidents.

The investigation identified the following causal factors:

1. Reduced friction on the wet ungrooved base course sections of the runway caused flight crews to experience reduced braking action and reduced lateral controllability on landing in strong crosswinds.

2. The Flight Operations Department Communication (FODCOM) advice published by the CAA regarding operations on runways notified ‘slippery when wet’, in wet conditions, was not communicated by operators to flight crews.

3. The passing, by ATC, of braking action reports based on Mu-meter friction assessments, gave flight crews a false confidence in the braking action available on the wet runway.

The investigation identified the following contributory factor:

1. G-BWDA landed in a crosswind outside the operator’s published limits and the subsequent use of reverse thrust was contrary to the advice contained in the company’s Operations Manual.

The AAIB has made five Safety Recommendations.

1 Factual Information

Events prior to 29 December 2006

On 1 November 2006, the aerodrome authority began a programme of runway resurfacing and re-profiling as part of a major project to resurface the manoeuvring area pavements. As a result, temporary ungrooved asphalt surfaces existed over some parts of the runway during the period when the incidents took place. A full width section, 295 metres long, around the mid-point of the runway, had a surface of ungrooved Marshall Asphalt base course[1], colloquially known as 'the patch' by airport staff, and referred to as such throughout this report. Figure 5 (page 34) shows the runway surface condition on 29 December 2006.

On 14 November 2006, the crew of a landing Embraer 145 reported to ATC that the runway surface condition was conducive to aquaplaning and, shortly after, the flight crew of a landing Airbus A319 reported aquaplaning on the left side of Runway 27, just west of the mid-point. The runway surface at the time of both landings was assessed for each third of its length as *'damp, wet, wet'*. The ATC watch log noted that *'water is proving slow to drain from the parts of the runway that have been worked on'*. ATC staff discussed this with the airport management, who advised that pilots should be told that due to runway resurfacing, temporary areas may be wet.

Using the guidance contained in CAP 683, '*The Assessment of Runway Surface Friction for Maintenance Purposes'* the airport authority issued a NOTAM on 15 November 2006, which stated:

> *'Due runway maintenance, sections of the runway between the intersections of taxiway foxtrot and delta may be slippery when wet. Braking action co-efficient readings will be available if required'*.

Throughout the days that followed, until 5 January 2007, the Aerodrome Safety Unit (ASU) routinely carried out Mu-meter runs on the runway. Mu-meter is one type of Continuous Friction Measuring Equipment (CFME); the airport had two Mu-meters for friction testing. Following each run, ASU staff passed friction values to ATC staff by radio. ATC staff converted those values to braking action descriptors, using the 'snow and ice table'[2] available to them in the Visual Control Room (VCR). These braking action descriptors, and/or the friction values, were subsequently passed to flight crews.

1 Marshall Asphalt base course is normally ungrooved; it is usually only the surface course laid on top that is grooved.

2 A table which enables friction values, assessed by Mu-meter, to be converted to descriptions of braking action, but is only relevant to operations on surfaces covered with snow and ice. The table is reproduced at Appendix F.

On the afternoon of 17 November 2006, when the runway surface was *'wet, wet, wet'*, the crew of a landing Embraer 145 reported that braking action in the middle section of the runway was *'poor'*. The Mandatory Occurrence Report (MOR) submitted by the crew described a *'total loss of braking action'* for about 3 seconds. That evening, a Mu-meter run was recorded in the ATC watch log as showing *'good braking action'*, and the runway surface was assessed as *'damp, wet, wet'*. The flight crew of a Fokker 100 aircraft which landed soon after the assessment reported that *'some of the middle bits of the runway have definitely not got good braking action'*.

Between 24 November 2006 and 27 November 2006 there were eight incidents reported verbally to ATC, of aircraft experiencing deceleration problems during the landing roll with aquaplaning being reported by flight crew in two of these events.

The Airport Authority did not receive any related MOR's prior to the incidents that occurred on 29 December 2006.

1.1 History of the flights

1.1.1 G-XLAC (Boeing 737-800) 29 December 2006 at 1150 hrs

The crew operated a return non-scheduled public transport (passenger) flight from BIA to Chambery Aix-les-Bains. They were aware of the NOTAM stating that the runway at BIA *'may be slippery when wet'* and also that rain was forecast for their return. The flight to Chambery was uneventful and the aircraft returned to BIA with the commander as the pilot flying.

Approaching BIA, the flight crew received the 1120 hrs ATIS which stated that the conditions were: surface wind of 190°/28 kt gusting to 39 kt, visibility of 8 km, one or two octas of cloud at 800 ft, aal and five to seven octas at 1,100 ft. The runway state was described by ATC as "DAMP, WET, DAMP" and the braking action as "GOOD". The flight crew briefed for an ILS approach and a landing with flap 30 selected, autobrake set to three and the use of full reverse thrust.

The commander carried out the approach to Runway 27 and disconnected the autopilot when he was visual with the runway. The aircraft, however, drifted off the extended runway centreline in the strong crosswind and the commander executed a go-around. Although he did not expect the weather conditions to change for a second approach, he stated that he felt the crew would be better prepared for a second attempt at landing.

The commander flew another ILS approach and became visual with the runway at about 400 ft agl. The wind readout on the Flight Management Computer (FMC) was 190°/57-60 kt[3]. Conditions were described by the commander as "very turbulent with very heavy rain". He disconnected the autopilot and continued the approach, positioning the aircraft slightly towards the upwind side of the runway.

The commander reported that he made the flare "as short as possible", as close as possible to the upwind edge of the runway. Although he achieved a short flare, the aircraft drifted slightly to the right, as he expected. Once all three landing gears were on the ground, the commander selected full reverse thrust and confirmed that the autobrake system was operating correctly. He assessed that the aircraft was decelerating normally and began using the toe brakes; this caused the autobrake to disconnect.

As the aircraft rolled onto the ungrooved centre section of the runway, the commander sensed that the wheels had 'locked up' and believed the antiskid system was not functioning properly due to the slipperiness of the surface. The aircraft veered towards the downwind (right) side of the runway, but remained on the paved surface. When the aircraft reached the grooved surface, the wheel brakes seemed to operate correctly again.

The commander reported that he brought the aircraft to taxi speed approximately 200 m from the end of the runway and considered that had the touchdown not been carried out towards the upwind edge of the runway, the aircraft would have departed the downwind side of the runway and run onto the grass. He thought the information received from ATC that the braking action was 'good' was misleading.

1.1.2 G-BWDA (ATR-72) 29 December 2006 at 1215 hrs

The flight crew were flying their third sector of the day, from Guernsey to BIA, having obtained the necessary pre-flight information, including NOTAMs and meteorological forecasts and reports. The NOTAMs, however, did not include any information about the condition of the runway at BIA, as the NOTAM filtering system in use by the company excluded NOTAMs more than 15 days old. The briefing pack provided to the flight crew included a list of the reference numbers of 138 NOTAMs which had been excluded by the search criteria.

3 This is not an accurate 'instant wind' value, but is a weighted average of very recent wind values computed from the inertial reference systems on board the aircraft. It gives an indication of the wind the aircraft has experienced in the last few moments.

The aircraft had been loaded in accordance with the company's standard loading instructions for the flight to BIA, with the centre of gravity position at landing calculated to be 24.2% of mean aerodynamic chord. This meant the aircraft was trimmed with the centre of gravity very slightly forward of the centre of its range at that mass.

The flight proceeded uneventfully and the flight crew received the 1150 hrs ATIS which stated that the wind was 180°/24-35 kt, visibility 3,500 m in slight rain and drizzle, one or two octas of cloud at 700 ft and overcast cloud at 1,000 ft. The temperature was 10°C and the runway condition was described as "DAMP, WET, DAMP". In accordance with company procedures, the co-pilot flew the ILS approach to Runway 27 with 30° of flap and the propellers at 100% rpm.

Whilst the aircraft was carrying out the approach, the ASU team conducted friction assessments of 'the patch' using a Mu-meter. They reported a friction of 0.44 in the westbound direction and 0.49 in the eastbound direction. They also measured the average friction over the entire runway length on the southern side of the runway; this gave an average value of 0.72.

During the last few miles of the approach, the tower controller broadcast the following wind information;

180°/23 kt	(landing clearance given at this point)
(83 seconds later)	190°/24 kt
(21 seconds later)	200°/26 kt
(18 seconds later)	170°/25 kt
(9 seconds later)	190°/34 kt

This final wind report was transmitted when G-BWDA was at a radio altitude of 70 ft and 15 seconds prior to touchdown.

The aircraft touched down normally at 1218 hrs, and the co-pilot gradually applied reverse thrust. The landing roll was without incident until, at a speed of approximately 75 kt, the aircraft yawed right slightly and the co-pilot applied left rudder. Subsequently the aircraft began to drift left of the runway centreline and both pilots recalled applying right rudder to correct this.

The co-pilot handed control to the commander[4] but retained control of the ailerons which he continued to apply into the wind. The commander recognised that the aircraft was still yawing and drifting to the left and, as the aircraft slowed, he applied a nosewheel steering input on the tiller in an attempt to correct this. However, the yaw and drift continued and the commander perceived that the aircraft was hydroplaning. It departed the paved surface onto the grass to the south and came to rest on a heading of approximately 227°M. The commander stated that the control inputs he had made in the latter part of the landing roll had no effect on the aircraft.

With the aircraft at rest, the commander spoke to the cabin crew and passengers, and ascertained that no injuries or damage had occurred in the cabin. At the suggestion of ATC, he attempted to make contact with the Rescue and Fire Fighting Service (RFFS) on 121.6 MHz[5] but experienced considerable difficulty in achieving adequate communication.

1.1.3 G-EMBT (Embraer 145) 29 December 2006 at 2001 hrs

This aircraft suffered an event during landing at 2001 hrs, which has been investigated separately and reported by the AAIB. The full report was published in Bulletin 3/2008 on 13 March 2008. The flight crew experienced difficulties keeping the aircraft straight as it rolled over 'the patch' during landing in strong crosswind conditions. The synopsis of the report stated:

> *'During the landing roll, in a strong crosswind, the aircraft's rudder hardover protection system (RHPS) tripped, which resulted in the loss of both rudder hydraulic systems and reversion to the rudder's mechanical mode. Despite the loss of hydraulic power to the rudder, the commander was able to maintain directional control using a combination of asymmetric braking and rudder. There was no fault found in the aircraft and no evidence of a rudder 'runaway'; high rudder pedal or brake pedal force application by the commander, or incorrectly adjusted pedal force microswitches, may have triggered the RHPS.*

4 The ATR aircraft type is fitted with one steering tiller for use on the ground, thus the pilot in the left seat must have control after landing.

5 121.6 MHz is a VHF communication frequency promulgated for use on the ground between flight crews and aerodrome fire and rescue services in the UK.

1.1.4 G-EMBO (Embraer 145) on 29 December 2006 at 2133 hrs

The flight crew reported for duty to fly return scheduled public transport (passenger) flights from BIA to Paris Charles de Gaulle. They were aware of the NOTAM stating that the runway *'may be slippery when wet'*, and that rain was likely. Although the commander was aware of the runway resurfacing work at BIA and had read NOTAMs describing it, he was not aware of difficulties other aircraft had experienced. However, on aircraft handover from the previous crew, he was told that an ATR-72 (G-BWDA) had been involved in a runway excursion earlier that day.

The commander operated the flight back to BIA as pilot flying; company standard operating procedures required flight crew to carry out monitored approaches, so control would pass from the commander to the co-pilot for the descent and initial approach, and the commander would re-take control for landing. The flight crew briefed for an ILS approach to Runway 27 and added 5 kt to the normal approach speed because of the anticipated turbulence.

The commander made contact with the approach radar controller at 2043 hrs and discussed the wind conditions. The controller stated that the wind had 'MAINLY BEEN AROUND TWENTY-FIVE KNOTS AND ABOVE CONSTANTLY'. At 2053 hrs, the aircraft entered the hold at BIA and the commander reported that he wished to monitor the wind for a few minutes before making the decision whether to land or divert. At 2059 hrs, the approach controller transmitted that the instant wind was 180°/20 kt and the two minute average was 180°/19-26 kt. The commander replied that he wished to make an approach. The approach controller vectored the aircraft for an ILS approach to Runway 27. At 2101 hrs the approach controller advised the flight crew that the runway was now flooded throughout its length and the commander stated that he wished to return to the hold pending a report on the braking action. The approach controller advised that it would not be possible to provide braking action until the runway ceased to be flooded. The commander then enquired as to whether a shower was affecting the runway, and the approach controller confirmed that it was.

At 2106 hrs, the approach controller advised that the runway surface was 'WATER PATCHES ON ALL THIRDS OVER 65% OF THE RUNWAY SURFACE, MEAN DEPTH IS 3 MM', and that braking action would shortly be provided. At 2116 hrs, the approach controller informed the commander that the instant wind was now 190°/20 kt, and the commander replied that he could make an approach but needed braking action information. The approach controller confirmed that the braking action check was in progress, and the commander began the approach in anticipation of receiving the braking action prior to touchdown.

At 2122 hrs, the approach controller passed an update of the runway surface condition, stating that all thirds were wet, and that 'BRAKING ACTION OVER THE WHOLE OF THE RUNWAY IS ZERO DECIMAL SEVEN TWO [PAUSE] WHICH IS GOOD [PAUSE] THE MID THIRD OF THE RUNWAY WHICH IS UNGROOVED BRAKING ACTION IS DECIMAL FIVE ZERO WHICH IS ALSO GOOD'. The commander replied that he wished to continue the approach.

At 2131 hrs, the tower controller cleared the aircraft to land and stated that the wind was 190°/19 kt. At this point the ASU passed Mu-meter readings of 0.52 and 0.53 for the un-grooved section of the runway. The co-pilot acknowledged the clearance to land, and the tower controller passed information based on the figures from the Mu-meter, stating that the braking action was 'GOOD'.

ATC broadcast the wind as from 190°/17 kt shortly before the aircraft landed. The aircraft broke out of cloud at 500 ft aal, and the commander disconnected the autopilot at 300 ft. The touchdown occurred with the left wing down and, in the commander's recollection, was "a little long". The commander began braking soon after touchdown concentrating on applying "even and symmetrical" braking whilst applying full left wing down aileron and full aircraft nose-down elevator. He very quickly experienced difficulties maintaining the runway centreline. The left main landing gear ran off the runway pavement and onto the grass area south of the runway before the commander gradually regained control of the aircraft and steered it back towards the runway centreline. The left main landing gear had run on the grass for 85 m; the nose and right main landing gear had remained on the runway. The aircraft came to a halt with all the landing gear back on the runway.

The tower controller transmitted to the aircraft '[CALLSIGN] JUST CONFIRM YOU'RE OK' and the co-pilot replied 'YEAH WE'RE FINE NOW BUT WE DID GO THROUGH THE GRASS [PAUSE] WE SKIDDED AWAY COMPLETELY ON THE MIDDLE SECTION'.

The crew stated their intention to taxi to their stand but the controller suggested they remain stationary awaiting aircraft inspection. This was conducted by the RFFS and although they assessed the aircraft as being undamaged, they identified that there was considerable grass and mud on the runway and that a runway edge light had been damaged. The aircraft was also inspected by a ground engineer, pins were inserted in the aircraft's landing gear and the aircraft taxied to a parking stand under its own power where the passengers disembarked normally.

The commander commented that the combination of moderate rain and the wet runway had made it difficult to see precisely where the edge of the runway surface was during the landing roll.

The aircraft operator carried out an investigation and the interim report stated:

> *'prior to [this incident], company air safety reports detailing three occasions of transient loss of braking action during the landing roll on Runway 27 had been received. No reports involving any loss of directional control had been received. Whilst the most recent of these three reports were still the subject of correspondence between [the company safety department] and Bristol Airport ATC/airport on the day of the incident, Company Flight Operations had not indicated any significant safety concern.'*

The investigation made three initial safety recommendations regarding takeoff and landing distance at BIA, use of crosswind limits applicable to a 'slippery' runway for operations at BIA whilst any part of the runway was 'wet', and both a one-off and ongoing review of NOTAMs throughout the company's network of destinations, to ensure that the company took action to introduce temporary operating restrictions where appropriate.

1.1.5 Events between 29 December 2006 and 3 January 2007

At 1346 hrs on 30 December 2006, an RJ-100 aircraft landed on Runway 27, which was reported to be "WET, WET, WET" at the time. A Mu-meter run completed 20 minutes earlier gave an average friction value of 0.42 in the middle portion of the runway. The flight crew reported the middle section of the runway as *'very slippery'*, and asked for it to be inspected.

Twenty minutes later, the flight crew of a departing Airbus A319 reported that the runway was *'very slippery'* in the middle section. A Mu-meter run carried out immediately after this report found the friction values to be 0.38 and 0.42 in the middle portion.

At 1530 hrs on 30 December 2006, the airport authority issued a NOTAM concerning the runway condition:

'due to rwy maint the rwy sfc btn the int of twys delta and foxtrot will be slippery when wet. variable friction co-efficient readings will be experienced throughout the rwy length and are avbl on request. acft handling difficulties may be experienced during crosswind conditions.'

This NOTAM stated that the runway 'will be' slippery when wet; the previous stated that it 'may be'.

1.1.6 G-XLAC (Boeing 737-800) 3 January 2007

The aircraft had flown from BIA to Fuerteventura on a non-scheduled public transport (passenger) flight and was returning to BIA with the commander as the pilot flying. The flight crew were aware of the NOTAM stating that the runway *'will be slippery when wet'*; forecasts indicated that rain was likely.

As the aircraft approached BIA at 1805 hrs, a Mu-meter friction assessment was carried out on 'the patch'. This gave a friction value of 0.52, and this information and the verbal description 'GOOD' were passed to the flight crew by the approach radar controller.

The METAR issued at 1820 hrs stated that the wind was 210°/15-25 kt, visibility was 10 km or more in moderate showers of rain, there were one or two octas of cloud at 500 ft, three or four octas at 800 ft, and five to seven octas at 1,000 ft. The temperature was 10°C and the dewpoint 9°C, and the runway was wet throughout its length.

The commander briefed and flew an ILS approach to Runway 27 using flap 40 and MAXIMUM autobrake to ensure the minimum stopping distance. He described the approach as *'demanding'* and stated that touchdown, at 1832 hrs, occurred in the landing zone and the automatic speedbrake system operated correctly.

The commander applied *'full'* reverse thrust and stated that he felt no response from the brakes and that the aircraft began to skid. He maintained directional control and, at about 110 KIAS, applied maximum pedal braking, which caused the autobrake to disconnect. However, he did not perceive a speed reduction as expected. He was concerned that the aircraft may overrun the runway end but recognised that as the thrust reversers had been deployed, it would not be possible to go around. As the aircraft ran from 'the patch' onto the grooved section of runway, the deceleration became more rapid and the aircraft was brought safely to a stop prior to exiting the runway at the runway end.

The commander stated that he had, in the past, made landings on contaminated runways with braking actions described as both 'medium' and 'poor', but that he had never experienced the lack of braking effectiveness which occurred on this occasion. After the landing, another Mu-meter run was carried out, and this also gave friction values between 0.45 and 0.52 in the ungrooved section.

1.2 Injuries to persons

1.2.1 Injuries to persons – G-XLAC 29 December 2006

Injuries	Crew	Passengers	Others
Fatal	–	–	–
Serious	–	–	–
Minor / None	9	186	–

1.2.2 Injuries to persons – G-BWDA 29 December 2006

Injuries	Crew	Passengers	Others
Fatal	–	–	–
Serious	–	–	–
Minor / None	4	52	–

1.2.3 Injuries to persons – G-EMBO 29 December 2007

Injuries	Crew	Passengers	Others
Fatal	–	–	–
Serious	–	–	–
Minor / None	4	13	–

1.2.4 Injuries to persons – G-XLAC 3 January 2007

Injuries	Crew	Passengers	Others
Fatal	–	–	–
Serious	–	–	–
Minor / None	7	187	–

1.3 Damage to the aircraft

The only damage was to G-BWDA which suffered damage to a blade on its left propeller, which was replaced.

1.4 Other damage

During the G-EMBO runway excursion a runway edge light was damaged.

1.5 Personnel information

Personnel information for each flight is included in Appendix E.

1.6 Aircraft information

1.6.1 G-XLAC aircraft information

Manufacturer:	The Boeing Commercial Airplane Group
Type:	Boeing 737-81Q
Aircraft Serial Number:	29051
Year of manufacture:	2000
Number and type of engines:	2 CFM56-7B26 turbofan engines
Total airframe hours:	22,339 hrs
Certificate of Registration:	Issued on 15 March 2006 and valid
Certificate of Airworthiness:	Valid until 14 March 2008

1.6.1.1 Boeing 737-800 general description

The Boeing 737-800 is a short to medium range twin engine jet airliner (see Figure 1). It seats up to 188 passengers and is powered by two CFM56 turbofan engines.

Figure 1

Boeing 737-800, G-XLAC (photo courtesy of Ian Meadows)

1.6.1.2 Boeing 737-800 control system description

The Boeing 737-800 has a conventional flight control system with mechanically commanded Power Control Units (PCUs) using hydraulic pressure to move control surfaces. The rudder is a single conventional rudder without tabs. A main and a standby rudder PCU control the rudder with mechanical inputs via cables and control rods from the rudder pedals.

The aircraft is equipped with a nosewheel steering system which is normally powered by hydraulic system A, but can be powered by hydraulic system B in the event of a failure. The primary means of controlling the nosewheel at low speed is via the nosewheel steering wheel (also known as the tiller), with limited steering control available using the rudder pedals.

1.6.1.3 Boeing 737-800 brake system description

Each of the four main gear wheels has a multi-disc hydraulic powered brake. The left and right brake pedals (part of the rudder pedals) provide independent control of the left and right main gear wheel brakes. The normal brake system is powered by hydraulic system B and can be powered by system A (alternate brake system) in the event of a failure. The brake system also comprises antiskid protection, locked wheel protection, touchdown/hydroplane protection, and an autobrake system. The maximum brake pressure is 3,000 psi.

1.6.1.3.1 Boeing 737-800 antiskid system - normal brakes

The antiskid system protects the aircraft from a skid condition by releasing brake pressure to a wheel which is about to skid. The wheel speed is measured by a speed transducer in each wheel and there are four antiskid valves which control the brake pressure to each wheel brake. If the antiskid system detects that one wheel is slowing down too quickly, it will command the antiskid valve to release some of the brake pressure to that wheel, until the wheel's speed starts to increase again. It will then allow brake pressure to be reapplied. Antiskid does not operate at an aircraft groundspeed below 8 kt.

Locked wheel protection is another part of the brake system which compares the wheel speeds of the two outboard or the two inboard pair of wheels. If the slower wheel's speed decreases to less than 30% of the faster wheel's speed, the locked wheel protection releases brake pressure from the slower wheel. Locked wheel protection does not operate at a groundspeed of less than 25 kt.

Touchdown/hydroplane protection is a system that compares wheel speed to ground speed. If a wheel's speed reduces to 50 kt less than the ground speed, this system releases pressure to that wheel's brake. Only the left outboard and right inboard wheels are protected by this system.

1.6.1.3.2 Boeing 737-800 autobrake system

The autobrake system provides automatic braking at pre-selected deceleration rates immediately after touchdown and for a rejected takeoff. Antiskid protection will reduce autobrake commanded brake pressure if a skid is detected. The autobrake select switch has six positions: RTO, OFF, 1, 2, 3, and MAX. The target deceleration rates and brake pressures for each of the autobrake settings are shown as follows:

Autobrake setting	**Deceleration rate (ft/s^2)**	**Deceleration rate (g)**	**Brake pressure (psi)**
1	4	0.124	1285
2	5	0.155	1500
3	7.2	0.224	2000
MAX/RTO	12 if below 80 kt 14 if above 80 kt	0.373 if below 80 kt 0.435 if above 80 kt	3000

The autobrake system will apply brake pressure up to the pressure limit listed in the table in order to achieve the target deceleration rate. If the autobrake is set to MAX for touchdown, the system will not apply the maximum 3,000 psi if a deceleration rate of 0.435 g can be achieved using less than 3,000 psi. The pilot can override the autobrake system at any time by depressing the brake pedals sufficiently to command at least 750 psi. If the autobrake pressure is above 750 psi when the pilot commands a pressure of 750 psi, then the brake pressure will reduce to the pilot commanded level. However, if a pilot were to rapidly apply a pressure that is the same or higher than the autobrake pressure, then a pressure drop would not occur.

1.6.1.4 Boeing 737-800 tyre pressures

The main gear tyre pressures for the Boeing 737-800 are 205 ± 5 psig, but there is a variable chart in the aircraft maintenance manual which permits this pressure to be reduced when operating below maximum gross weight.

1.6.1.5 Boeing 737-800 performance

Performance information relating to flight planning for the aircraft (ie, that used prior to departure to assure the safety of a proposed operation) was contained in the manufacturer's Flight Planning and Performance Manual. Performance information for use in flight was contained in the Quick Reference Handbook, available on the flight deck. The two sets of information differed in that information to be used in flight was presented largely in an un-factorised form, whereas that used prior to flight incorporates safety factors. Data was presented for operations on dry, damp, wet, and contaminated runways, and for braking action good, medium, and poor, but no data was presented for wet runways which had been notified 'slippery when wet'.

The manufacturer shows a maximum demonstrated crosswind component of 33 kt for G-XLAC for landing.

1.6.2 G-BWDA aircraft information

Manufacturer:	Avions De Transport Regional (ATR)
Type:	ATR 72-202
Aircraft Serial Number:	444
Year of manufacture:	1995
Number and type of engines:	2 Pratt & Whitney Canada PW124B turboprop engines
Total airframe hours:	19,488 hours
Certificate of Registration:	Issued on 29 August 2003 and valid
Certificate of Airworthiness:	Valid until 28 August 2008

1.6.2.1 ATR 72 general description

The ATR 72 is a twin-turboprop short-haul regional airliner (see Figure 2). It seats up to 72 passengers and is powered by two Pratt & Whitney PW124B turboprop engines.

Figure 2

ATR 72 aircraft, G-BWDA (photo courtesy of Stuart Lawson)

1.6.2.2 ATR 72 control system description

The ailerons, elevators and rudder on the ATR 72 are all mechanically actuated without hydraulics. Two spoilers augment roll control and these are hydraulically actuated. The rudder has a spring tab which moves in the direction opposite of rudder movement to help reduce rudder pedal forces. The tab's travel increases with airspeed so that pedal force is reduced more when aerodynamic forces are high. The rudder is linked to the aircraft structure by a damper which regulates rudder travel speed and also reduces rudder movement on the ground as a result of wind gusts. A rudder Travel Limitation Unit reduces maximum rudder deflection at airspeeds above 180 kt. The maximum rudder deflection below this speed is ±27°.

The nosewheel steering system is mechanically controlled and hydraulically operated. The nosewheel steering position is controlled by a steering control hand wheel mounted on the commander's left console. During takeoff, landing and taxiing operations the nosewheel steering angle is limited to ±60°. During towing operations, with no hydraulic pressure in the system, the nosewheel can be deflected up to ±91°. There is no connection between the rudder pedals and the nosewheel steering system. There is no maximum speed limit for nosewheel steering operation, and the Flight Crew Operating Manual (FCOM) advises that the commander take control of the nosewheel steering at a speed no lower than 40 kt.

1.6.2.3 ATR 72 brake system description

The four main gear wheels are equipped with multidisc carbon brakes which are each operated by a set of hydraulically powered pistons. Normal braking is controlled by brake pedals which are part of the rudder pedals and permit the use of differential braking to assist with steering. The aircraft is fitted with an antiskid system which operates on all four main wheels at speeds above 10 kt. The system measures each wheel speed and moderates the pilot commanded brake pressure to obtain maximum stopping performance without skidding. The ATR 72 is not equipped with an autobrake system but, maximum braking is possible without restriction down to a stop, regardless of runway condition, provided that antiskid is operative.

1.6.2.4 ATR 72 reverse thrust description

The four-bladed propellers on the ATR 72 are variable pitch and can be set to negative blade pitch angles for reverse thrust operations. Reverse thrust is commanded by moving the power levers aft of Ground Idle into the reverse thrust range. Maximum reverse thrust can be used down to a stop if required, although to minimise flight control shaking, it is advised that reverse thrust is reduced to Ground Idle below 40 kt.

1.6.2.5 ATR 72 performance

Performance information relating to flight planning for the aircraft (ie, that used prior to departure to assure the safety of a proposed operation) and to enable calculations in flight was contained in the FCOM and other documents. Information to be used in flight, was presented in an un-factorised form, whereas that used prior to flight incorporated safety factors. Both factorised and un-factorised data was presented for operations on dry, damp, wet, and contaminated runways, but no data was presented for wet runways which had been notified 'slippery when wet'.

The operator's operations manual Part B included the following information in the 'Limitations' section:

'Maximum Crosswind Component for Take-Off and Landing
The following maximum crosswind components apply:

Dry Runways	*30 kt*
Wet Runways	*25 kt*
Contaminated Runways	*15 kt with Braking Action Medium*
Contaminated Runways	*5 kt with Braking Action Medium/Poor'*

1.6.2.6 ATR 72 operations in strong crosswinds

The operator's operations manual part B included the following instruction:

> *'To increase nose-wheel steering effectiveness in strong cross-wind conditions, load the aircraft to obtain a forward CG.'*

The operator had not established a procedure by which this could be accomplished and some members of the operator's staff, when interviewed, were not aware of this instruction. The commander of G-BWDA was not aware of this instruction.

The 'crosswind landing' section of the operations manual part B also stated:

> *'Any reluctance to use sufficient into wind aileron will lead to the airframe listing away from the wind direction due to the close tracked main undercarriage. This must be avoided to ensure no additional directional control difficulty.*
>
> *If reverse is required, apply reverse slowly and symmetrically. If problems with directional control occur reduce reverse or select ground idle.'*

With regard to normal landing technique, the manual stated:

> *'F/O holds control column fully forward and aileron into wind as required to keep wings level.'*

1.6.3 G-EMBO aircraft information

Manufacturer:	Empresa Brasileira De Aeronautica SA (Embraer)
Type:	EMB-145EU
Aircraft Serial Number:	145219
Year of manufacture:	2000
Number and type of engines:	2 Allison AE3007 turbofan engines
Total airframe hours:	14,156 hrs
Certificate of Registration:	Issued on 18 February 2003 and valid
Certificate of Airworthiness:	Valid until 13 March 2008

1.6.3.1 Embraer 145 general description

The Embraer 145 is a 50-seat regional jet powered by two Allison AE3007 turbofan engines (see Figure 3).

Figure 3

Embraer 145 aircraft, G-EMBO (photo courtesy of Michael Brazier)

1.6.3.2 Embraer 145 control system description

The rudder on the Embraer 145 is split into two sections in tandem: forward and aft. The forward rudder is driven by the control system while the aft rudder is mechanically linked to the forward rudder and is thus deflected as a function of forward rudder deflection. The forward rudder is driven by two rudder actuators connected to a PCU in the rear fuselage. The PCU is commanded by the rudder pedals via control cables that run from the pedals in the flight deck to the PCU. The maximum rudder deflection on the ground is ±15° and in the air is ±10°. The corresponding rudder pedal deflection on the ground is ±9° and in the air is ±6°.

The nosewheel steering system is electronically controlled and hydraulically operated. The nosewheel steering position can be controlled by the rudder pedals or by the steering handle (also known as the tiller) on the commander's left console. There is no steering handle on the co-pilot's side. The pedals can command up to ±5° of nosewheel steering angle, and the steering handle can command up to ±71°. If the pedals and steering handle are used in combination, then a maximum of ±76° of nosewheel steering angle can be obtained. The steering handle is normally only used below a speed of 40 kt.

1.6.3.3 Embraer 145 brake system description

The Embraer 145 has two main landing gears, with two wheels on each gear. Each wheel has a disc brake and an associated hydraulic brake control valve. Normal braking is controlled by toe brakes on the rudder pedals. The aircraft is fitted with an anti-skid system which is designed to provide the maximum allowable braking effort for the runway surface in use, while preventing skidding. This is accomplished by measuring each wheel speed. If one wheel speed drops significantly below the aircraft's average wheel speed, a skid is probably occurring, so the brake pressure is relieved to the appropriate wheel brake until its speed recovers. The wheels and corresponding brakes are numbered sequentially from one to four (left outboard is number one and right outboard is number four).

The anti-skid system does not apply pressure on the brakes, but only relieves the pilot-commanded pressure to avoid a skid. Therefore, in order to steer the aircraft using asymmetric braking, during a heavily braked landing, the pilot needs to reduce brake pressure on the side opposite to the direction of turn, instead of applying pressure to the desired side.

The Embraer 145 does not have an autobrake system and G-EMBO was not fitted with the optional thrust reverser system.

1.6.3.4 Embraer 145 performance

The operator of G-EMBO had published performance information in the operations manual, and also operated a computerised performance calculation system at its head office; flight crew could request calculations to be made to meet operational needs. The operations manual gave advice and information about operation on slippery runways, but did not define how flight crews should make performance decisions on wet runways notified as *'may be slippery when wet'*. The slippery runway table in the operations manual required knowledge of braking action before slippery runway calculations could be made.

1.7 Meteorological information

1.7.1 Meteorological information relating to 29 December 2006

Analysis of the relevant meteorological data showed that at 0600 hrs on 29 December 2006, a complicated, multi-frontal situation existed over the UK. A cold front over Bristol separated a moist, south-westerly warm sector and a returning polar maritime air mass. A second frontal system moved rapidly into the area, bringing further moist, warm sector conditions to the Bristol area from 1200 hrs. By 1800 hrs, the south-west was still under moist, warm sector conditions, with a second enclosed warm sector over St George's Channel at 1800 hrs. In summary, from the early hours of the morning the area was mostly affected by a strong and gusty, south-south-west to south-westerly surface wind.

Two of the Terminal Aerodrome Forecasts (TAFs) that cover the period of the aircraft incidents are as follows:

> 290413 16015G25KT 9999 SCT010 BKN020 TEMPO 0407 7000 BKN014 TEMPO 0713 6000 RA BKN008 BECMG 0811 18022G 35KT PROB30 TEMPO 1013 4000 +RA BKN004=

> 291601 17018KT 5000 -RA BKN008 TEMPO 1619 18020G32KT 9999 NSW BKN012 TEMPO 1901 20023G35KT 3000 +RA RADZ BKN004=

The relevant Meteorological Actual Reports (METARs) for the incidents are as follows:

> 291120Z 19028G39KT 8000 FEW008 BKN011 10/09 Q1007
> 291150Z 18024G35KT 3500 -RADZ FEW007 OVC010 10/09 Q1008
> 291220Z 18023KT 3500 -RA SCT006 BKN008 10/09 Q1008
> 291820Z 18021G31KT 7000 -RA BKN004 11/10 Q1004
> 292120Z 18023G35KT 8000 RA SCT005 BKN007 11/11 Q1001

1.7.2 Meteorological information relating to 3 January 2007

Analysis of the relevant meteorological data showed that at 0600 hrs, a broad warm sector covered the UK with a moist, tropical maritime airflow. An additional warm front was over Pembrey, south-west Wales, at 0600 hrs, and crossed Bristol a little less than three hours later. At about 1800 hrs, a cold front was over Cardiff and crossed Bristol about an hour later.

The TAF that covers the period of the aircraft incident was:

> 031601 22020G35KT 9999 -RA BKN012 TEMPO 1619 4000 -RADZ BKN005 PROB30 TEMPO 1719 23025G45KT +RA BECMG 1820 25022G37KT SCT015 PROB30 TEMPO 1901 7000 SHRA BKN012=

and the actual report was

031820Z 21015G25KT 9999 SHRA FEW005 SCT008 BKN010 10/09 Q1010

1.7.3 Reported runway conditions for 29 December 2006 and 3 January 2007

Date	29/12/2006	
Time	**Incident**	**Reported Runway Condition**
11:12		Damp-Wet-Damp
11:50	G-XLAC	
12:30	G-BWDA	
13:56		Wet-Wet-Wet
14:03		Wet-Wet-Wet
14:51		Wet-Wet-Wet
19:23		Damp-Wet-Damp
20:01	G-EMBT	
21:06		Flooded-Flooded-Flooded
21:12		Water Patches-Water Patches-Water Patches
21:15		Water Patches-Wet-Wet
21:25		Wet-Wet-Wet
21:35	G-EMBO	
Date	**03/01/2007**	
18:05		Wet-Wet-Wet
18:32	G-XLAC	
18:43		Wet-Wet-Wet

1.8 Aids to navigation

Not applicable.

1.9 Communications

1.9.1 Runway state reporting means and methods

The runway state is typically assessed by airport authority staff often in vehicles moving around the airport or by ATC staff from the visual control room. Instructions regarding assessment of runway state were included in both the UK Aeronautical Information Publication (AIP) and the Manual of Air Traffic Services Part 1 (MATS Part 1)(CAP 493). At BIA, the responsibility for the runway surface state assessment rests with the aerodrome authority.

MATS Part 1 included the following definitions regarding reporting runway conditions:

'Dry

The surface is not affected by water, slush, snow, or ice.

NOTE: Reports that the runway is dry are not normally to be passed to pilots. If no runway surface report is passed, pilots will assume the surface to be dry.

Damp

The surface shows a change of colour due to moisture. NOTE: If there is sufficient moisture to produce a surface film or the surface appears reflective, the runway will be reported as WET.

Wet

The surface is soaked but no significant patches of standing water are visible.

NOTE: Standing water is considered to exist when water on the runway surface is deeper than 3mm. Patches of standing water covering more than 25% of the assessed area will be reported as WATER PATCHES.

Water patches

Significant patches of standing water are visible.

NOTE: Water patches will be reported when more than 25% of the assessed area is covered by water more than 3mm deep.

Flooded

Extensive patches of standing water are visible.

NOTE: Flooded will be reported when more than 50% of the assessed area is covered by water more than 3mm deep.

Water depth on runways is typically measured using washers of known thickness, placed on the runway surface by a human observer.

The AIP noted that 'for JAR-OPS performance purposes, runways reported as DRY, DAMP or WET should be considered as NOT

CONTAMINATED' and that 'for JAR-OPS performance purposes, runways reported as WATER PATCHES or FLOODED should be considered as CONTAMINATED.'

1.9.2 Braking Action

The process by which braking action should be assessed and communicated to pilots is described in MATS Part 1. It stated that when reports of braking action are passed to pilots by radio, they should be in plain language and an assessment should be given sequentially for each third of the runway to be used. It stated:

> *'in conditions of slush or thin deposits of wet snow, friction measuring devices can produce inaccurate readings. Therefore, in conditions of slush, or uncompacted snow, no plain language estimates of braking action derived from those readings shall be passed to pilots.'*

No reference was made to braking action reports on dry, damp, or wet, runways.

In explaining the terms used, it stated:

> *'the word 'good' is used in a comparative sense and is intended to mean that aircraft generally, but not specifically, should not experience undue directional control or braking difficulties, but clearly a surface affected by ice and/or snow is not as good as a clean dry runway.'*

The MATS Part 2 in use at the airport included the following instruction:

> *'Contamination by water*
>
> *The measurement of the runway friction value will not normally be required but if requested by a pilot this value will be measured by mu-meter (MATS Part 1 Section 9 Chapter 3 pages 2-3 refer).'*

The reference to MATS Part 1 referred to above was erroneous, as that section was removed some years before the events described in this report; the investigation was not able to identify in exactly which revision it was removed. Following the incidents investigated in this report, this MATS Part 2 instruction was removed.

Prior to 16 November 2006, this practice was not in place at BIA but after this date it became common for controllers to pass either braking action descriptions in words, or the figures output by the Mu-meter, or both. It also became common for controllers to pass such information both for the runway as a whole, and specifically for the 'patch'.

On 5 January 2007, conversations took place between the airport authority, Bristol ATC and the CAA regarding the passing of braking action reports. The CAA subsequently directed ATC staff at the airport that:

> *'the passing of braking action on a wet runway is to cease. If an aircraft requests any braking action information [controllers] are to advise that "braking action is unavailable".'*

MATS Part 1 instructions regarding braking actions reports.

MATS Part 1 includes instructions to controllers regarding:

> *'Essential aerodrome information', which is defined as 'concerning the state of the manoeuvring area... which may constitute a hazard to a particular aircraft.'*

Such information must be issued to pilots in sufficient time to ensure the safe operation of aircraft.

Essential aerodrome information includes:

> *'reports on the estimated braking action determined either by CFME[6] or by reports from pilots of aircraft which have already landed.'*

The information must include a description of the prevailing conditions, the time of measurement or report, and the type of aircraft if an aircraft report.

1.9.3 UK AIP

The UK AIP stated:

> *'when a runway is contaminated by water (i.e. more than 3 mm), wet snow or slush, a braking action report will not be available due to the limitations of existing friction measuring equipment..., however,*

6 Continuous Friction Measuring Equipment.

> *a runway surface condition report will normally be available stating the type of contaminant and its respective depth.'*

Although the AIP stipulated that braking action reports would not be made available on a runway 'contaminated' by water, it did not specifically state that CFME was not to be used on a runway which was simply 'wet'. The CAA's position was that there was no intention that such friction assessments in the wet be used to determine braking action.

No table existed in the UK to enable the interpretation of CFME readings on wet surfaces into braking action reports relevant to aircraft operations.

1.9.4 *'Slippery when wet'*

The definition of the term *'slippery when wet'* is described in the MATS Part 1. It stated:

> *'wet surface friction characteristics of the runways at certain aerodromes have been calibrated to ensure that they are of an acceptable quality. If the quality deteriorates below an acceptable level the particular runway will be notified as liable to be slippery when wet.'*

This information is repeated in AIC 15/2006 which also states that when a runway is notified *'may be slippery when wet'*, aircraft operators may request additional information relating to that notification from the aerodrome operator, and that:

> *'any performance calculations or adjustment made as a result of this information is the responsibility of the aircraft operator.'*

A *'slippery when wet'* NOTAM needs to be issued if a friction survey determines that the friction level has dropped below the Minimum Friction Level (MFL) (in accordance with CAP 683).

1.9.5 Notice to Aerodrome Licence Holders (NOTAL) 9/2006

NOTAL 9/2006, 'Winter operations' laid out the requirements placed upon aerodrome authorities regarding safe operations in adverse weather conditions. It stated:

'To provide for safe operations in adverse winter conditions, appropriate information must be made available to pilots and aircraft operators. However, this information has to be reliable and relevant to the aircraft operation or movement. The Aerodrome Licensee is responsible for the determination, measurement and dissemination of information on the condition of the movement area for use by aircraft, particularly if there is any contamination by water, snow, slush or ice. Similarly, the Licensee is responsible for the treatment of any contamination or the withdrawal of any part of the movement area that is unfit for use.

As part of an aerodrome's safety management system, plans and procedures for winter operations should be reviewed as necessary and in a timely manner.'

The NOTAL also stated:

'In practical terms.., using CFME in conditions beyond the technical capabilities of the equipment and then making those potentially inaccurate readings available to aircraft operators or flight crew (via air traffic services) is not permitted.'

For ASU staff at BIA, the relevant operating instructions were contained within the ASU Departmental Instruction 04/07, titled *'The assessment and reporting of runway surface conditions'*. This document was written to reflect the requirements set out in NOTAL 9/2006.

1.9.6 Operational advice and information to flight crews

The CAA publishes FODCOMs (Flight Operations Department Communications) on a variety of topics. In addition to being published on the CAA website, they are sent to senior managers at companies holding Air Operators Certificates. They are not sent to private operators or foreign operators flying into the UK. Pilots are required to operate their aircraft according to the instructions and advice contained in their operations manuals. However, the inclusion of FODCOM advice into these manuals is at the discretion of the aircraft operator and not mandatory.

FODCOM 19/2006, entitled ‘Winter operations’ was published on 30 October 2006. Its purpose was:

> *‘to review and refresh some of the procedures and best practice that operators should adopt during winter operations.’*

and it included information and advice about operations on ‘slippery when wet’ runways.

The FODCOM stated:

> *‘Braking action is assumed to be poor on a wet runway that is notified as one that may be slippery when wet. Operators should ascertain from aerodrome operators the location and dimension of the part of the runway that has fallen below the minimum friction, ‘slippery when wet’ trigger level, in order that they can assess whether aeroplane performance is affected.*
>
> *There is no reliable correlation available between the readings of Continuous Friction Measuring Equipment (CFME) on a runway contaminated with water, slush and snow, and aircraft braking performance. Performance calculations must not be based on such readings. They will not be made available at licensed aerodromes in the UK.’*

The operators of the aircraft involved in these events had not incorporated the advice in this FODCOM regarding runways notified as *‘may be slippery when wet’* into their operations manuals or made their flight crews aware of its contents. The CAA did not audit operators to establish that these processes had taken place.

1.9.7 RFFS Communication

The flight crews of G-BWDA and G-EMBO experienced some difficulties in communicating with the Aerodrome Fire and Rescue Service on 121.6 MHz. RFFS staff also reported difficulties in receiving the first notification of aircraft emergencies from ATC. The RFFS report stated:

> *‘portable radio comms were abysmal because of constant equipment failure due to defective batteries and radios,’*

and included two recommendations:

> *'connection of Fire Station public address system to direct link to ATC VCR (Visual Control Room) to allow controller to pass turnout information direct to the station [public address system]' and 'replacement of all radios and batteries with new equipment.'*

The RFFS reported that these recommendations had widespread implications. Plans were already in place for a new fire station to be commissioned before the end of 2010 and this station was to have facilities for direct ATC access to the public address system within the station. A decision had been made not to replace the RFFS radio equipment in isolation but to equip the entire airport with new communications systems.

1.10 Aerodrome information

1.10.1 General

Bristol International Airport (ICAO code EGGD) has one runway designated 09-27. It was specified by the UK AIP[7] as having a length of 2,011 m and a width of 46 m. Due to a displaced threshold, the Landing Distance Available (LDA) on Runway 27 was 1,876 m. The Runway 27 displaced threshold elevation was 601 feet amsl.

1.10.2 Runway resurfacing

1.10.2.1 Requirements for runway surfaces

Guidance on the desirable physical characteristics of runways is set out in CAP 168 *Licensing of Aerodromes*[8] and this is based on the international requirements in ICAO Annex 14. The guidance differs depending upon the runway's code number. Runways with a takeoff distance available of more than 1,800 m, such as Runway 09-27 at BIA, are code 4. Among the guidance relating to a code 4 runway is that the transverse runway gradient should not exceed 1.5%, but the transverse profile may be cambered or sloping. Among the guidance relating to the longitudinal profile of a code 4 runway is that the radius of curvature of any curved surfaces should be no less than 30,000 m.

7 UK Aeronautical Information Publication, reference AD 2-EGGD-1-4 (23 Dec 04).
8 CAP 168 Licensing of Aerodromes, Seventh Edition 8 May 2006.

The guidance concerning new or resurfaced runways include providing a hard durable surface that will not generate loose materials or contaminants, provide good surface water drainage and provide a surface friction level at or above the Design Objective Level (DOL) defined in CAP 683[9]. The runway surface friction guidance in CAP 683 applies to all paved runways used for public transport operations and all paved runways exceeding 1,200 m. The DOL friction value is 0.72 or greater when measured with a Mu-meter and 0.80 or greater when measured with a GripTester. The Minimum Friction Level (MFL) is 0.50 with a Mu-meter and 0.55 with a GripTester.

1.10.2.2 Runway resurfacing work at BIA

The runway at BIA had previously been re-surfaced in 1990 and at that time the runway's profile was not completely compliant with CAP 168. The CAA had conceded at the time that achieving full CAP 168 compliance within one re-surfacing operation was not practicable on economic grounds. Therefore, in 2006, a resurfacing project was begun that would make the runway fully CAP 168 compliant in cross-section and improve compliance of its longitudinal profile by about 10%. The resurfacing work began on 1 November 2006 and was completed by 22 March 2007. Each night the runway was closed at 2300 hrs for work to begin, and it re-opened at 0615 hrs for normal operations. The work was carried out at night and during the winter time to minimise disruption to night-time charter flights.

The technical specification used for the asphalt materials was the UK Defence Estates Specification 013 'Marshall Asphalt for Airfields' (published August 2005). In addition to these requirements the bitumen binder had to be 70/100 pen grade where the Marshall Stability requirement was 10 kN; and the coarse aggregate had to have a minimum Polished Stone Value (PSV) of 60. Furthermore, temporary ramps between asphalt layers had to have a maximum longitudinal gradient of ±1% and a maximum transverse gradient of ± 2%, with spacing between successive ramps of not less than 150 m. An onsite laboratory was used to monitor compliance with the materials specifications.

The runway surface at BIA is made of Marshall Asphalt which consists mainly of stone material bonded together with bitumen. The top layer is called surface course (also known as wearing course) and the layer beneath this is called base course (also known as binder course). Both layers are made of Marshall Asphalt, but the base course has a more indented texture

9 CAP 683 The Assessment of Runway Surface Friction for Maintenance Purposes, Third Edition 14 May 2004.

and larger aggregate size compared to the surface course. A regulating course can also be used when reshaping of the runway's profile is required. A regulating course is usually made up of a 'base course' mixture which can be laid and compacted in thicker layers than a 'surface course' material because it contains a larger aggregate size. A surface course is then laid on top of the base course.

Water does not drain through the surface of Marshall Asphalt, so in order to meet friction requirements in the wet, transverse grooves are made in the surface (see Figure 4). The grooves are typically 3 to 4 mm wide and 4 mm deep with 25 mm spacing, and combined with a transverse slope, these grooves allow water to drain towards the sides of the runway.

Figure 4

Section of original weathered grooved Marshal Asphalt runway surface.
Grooves are 3 mm wide, 4 mm deep with 25 mm spacing
(photo courtesy J. Barling)

The approach to the resurfacing works was to start with the reshaping and base course layers before beginning to lay the surface course starting from the 09 end of the runway. Due to bad weather, laying of the surface course was delayed and by 16 November 2006 most of the base course had been laid without any surface course. Approximately 60 m of surface course was then laid during a typical night's work, starting at the 09 threshold end and progressing eastwards. The new surface course was then left for 72 hours before grooving to allow time for evaporation of volatile components and for cooling so that a degree of surface hardening could take place. This minimised any damage to the new surface course during the saw-cutting process. Typically no more than 100 m of un-grooved surface course was exposed at any one time.

The state of the runway resurfacing works between 29 December 2006 and 3 January 2007 is shown in Figure 5. The white sections in this diagram represent the original weathered runway surface consisting of grooved Marshall Asphalt (see sample in Figure 4). The green sections consist of new base course and regulating course. The purple sections consist of new surface course that has not yet been grooved. The blue section consists of new surface course that has been grooved. The green and purple sections, taken together, represent the surface area of the runway that was un-grooved.

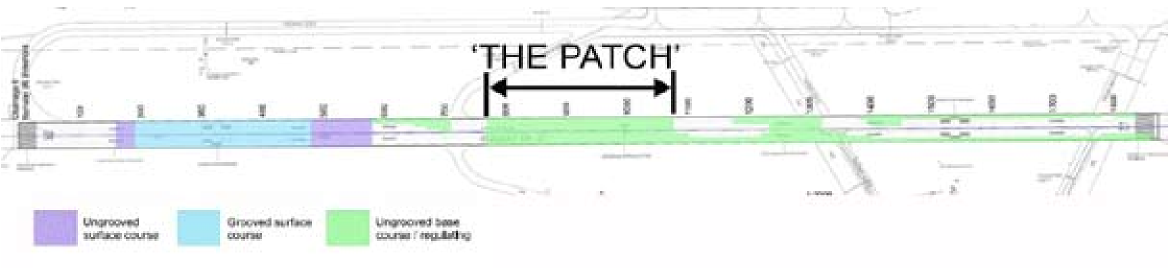


Figure 5

State of runway surface between 29 December 2006 and 3 January 2007

The difference in water drainage capability of the grooved surface compared to the un-grooved surface is visible in Figure 6, which is a snapshot taken from the RFFS video of the incident scene shortly after G-BWDA departed the runway on 29 December 2006.

Figure 6

Image taken shortly after G-BWDA departed the runway, looking eastwards towards the 27 threshold

1.10.2.3 Runway rectification work following incidents on 29 December 2006 and 3 January 2007

Following the incidents on 29 December 2006 and 3 January 2007, the airport operator decided to improve the braking characteristics of the un-grooved base course under wet conditions. Closing the runway until the base course had been covered with surface course and then grooved was considered uneconomical. It was considered that grooving the base course might provide a temporary solution. It is not normal practice in the UK to groove base course because its more indented texture and larger aggregate size makes damage to the groove shoulders more likely following multiple landings. Therefore, on 7 January 2007 a trial area of base course 10 m long was grooved and subjected to a day of landings. An inspection the following day revealed that the grooved base course was holding up well and probably would not present a FOD (Foreign Object Damage) risk in the short term. Figure 7 shows the difference between the temporary grooved base course in the foreground and the un-grooved base course behind it.

Figure 7

Temporary grooved base course in foreground and un-grooved base course behind it. Grooves in the base course are 4 mm wide, 4 mm deep with 25 mm spacing (photo courtesy J. Barling)

The runway was subsequently closed between 1400 hrs on 7 January and 1000 hrs on 8 January 2007 to permit grooving of the exposed base course. Normal resurfacing operations resumed on 11 January 2007 which included laying surface course on top of the grooved base course, after machining away the grooves.

The airport operator carried out frequent monitoring of the temporary grooved base course and by 10 January 2007 the grooves had remained generally intact with little sweeping necessary. However, over the 12-day period that the grooved base course was exposed, a small quantity of aggregate was lost from the groove ridges.

1.10.2.4 Independent runway surface inspection on 7 January 2007

The AAIB employed an experienced runway surface consultant to provide an independent evaluation of the runway surface condition. He examined the runway on 7 January 2007 before the temporary grooving was started. In his opinion, the newly laid base course was well laid, '*fairly tight knit*', with only small areas of segregation of the mix and no evidence of irregularities in the profile. The surface at the time of inspection was damp to wet and no '*ponding*' was present. He also reported that the original weathered grooved Marshall Asphalt:

> *'surface had good macrotexture, having lost most of the fine material at the surface through wear and weathering, exposing coarse aggregate fractions of the mixed material.'*

Only a cursory visual examination of the new ungrooved Marshall Asphalt surface course was made as this had not played a part in the G-BWDA and G-EMBO runway excursion incidents. He reported that this surface appeared typical of a well laid new Marshall Asphalt surface course, with a tight surface with little macrotexture.

1.11 Flight Recorders

Recorded data was successfully recovered from each aircraft by the operators, and sent to the AAIB for analysis. Despite a 2-hour Cockpit Voice Recorder (CVR) being fitted to G-EMBO, the voice data was overwritten before the CVR was impounded.

The condition of the runway surface affected the three aircraft in different ways. The G-XLAC flight crews reported concerns of runway overruns whereas the G-BWDA and G-EMBO crews reported lateral control issues.

1.11.1 Longitudinal Effects on G-XLAC

A number of recorded parameters were available to characterise the longitudinal landing performance of G-XLAC. One which gives the broadest view of the rate at which the aircraft was slowing down is the longitudinal acceleration. It takes into account all forms of aircraft drag force: aerodynamics, reverse thrust and braking. The total longitudinal retardation force is a product of the aircraft mass and longitudinal acceleration.

1.11.1.1 Deceleration vs. Runway Position

The touchdown positions for both G-XLAC landings have been estimated using the recorded localiser and glideslope deviations. Knowing the groundspeed at the touchdown point and integrating the longitudinal acceleration twice, allowed an estimate of aircraft position on the runway to be calculated. Figure 8 shows the estimated positions of G-XLAC's landings, with the corresponding recorded longitudinal acceleration[10].

Landings were performed on Runway 27 so, for ease of plotting, the data is presented showing the landings from left to right. The areas highlighted in green are the areas of ungrooved base course.

The two predominant areas of ungrooved base course start at approximately 550 m and 800 m from the Runway 27 threshold. The larger of the two green areas marked 'the patch' in Figure 8, shows a notable drop in deceleration for each landing.

Analysis of the G-XLAC event of 29 December 2006 has provided the most useful results of the two incidents, as maximum braking was commanded throughout the transition over 'the patch'.

1.11.1.2 Deceleration Components

Data from the G-XLAC events of both 29 December 2006 and 3 January 2007 was forwarded to the manufacturer who analysed the landing performance. This, along with use of aircraft models of thrust and aerodynamics, allowed the contributions to the aircraft deceleration from the aerodynamic, reverse thrust and landing gear effects, to be separated.

Figure 9 shows a combined plot of the decelerations for the G-XLAC landing on the 29 December 2006. The 'GEAR CONTRIBUTION' in this graph constitutes the net deceleration component from the landing gear which includes rolling resistances and braking forces. In this aircraft configuration, the main contributor to the 'GEAR CONTRIBUTION' was from the braking. The aerodynamic contribution in Figure 9 decreased as expected, as the airspeed decreased.

10 The position relative to the runway is an estimated position and is subject to a number of inaccuracies. These inaccuracies can arise from sources including accelerometer drift, estimated touchdown position, wind speed and direction. Some small adjustments were made to align the drop in deceleration of each aircraft by adjusting the touchdown point.

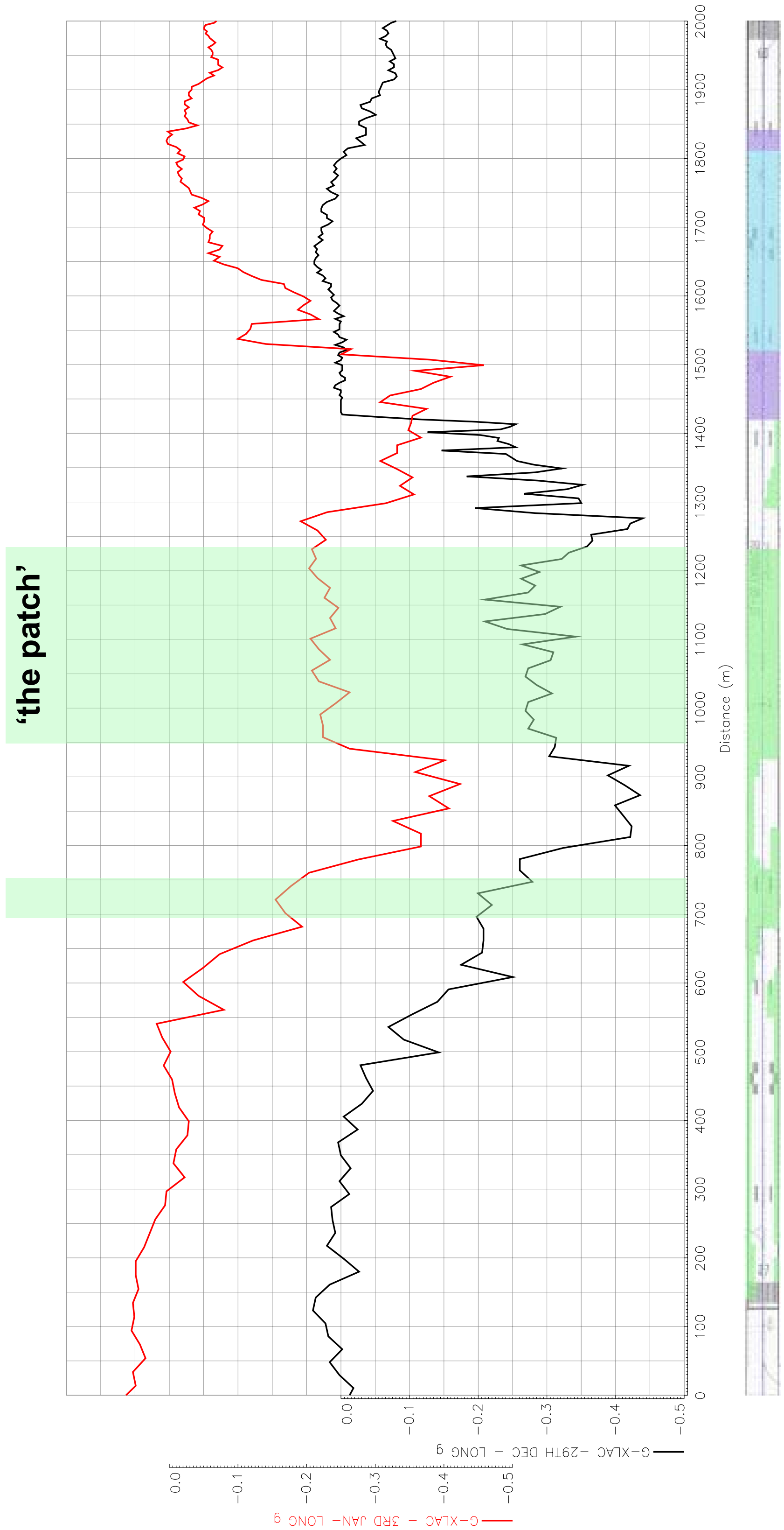


Figure 8

G-XLAC longitudinal acceleration vs. runway position
for incidents on 29 December 2006 and 3 January 2007

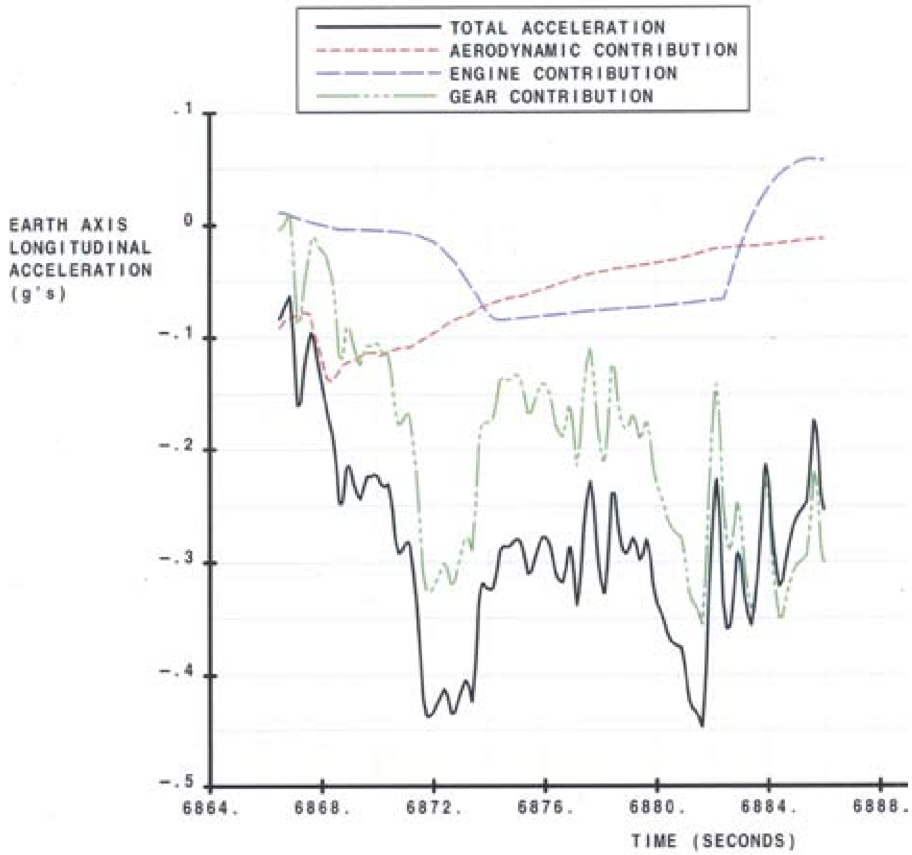


Figure 9

G-XLAC component deceleration contributions
29 December 2007
(Reproduced courtesy of Boeing)

Just after touchdown, the largest single contributor to the aircraft deceleration was from the landing gear. At this point, the aircraft deceleration peaked at -0.44g. After around 2 seconds, a notable reduction in deceleration occurs down to around -0.3g due to a decrease in the landing gear contribution. The deceleration drop was largely restored by the increase in reverse thrust at around the same time (dashed blue line). With full brake pressure commanded, the antiskid system operated and reduced the brake pressure, thus reducing the overall deceleration.

The deceleration components for the G-XLAC landing on 3 January 2007 are shown in Appendix C, Figure C1. Both G-XLAC landings show a similar characteristic in that, just after touchdown, the deceleration contribution from the landing gear was significant.

1.11.1.3 Braking Coefficient

The braking coefficient is defined as the ratio of the decelerating force from the braking system, relative to the normal load applied to the tyres. This coefficient is a term which includes effects due to the runway surface, contaminants and the aircraft braking system (antiskid efficiency[11], brake wear, tyre wear etc). It is a better measure of the effectiveness of an aircraft's braking system, in given runway conditions, than the longitudinal deceleration. This is not the same as the tyre-runway friction coefficient because it includes contributions from the aircraft's braking system.

A braking system operates either under torque-limited or friction-limited conditions. A torque-limited situation is one where the amount of braking force which can be applied through the tyre is limited by the amount of applied brake torque. In this case the tyre-runway friction can react the applied brake torque, so antiskid is inactive. The braking coefficient in a torque-limited case is a function of the level of brake pressure applied.

A friction-limited situation exists where the amount of braking force which can be applied is limited by the friction between the tyre and the runway. In this case, the antiskid is regulating the brake pressure to ensure the wheel continues to rotate at an optimum speed, to provide the best available grip. As long as the system is friction-limited, the braking coefficient represents the maximum braking coefficient for the runway surface.

For the G-XLAC landing on 29 December 2006, runway conditions were reported as *'damp, wet, damp'*. This runway surface was friction-limited on the ungrooved area as confirmed by Figure 9 which shows the landing gear deceleration component decreasing, despite full brake pressure being applied. In this case, the maximum braking coefficient can be calculated using the landing gear deceleration contribution and the normal load applied to each landing gear (essentially the aircraft weight minus lift).

The manufacturer of G-XLAC provided the braking coefficient data for this landing which is shown in Figure 10. The lower the braking coefficient, the more slippery the surface (minimum 0, maximum 1).

Figure 10 shows the braking coefficient increasing after touchdown, up to a peak of 0.33. After transitioning on to the ungrooved surface, the braking coefficient dropped to a minimum of 0.11. Transition back on to the grooved surface lead to an increase up to a maximum of 0.36.

11 Antiskid efficiency is defined as the effectiveness of the antiskid system to modulate the brake pressure and subsequently braked wheel speed, to give optimum grip.

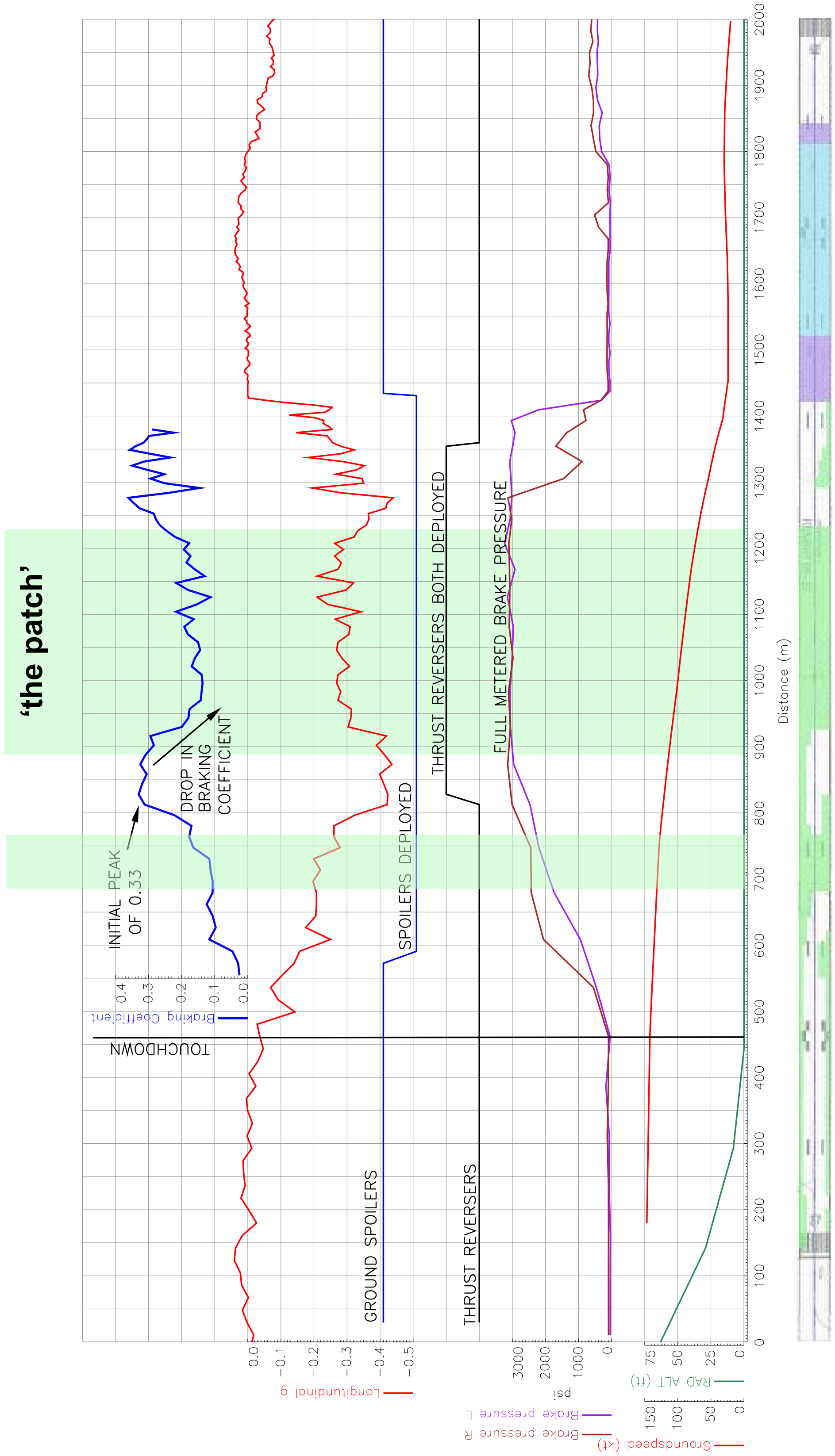


Figure 10

G-XLAC Braking coefficient from 29 December 2006

1.11.2 Lateral Effects

G-BWDA and G-EMBO both departed the left side of Runway 27 on 29 December 2006. With a crosswind from the left, aircraft have a tendency to yaw to the left when on the ground due to the 'weather cocking' effect of the vertical stabiliser. At higher speeds on the ground, this is counteracted using the aerodynamic effects of the rudder. As speed reduces and the rudder becomes less effective, there is a higher reliance on the nosewheel steering and differential braking for directional control. Relying on the landing gear for directional control therefore relies on the available grip between the tyres and the runway surface.

1.11.2.1 G-BWDA

Data for G-BWDA was provided by the operator's Flight Data Monitoring (FDM) programme. This data was recorded from the same data concentrator as the Flight Data Recorder (FDR).

The approach to BIA was made with the autopilot disengaged, 28° of flap and heading slightly into wind. Data shown in Appendix C, Figure C2, begins with the aircraft just prior to touchdown. In the 10 seconds prior to touchdown, a number of rolling manoeuvres are noted from -9.5° left, to 4.6° right and then back to -11.9° left.

Touchdown occurred at 12:18:25 hrs at an airspeed of around 100 kt. The power levers were slowly moved into the reverse thrust range and torque on both engines increased over 10 seconds. Reverse thrust was maintained until the aircraft came to a stop. Ground spoilers deployed on touchdown and the aircraft decelerated to a steady state longitudinal acceleration of -0.26g within four and a half seconds. No brake pressure or pedal angle parameters were recorded so it was not possible to ascertain the level of braking applied.

The recorded localiser deviation suggests that touchdown was achieved almost on the runway centreline. At the point of touchdown, 3.4° of left rudder was applied with a roll angle of 1.8° to the right and the left aileron deflected 1.3° up (maximum deflection is ± 14°). During the next four seconds, progressively more and more right rudder was added to a maximum of -26.7° (maximum travel is ± 27°). Heading then began to increase (right yaw), after which 15.4° of left rudder was applied.

This led to a decrease in heading (left yaw) and with this left rudder maintained, at a groundspeed of 76 kt, the localiser deviation shows G-BWDA starting to deviate to the left of the runway centreline. Rudder position was then again reversed to provide -25.0° of right rudder in an attempt to arrest the rate of turn. However, with this rudder input maintained, localiser deviation continued to increase, signifying the aircraft moving to the left of the runway centreline. When the aircraft came to a rest, heading had decreased to 227°.

Nosewheel steering angle and tiller position were not recorded and with no mechanical linkage between the rudder pedals and nosewheel steering, pilot inputs cannot be ascertained.

Appendix D shows where G-BWDA stopped on the grass, just beyond the green area of ungrooved base course. The photograph in Appendix D shows where the runway surface transitions from ungrooved base course, to the normal runway surface condition. This confirms that G-BWDA was located on the ungrooved base course area as it left the runway.

Appendix C, Figure C2 also shows the longitudinal acceleration relative to time which did not show any significant loss in deceleration while the aircraft was on the runway. Braking system data was also not available so it is unknown what the landing gear contribution to the deceleration was and whether the braking was symmetric. However, if the runway condition was slippery, it would have had some impact on the tyre adherence to the runway. The drop in deceleration towards the end of the landing shown in Appendix C, Figure C2 was most likely caused by the wheels contacting the grass.

1.11.2.2 G-EMBO

The aircraft landed at around 2133 hrs at a computed airspeed of around 136 kt with 45° of flap and on a heading of 263°. The spoilers deployed immediately; no thrust reversers were fitted.

Recorded data indicated that 3.5 seconds after touchdown, brake pressures on wheels one and three increased[12], which led to an increase in longitudinal deceleration, peaking at -0.32g (see Appendix C, Figure C3). The deceleration then decayed, coinciding with a decrease in brake pressures. The pressures did not then rise above 360 psi (maximum is 3,000 psi) for the next six seconds.

During this six-second period, progressively more and more right rudder pedal was applied to counteract a slow decrease in heading. The heading continued to decrease, despite further rudder pedal inputs, and 14 seconds

12 Brake pressure is only recorded on wheels one and three.

after touchdown, at a groundspeed of 67 kt, full right rudder pedal deflection was recorded, with heading still decreasing. Although left wing down roll had been commanded from touchdown, at this point this was reversed to right wing down roll with the control wheel deflected to 24 degrees (maximum deflection is 41 degrees). The longitudinal deceleration then began to increase in line with brake pressure on wheel three, just as the localiser deviation shows the aircraft deviating to the left of the runway centreline. As this deviation continued, the heading started to increase. Right rudder pedal demand was reduced as the heading continued to increase and left rudder pedal was slowly applied to reduce the rate of turn. Brake pressure on wheel three then increased significantly up to 1,236 psi as the localiser deviation decreased and the aircraft regained position on the runway centreline.

The low brake pressure coincided with a decrease in longitudinal deceleration and an increase in the heading. The reason for the drop in brake pressure was either due to the pilot reducing the brake pedal input, or the antiskid reducing the pressure after detection of a skid. This cannot be confirmed as the brake pedal angle and wheel speeds were not recorded, so the command to the brakes cannot be ascertained. Brake pressure was also only recorded on two brakes and only every second[13].

1.12 Aircraft examinations

1.12.1 G-BWDA examination

One blade from the left propeller had sustained some impact damage, most likely from clumps of dirt that had been thrown up during the runway excursion. There was a lot of mud inside the gear bay and on the landing gear; this was washed off to allow examination. Both nosewheel tyres were found worn close to limits. Each tyre had four grooves and the remaining tread depth was an average of 1.3 mm for the two centre grooves and 2.6 mm for the outer grooves on both tyres. The tyres are required to be replaced when the bottom of any groove is reached at any location; the wear on the tyres had not reached this limit. No anomalies were noted on the four main wheel tyres and they had tread depths remaining of between 3 mm and 6 mm. The normal nosewheel tyre pressures on this aircraft type were 64 to 66 psi and the normal main wheel tyre pressures were 114 to 119 psi. The tyre pressures were not measured after the incident: however, they were routinely checked every three days.

13 Antiskid systems regulate brake pressure at a rate much faster than 1 Hz.

1.12.2 G-EMBO examination

G-EMBO did not sustain any damage from its runway excursion, but the left main gear brake units were subsequently replaced due to dirt ingress. The left main landing gear tyres were also removed for inspection. They had not sustained any damage and were only about 30% worn with 7.2 mm of tread depth remaining. The tyre pressures on G-EMBO had been checked daily; the last recorded values on 21 December 2006 were 80 to 86 psi for both nosewheel tyres and 147 to 150 psi for the four main wheel tyres.

1.12.3 G-XLAC examination

G-XLAC did not undergo any special inspection as it did not depart the runway in either incident. There were no reports from general daily checks that there were any anomalies with the tyres or any relevant anomalies with the aircraft. The operator's standard policy was to maintain the tyre pressures at 200 +5/-0 psig and to check tyre pressures each day.

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

None.

1.17 Organisational and management information

The operator of G-EMBO was acquired by another established operator after the incident and the new operator does not plan to operate Embraer 145 aircraft in the long term. However, action was taken to introduce procedures for operations in wet conditions on runways which had been notified *'slippery when wet'*, introducing a crosswind limit of 10 kt. At another UK airport, where similar runway works were carried out in 2007, the operator took action to consider any lengths of runway promulgated as *'slippery when wet'*, as being absent from runway distances, for performance calculation purposes.

Following the events on 29 December 2006, one operator took action to impose a temporary maximum crosswind of 15 kt on its Airbus A319 fleet, for all departures from BIA.

Following the event on 3 January 2007, there was further discussion, both formal and informal, between the airport authority and operators. On 5 January 2007, some operators took action to cease flying at the airport altogether, and others imposed restrictions on their operations. The additional restrictions typically included application of crosswind limits similar to those applicable on slippery runways and performance adjustments to take account of poor friction in the landing and rejected takeoff cases.

1.17.1 ICAO and CAA action

AAIB investigators met with CAA staff to discuss the events described in this report. CAA staff explained that CAA policy with regard to runway friction is derived from the provisions of Annex 14 to the ICAO Convention.

At the first meeting of the ICAO Aerodrome Operations and Services Working Group (AOSWG), in 2005, it was agreed that the provisions in Annex 14 Volume 1 relevant to runway surface friction should be reviewed. The basis of such review was to be the safety factors inherent in the measurement of runway surface friction where the runway is contaminated. At the third meeting of the group, in March 2006, the UK CAA proposed considerable amendment to the Annex. The CAA's view was that, except on runways covered by compacted snow or ice, friction values should not be used as a basis for aircraft operations. Their reasons for this viewpoint were an absence of a common method across the world, doubts about the accuracy of such measurements, the difficulty in reading friction measurements across to aircraft operations and concerns that such measurements are time-critical.

The Group recommended that a task force should be established to investigate runway surface friction issues and subsequently to develop an action plan for submission to the ICAO Aerodromes Panel. Draft terms of reference for a proposed Friction Task Force, along with some of the friction related issues which the Group felt needed to be addressed at a global level, were outlined. The CAA has a seat on this task force.

1.18 Additional information

Runway friction measurement

The CAA published guidance to aerodrome licensees on runway friction in two principal documents, CAP 168, *'Licensing of Aerodromes'* and CAP 683, *'The Assessment of Runway Surface Friction for Maintenance Purposes'*.

CAP 168, *'Licensing of Aerodromes'*

CAP 168, *'Licensing of Aerodromes'*, gives advice and direction to aerodrome licensees regarding runway surfaces:

> *'The aim should be to provide in the first instance a runway surface that is clean and has a uniform longitudinal profile and friction levels that will give satisfactory braking action in wet conditions. These issues should be addressed at the time of the design of runways, pavements or subsequent resurfacing.'*

Another relevant passage deals with surface friction characteristics:

> *'The surface of a new runway or a newly resurfaced runway should be designed and constructed to enable good braking action to be achieved by aeroplanes in wet runway conditions. When a new runway is built or an existing runway resurfaced, the wet surface friction characteristics shall be assessed in order to classify the friction level.'*

In a section entitled *'New Asphalt Runways'*, the publication stated:

> *'New or resurfaced runways with an asphalt surface normally do not provide adequate friction levels for aircraft operations immediately after the new surface has been placed... In these circumstances it is generally necessary to treat the surface by either the application of a coarse textured slurry seal, grooving or the addition of a porous friction course.'*

The publication provided advice regarding the application of slurry and the grooving process.

CAP 683, *'The Assessment of Runway Surface Friction for Maintenance Purposes'*

CAP 683 reflected the CAA's interpretation of the Standards and Recommended Practices laid down in Annex 14 to the Convention on International Civil Aviation, in so far as they had been adopted by the UK in respect of runway surface friction testing.

The purpose of the document was to outline the procedures for undertaking runway surface friction assessments and to define the criteria by which friction values were assessed on runways under specified conditions.

The criteria in the document applied to all paved runways exceeding 1,200 metres in length and all paved runways used for public transport operations. The document detailed methods for assessment of runway friction, using the Mu-meter and GripTester (the two types of CFME most commonly used in the UK).

The document stated that the friction characteristics of a runway can also *'alter significantly'* following maintenance activities. It stated that a runway surface friction assessment:

> *'should be conducted following any significant maintenance activity conducted on the runway and before the runway is returned to service.'*

Further, it added:

> *'Runway surface friction assessments should also be conducted following pilot reports of perceived poor braking action...'*

Management of works in progress

CAP 168, '*Licensing of Aerodromes*', details the responsibilities of aerodrome licensees with regard to work on operational areas. It stated:

> *'Wherever major work affecting operational areas is planned, aerodrome licensees must be satisfied that unacceptable risks generated by Works in Progress (WIP) have been identified and removed, and that procedures are provided and followed which ensure no adverse impact upon levels of safety.'*

1.18.1 Friction Measuring Equipment

The friction measuring equipment commonly used today to measure runway friction are continuous friction measuring devices, known as CFME. These devices continuously measure friction as they travel along the length of a runway. The two types of CFME accepted by the CAA for use in the UK are the GripTester and Mu-meter. Other types of CFME can be used if their performance can be demonstrated, to the satisfaction of the CAA, to provide comparable results with the Mu-meter and GripTester. The Mu-meter, manufactured by Douglas Equipment, was in use at BIA.

1.18.1.1 Douglas Mu-meter Mk6 CFME

The primary Mu-meter used by BIA was the Mk6 Mu-meter; a Mk5 unit was available as a backup. The Mk6 Mu-meter is a three-wheeled trailer as shown in Figure 11. The centre wheel is used to measure distance, and the two outer wheels are connected by a load cell to measure drag resistance. These two outer wheels are toed-out at an angle of 7.5° so that they are partially skidding as they are pulled along. Strain gauges in the load cell measure the force by which the wheels are being forced apart. This force can be correlated to the coefficient of friction[14] (mu) between the runway surface and the Mu-meter's tyres, and is calculated by a laptop computer connected to the Mu-meter. The laptop is also used by the driver of the towing vehicle to set up each measuring run and to monitor his driving speed. The target speed for the Mk6 Mu-meter is 64 km/hr (40 mph). The Mu-meter can be used in dry, wet, compacted snow, or icing conditions; it can also be operated in a self-wetting mode. CAP 683 states:

> *'A runway surface friction assessment is conducted under controlled conditions using self-wetting CFME, to establish the friction characteristics of a runway and to identify those areas of a runway surface that may require attention.'*

In self-wetting mode a water tank trailer is used to spray a metered amount of water (nominally creating a surface covering 0.5 mm deep) under the wheels in order to measure runway friction in simulated wet conditions.

14 The coefficient of friction (known as 'mu' for the Greek symbol μ) is a dimensionless quantity used to calculate the force of friction (static or kinetic). The coefficient of friction is defined as the ratio of the friction force (F), between the two surfaces in contact, to the normal force (N) between the object and surface ($\mu = F/N$). The coefficient of friction is not a 'material property' but rather a 'system property' as it is dependent upon the physical characteristics of two surfaces, and is also dependent upon variables such as speed and temperature.

The Mu-meter is calibrated by pulling it over a plywood strip that is coated with grit bound in an epoxy resin. The surface feels rough to the touch and is designed to generate a mu of 0.77 between the surface and the Mu-meter's tyres. Calibration of the Mk6 Mu-meter is generally only required if the tyres are changed or if the unit starts to generate unusual readings.

Figure 11

Douglas Mu-meter Mk6 CFME used by BIA
shown here using the self-wetting equipment
(photo courtesy Douglas Equipment Limited)

1.18.2 Friction Measurement Data from BIA

The airport operator carried out a number of friction measurement runs throughout the resurfacing works using the Mu-meter. No runs with self-wetting were carried out until 10 January 2007, after the runway excursion incidents. The operator reported that between the middle of November and the end of December the runway was never dry enough for a Mu-meter run with self-wetting. There was one dry period on 8 December but no staff were available to conduct the runs. However, many Mu-meter runs were undertaken in damp and natural wet conditions. These types of runs give good relative friction values across a length of runway, but the absolute values need to be treated with caution.

An example result of a Mu-meter run carried out in natural wet conditions is shown in Figure 12. This run was undertaken over the whole runway length on 29 December 2006 at 2125 hrs, 10 minutes prior to G-EMBO departing the side of the runway. The runway surface condition at the time was declared as *'wet, wet, wet'*. The friction readings varied from a minimum of 0.4 to a maximum of 0.95. The runway surface condition is depicted along the distance axis. There is a good correlation between low friction readings and the ungrooved surfaces (purple and green). The grooved surfaces (blue and white) all have higher friction readings. Marshall Asphalt runway surfaces with good friction characteristics typically have Mu-meter values of up to 0.8 in dry conditions. The high readings above 0.9 in Figure 10 in wet conditions are unusual. The Mu-meter was calibrated on 29 December 2006 at 1600 hrs using the calibration board; however, Mu-meter runs undertaken both before and after this calibration show similarly high friction readings above 0.9. One run at 2350 hrs on the same day revealed a number of friction readings equal to 1.0. Neither the airport authority nor the Mu-meter manufacturer could explain this anomaly but it indicates that all the actual friction values were probably lower than measured.

Some short Mu-meter runs of 300 m were also carried out on 29 December 2006 over the longest stretch of ungrooved base course ('the patch', shown in green in Figure 5). These were referred to as 'patch runs' by the operator. A summary of average Mu-meter measurements for the 'patch runs' and the full runway length runs on 29 December 2006 are shown in Table 1.

Table 1 lists the average mu for each run in both directions and then lists the dual average, which is the average of the two runs. Several Mu-meter runs of the ungrooved 'patch' revealed friction values less than the MFL of 0.50. This data was compiled by the airport operator and it does not include minimum mu values or the lowest 100 m rolling average as recommended by CAP 683 for evaluating runway surfaces against the MFL. Furthermore, given that these runs were not carried out in controlled dry conditions with self-wetting, the overall averages need to be treated with caution. The clearest information about the state of the runway surface was revealed in the relative differences of friction values in Figure 10. The typical friction of the new ungrooved portions was approximately 0.4 mu less than the original grooved sections.

On 10 January 2007 the airport operator carried out Mu-meter runs in dry conditions with self-wetting to evaluate the temporary runway surfaces against CAP 683 requirements. This was done after the temporary base course surfaces were grooved, so the friction of the ungrooved base course was never

Full Runway Length Mu-meter Runs on 29/12/06			
TIME	**Average Mu 27-09**	**Average Mu 09-27**	**Dual Average**
11:05	0.76	0.82	0.79
12:14	0.72	n/a	n/a
16:29	0.74	0.81	0.78
21:23	0.70	0.75	0.73
23:48	0.74	0.79	0.77
300 m Patch Mu-meter Runs on 29/12/06			
TIME	**Average Mu 27-09**	**Average Mu 09-27**	**Dual Average**
6:59	0.63	0.60	0.61
8:21	0.42	0.43	0.43
11:02	0.66	0.70	0.68
12:12	0.44	0.49	0.46
14:01	0.60	0.49	0.54
14:50	0.56	0.52	0.54
16:41	0.69	0.74	0.72
21:30	0.50	0.53	0.51
23:54	0.49	0.57	0.53

Table 1

Summary of Mu-meter Runs carried out on 29 December 2006

measured in controlled self-wetting conditions. An example friction run plot from 10 January 2007 is shown in Figure 13. This run was carried out with the Mu-meter displaced 4 m left of the centreline. Runs in other lateral positions showed similar results. The lowest 100 m rolling average was not listed, but the small figures at the top of the graph are the averages for 100 m sections. The lowest 100 m average measured in this run was 0.67 which was above the MFL. Of significant note is that the large peaks and troughs from the run on 29 December 2006 (Figure 12) have disappeared.

To further illustrate the change in friction characteristics after the temporary grooves were made, the Mu-meter manufacturer provided the AAIB with some 2D colour-coded plots of measured friction for 5 January 2007 and the survey runs on 10 January 2007. These plots are included in Appendix B.

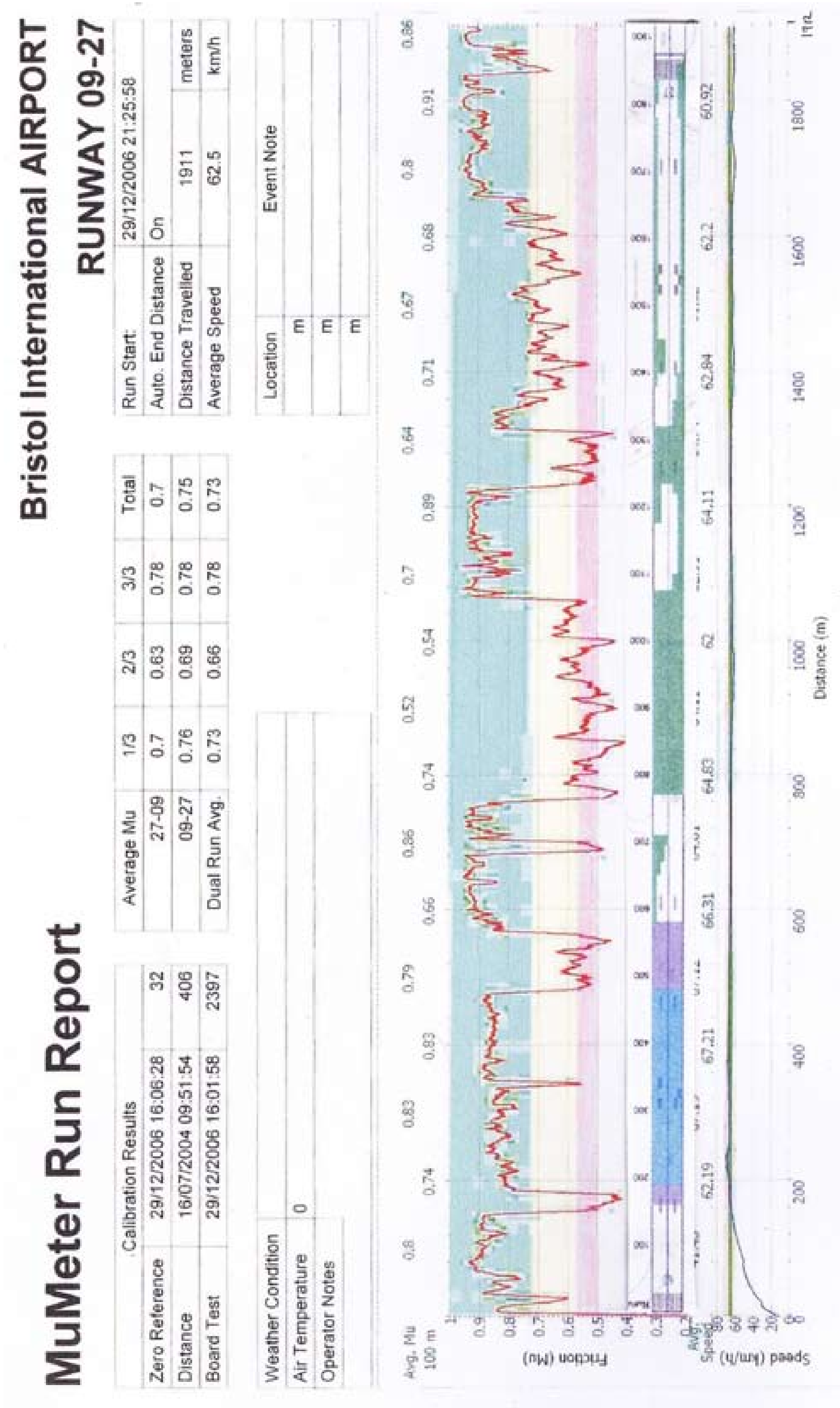


Figure 12

Friction measurement run of Runway 09-27 on 29 December 2006 when the runway state was *'wet, wet, wet'*. The runway surface condition at the time is depicted at the bottom

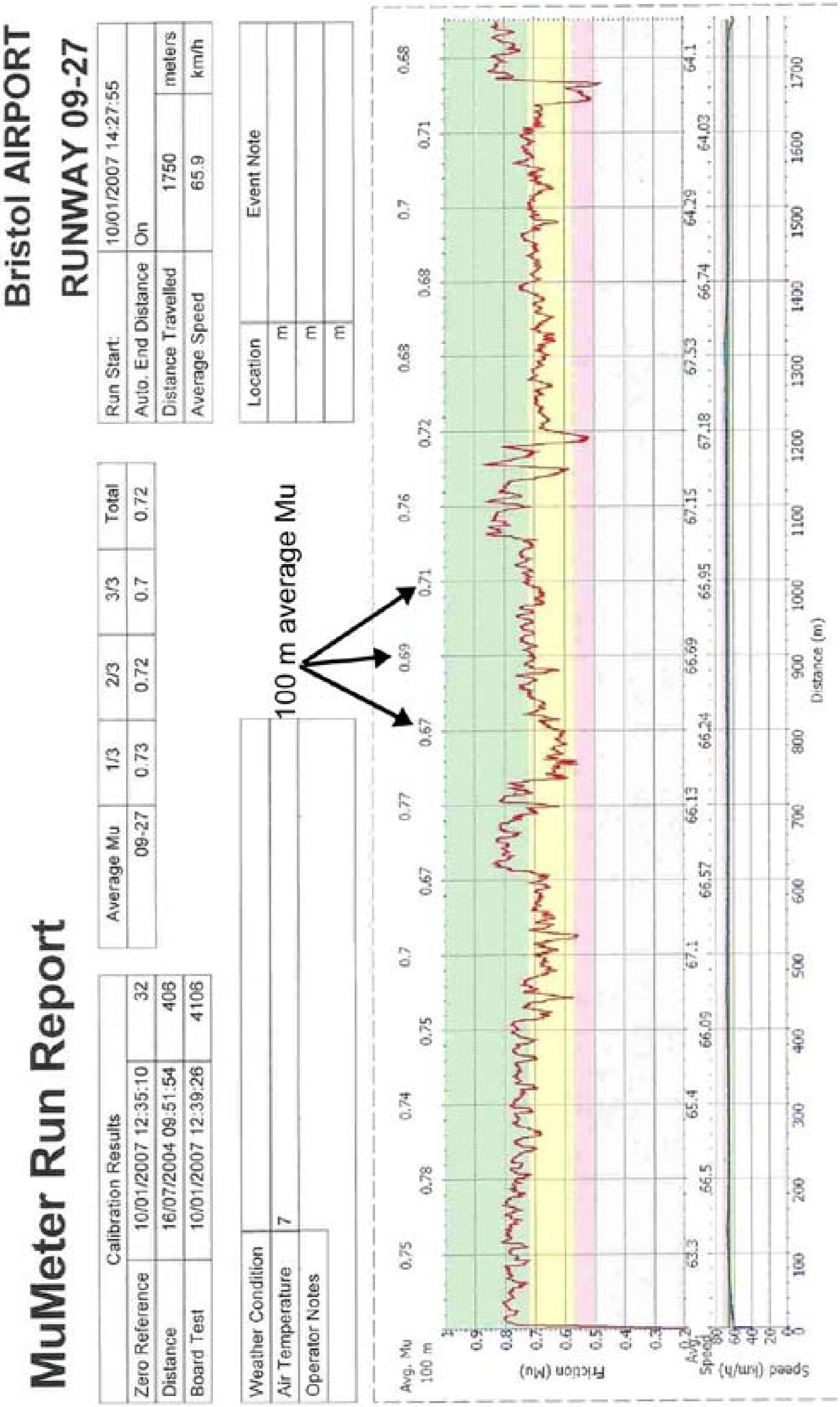


Figure 13

Friction measurement run of Runway 09-27 on 10 January 2007 using self-wetting on a dry runway, displaced 4 m left of the centreline

1.18.3 Previous runway resurfacing works at Luton Airport

The same design and construction companies that carried out the BIA runway resurfacing works also carried out runway resurfacing at Luton Airport earlier in 2006.

At Luton, part of the runway resurfacing works included replacing the central 15 m, highly trafficked, portion of the runway with new base course along approximately 75 % of the runway length. This was to be carried out before the surface course overlay was begun. It was identified that during the resurfacing works aircraft would be operating on a number of different surface types, including existing grooved Marshall Asphalt, new ungrooved Marshall Asphalt base course, new ungrooved Marshall Asphalt surface course and new grooved Marshall Asphalt surface course.

The Luton airport operator specified in the works contract that should the minimum friction level, measured by a 100 m rolling average, of any temporary surface course drop below 0.55 (as measured by a GripTester), then the contractor would be required to retexture[15] the temporary surface to improve its friction. An exception was made during the period between laying the surface course and the grooving operation, when the operator would accept one continuous section not exceeding 200 m providing less than the minimum friction level. There was no restriction on the maximum length of ungrooved base course; this was considered to have sufficiently better friction characteristics than ungrooved surface course.

The resurfacing work began on 1 March 2006 and was completed on 15 June 2006. Throughout this period, friction measurements were taken on a nightly basis under self-wetting conditions. Despite the numerous different surface conditions, all the measured friction levels were above the MFL and the lowest recorded friction was 0.63 with the GripTester. Therefore, at no time did the airport operator need to notify the surface as ‘may be slippery when wet’. Based on the high friction measurement readings the contractor received permission from the operator and the CAA to increase the maximum ungrooved surface course length to 300 m. Therefore, between 27 April 2006 and 5 June 2006 the ungrooved length of surface course varied between 210 m and 300 m. When wet weather was forecast, new surface course was not laid on the main runway; instead, resurfacing was done with base course, or work was carried out on the runway shoulders.

15 The type of retexturing was not specified but the contractor reported that they would have considered ultra high pressure water jetting, the Klaruw retexturing process (a controlled percussive process), or temporary grooving.

The experience gained during the Luton resurfacing works gave the contractors confidence that the friction levels of the long sections of ungrooved base course at BIA would not cause an operational problem.

1.18.4 Previous runway resurfacing works at Belfast City Airport

The same runway designer was involved with runway resurfacing work at Belfast City Airport which was carried out between November 2003 and February 2004. During this resurfacing programme the base course and regulating course were laid continuously along the full length of the runway before any surface course operations were begun. Heavy Duty Macadam (HDM) was used for the base course, with the intention of laying a surface course of Marshall Asphalt. During the period from early November until late December, friction values of the ungrooved HDM base course were measured at about 0.65 with a GripTester. These high friction values were attributed to the coarse texture of HDM coupled with the good water shedding properties of the reshaped runway.

Considering the relatively short runway length (Runway 22 has an LDA of 1,767 m) concern was raised that the ungrooved Marshall Asphalt surface might provide an unacceptably low friction level. A consultation with airlines was undertaken at an early stage and the main Airbus A321 operator agreed that they were happy to continue operations as long as no stretch of runway of more than 100 m was measured as having a friction less than the MFL. Based on this requirement the contractor ensured that no more than 100 m of surface course was left ungrooved at any one time. The surface course was laid during January and February 2004 with the friction tests on the ungrooved Marshall Asphalt surface measuring between 0.55 and 0.58 with the GripTester.

1.18.5 Risk assessment carried out by BIA prior to runway resurfacing works

BIA produced a '*Safety Case*' report on 22 September 2006 to provide evidence and argument that the runway resurfacing project had been designed and would be '*constructed and brought into operational service in a safe and efficient manner*'. It included a risk assessment outlining the potential hazards, their severity, their likelihood of occurrence and risk reduction measures.

The hazards associated with the project were listed under four categories: '*Batching Plant', 'Taxiway Golf', 'Runway'* and *'Taxiway Zulu'*. Under the 'Runway' category the following three hazards were identified:

- Aircraft movements will conflict with contractors
- Vehicles, not associated with the work will conflict with contractors
- Debris left on the works area may present a hazard to aircraft operations

The severity of the first two hazards was categorised as 'accident from collision with plant or personnel', and the severity of the debris hazard was categorised as 'significant incident from damage to aircraft'. The risk reduction measures for these hazards were listed as follows:

> *'The runway will be closed during construction periods. At the end of each shift the runway will be cleaned, inspected and returned to operational service.'*

The '*Safety Case*' report did not mention friction and did not include any hazards relating to aircraft having braking or directional control difficulties on the temporary runway surfaces. According to the BIA Operations Director, the friction requirements were implied in the report by references in the '*Safety Case*' to CAP 168 and CAP 683. He said that all temporary surfaces were required to meet the MFL of 0.5 (based on mu-meter measurements).

In addition to the '*Safety Case*' report, BIA had produced a '*Project Risk Register*'. This included one risk/hazard relating to friction which was listed as '*Unacceptable post construction friction readings*'. The mitigation measure for this risk was '*Selection of Materials*' and the risk owner was the contractor.

1.18.6 Hydroplaning[16]

There are three types of hydroplaning: viscous hydroplaning, dynamic hydroplaning, and reverted rubber hydroplaning. All three can degrade both the braking and directional controllability of an aircraft.

Viscous hydroplaning: This can occur on wet runways and is a technical term used to describe the normal slipperiness or lubricating action of the water. Viscous hydroplaning occurs when a tyre is unable to puncture the thin residual film of water left on a paved surface. This water lubricates the surface and reduces its friction. This type of lubrication can be reduced by making the runway surface rough. Viscous hydroplaning can occur at water depths of less than 0.025 mm.

16 The information on hydroplaning has been obtained from: *Aircraft Accident Investigation* by Richard H. Wood and Robert W. Sweginnis, and from an article in *Flight Safety Australia*, September-October 2000, by Graham Bailey.

Dynamic hydroplaning: This is the phenomenon that is normally referred to as aquaplaning. It can occur when an aircraft lands fast enough on a sufficiently wet runway. When the aircraft's speed and water depth are sufficient, inertial effects prevent the water from escaping from the tyre footprint area, and the tyre is held off the pavement by the hydrodynamic force. Dynamic hydroplaning requires a minimum water depth of 0.25 mm for worn tyres and 0.76 mm for new tyres. Dynamic hydroplaning is also a function of tyre pressure. Studies indicate that the minimum speed (in knots) for dynamic hydroplaning to occur is approximately $9\sqrt{p}$, where p is the tyre pressure in psi[17].

Reverted rubber hydroplaning: This situation can follow dynamic or viscous hydroplaning and results when the aircraft wheels become locked. The locked wheels create enough heat to vaporise the underlying water film forming a cushion of steam that eliminates tyre to surface contact. Indications of an aircraft having experienced reverted rubber hydroplaning, are distinctive 'steam-cleaned' marks on the runway surface and a patch of reverted rubber[18] on the tyre.

Hydroplaning affects both the stopping distance and directional control of an aircraft. According to Wood and Sweginnis:

> *'the loss of cornering or side-force capability when braked wheels are operated at slip ratios greater than 25% can account for the tendency of an aircraft to weathervane into the wind when braking on wet runways during crosswind landings.'*

1.18.6.1 Estimated dynamic hydroplaning speeds for the incident aircraft

Using the equation $9\sqrt{p}$ and the estimated tyre pressures for the incident aircraft, the following estimated minimum dynamic hydroplaning speeds can be calculated:

	Main gear		**Nose gear**	
Aircraft	**Pressure (psig)**	**Speed (kt)**	**Pressure (psig)**	**Speed (kt)**
G-BWDA	114 - 119	96 - 98	64 - 66	72 - 73
G-EMBO	147 - 150	109 - 110	80 - 86	80 - 83
G-XLAC	200 - 205	127 - 128	n/a	n/a

Table 2

Dynamic Hydroplaning Speeds

17 The equation $9\sqrt{p}$ applies to a rolling wheel. If the wheel becomes locked, then the dynamic hydroplaning speed is reduced to $7.7\sqrt{p}$.

18 Reverted rubber refers to rubber that has reverted to its un-cured state and become sticky and tacky.

1.18.7 National Transportation Safety Board (NTSB) (USA) N471WN Chicago Midway International Airport investigation

On 8 December 2005, a Boeing 737-700 aircraft, registered N471WN, overran the end of runway 31C at Chicago Midway International Airport. The NTSB investigated the accident and issued a report in October 2007 (report reference NTSB/AAR-07/06). The report included discussion of a number of safety issues, including *'runway surface condition assessments and braking action reports.'*

The report also included an analysis of the assessment of runway surface conditions, and this discussion of the use of aircraft-generated friction measurements:

> *'The circumstances of this accident demonstrate the need for a method of quantifying the runway surface condition in a more meaningful way to support airplane landing performance calculations. The Safety Board and industry practice of analyzing an airplane's actual landing performance in the aftermath of an accident based on airplane-recorded data demonstrates that runway surface condition and braking effectiveness information can be extracted from recorded data.'*

Two of the recommendations were:

> *1. Establish a minimum standard for 14 Code of Federal Regulations Part 121 and 135 operators to use in correlating an airplane's braking ability to braking action reports and runway contaminant type and depth reports for runway surface conditions worse than bare and dry. (A-07-63)*
>
> *2. Demonstrate the technical and operational feasibility of outfitting transport-category airplanes with equipment and procedures required to routinely calculate, record, and convey the airplane braking ability required and/or available to slow or stop the airplane during the landing roll. If feasible, require operators of transport-category airplanes to incorporate use of such equipment and related procedures into their operations. (A-07-64)*

1.18.8 Previous incidents and AAIB Safety Recommendations

In 2003 the AAIB issued a report on an incident to an Embraer 135 which overran a slush covered runway while landing at Norwich Airport. A number of Safety Recommendations were made including:

> *'It is recommended that the CAA encourage research that could lead to the production of equipment that can accurately measure the braking action of runways under all conditions of surface contamination. (Safety Recommendation 2003-96)'*

The CAA response was:

> *'The CAA accepts this recommendation. In response to the concerns of airlines when operating on runways of inferior friction characteristics, the CAA has convened a working group, involving airlines, aerodrome operators, research and development bodies and manufacturers of runway friction measurement devices, to address operational runway friction issues, including winter operations. The working group recognises that research worldwide has so far failed to provide an accurate measurement of friction or braking action on a runway contaminated by slush and wet snow, and that there are wider operational issues such as the reliability of the reported measurement, that also need to be addressed.'*

In addition to the challenges and costs of developing a friction measurement device suitable for runways contaminated by slush and wet snow, manufacturers also have to consider whether there is sufficient market for such a device. However, the CAA is content to continue to encourage research that could lead to the production of equipment that can measure accurately the braking action under all conditions of surface contaminant.

During the consultation period for issuing this report, the CAA provided further update which confirmed that research had been carried out on a modified friction measuring device which could measure runway friction under contaminated runway conditions. The detail of this research was presented to the European Aviation Safety Agency (EASA) in June 2008.

2 Analysis

During the period of runway resurfacing work, at least 10 flight crews reported a loss of retardation during landing on the ungrooved base course section of the runway in wet conditions. The two incidents to G-XLAC considered in this report are typical of these. This reduction coincided with the lower friction levels measured by the Mu-meter and the reduction in calculated braking coefficient. The poor retardation reported by flight crews can be attributed to reduced friction in some areas of the runway, and the correct functioning of aircraft anti-skid systems, which reduced brake pressure to prevent skidding.

The flight crews of both G-BWDA and G-EMBO lost directional control on the area of ungrooved base course. Both aircraft ran onto the ungrooved portion during their landing rolls, when the flight crews were reliant upon nosewheel steering and/or differential braking for directional control in the strong crosswind. At these speeds, the aerodynamic effect of rudder was not sufficient to maintain direction. Both the wheel brakes and nosewheel steering rely on tyre adherence to the runway surface; the slippery runway reduced this effectiveness.

Although the G-XLAC incidents differ from those concerning G-BWDA and G-EMBO, the environmental factors common to all were a combination of areas of temporary runway surface, wet weather and strong crosswinds.

2.1 Runway resurfacing

2.1.1 Planning of resurfacing works

The runway resurfacing work at BIA was more complex than a normal runway resurfacing programme because an attempt was being made to reshape some sections of the runway to better conform with the CAP 168 profile limitations, while at the same time resurfacing the whole runway. This meant that instead of starting at one end and working forwards in small sections, a number of separate areas ended up with different surface types as the reshaping base/regulating course was laid.

BIA carried out a risk assessment as part of its safety case for the runway resurfacing works, but it did not include the risk of an aircraft leaving the side or the end of a runway due to inadequate friction in wet conditions. The safety case only discussed the risk of FOD and the risk of collisions with contractor equipment and personnel. A separate risk register included 'unacceptable post-construction friction readings' as a risk, but this was considered to be the responsibility of the contractor and was to be mitigated against by 'selection of materials'. The BIA operator assumed that as long as the surface materials were controlled, the friction of the ungrooved surfaces would be adequate because previous runway resurfacing works had shown them to be adequate.

The airport operator did not specify in its documentation minimum friction levels for the temporary surfaces or any other contingency plans in case surfaces dropped below those levels, beyond controlling the materials. The runway resurfacing plans at Luton and Belfast City did consider these factors and contingency plans were in place. The operator had also not specified what measures would be taken if weather conditions precluded a friction survey using self-wetting in accordance with CAP 683. Although a risk assessment plan was in place, it did not satisfactorily address the hazards that could be faced by departing and arriving aircraft in wet and windy weather.

The AAIB considered that the CAA should require airport operators to develop a satisfactory operational risk assessment plan, addressing the risk to aircraft, before initiating any runway resurfacing. Such a plan should, as a minimum, satisfy all guidance and instruction contained in CAP 683 and relevant guidance and instruction contained in CAP 168.

In response to this consideration the CAA published CAP 781 '*Runway Rehabilitation*' on 20 June 2008. CAP 781 states in a section entitled '*Risk Assessment*':

> *'The CAA will expect to see and approve comprehensive safety assurance documentation addressing the risks to aircraft, which shows all identified hazards have been assessed and reduced to tolerable levels or otherwise mitigated before work starts.'*

A contributory factor to the lack of contingency planning and the incidents themselves was a belief by the contractors that a temporary ungrooved base course did not represent a significant risk. They were more concerned about ungrooved surface course and were limiting the length of ungrooved surface course to 100 m. This belief was based on past experience including the experience at Luton and Belfast City where satisfactory friction readings were obtained from the ungrooved base course. However, the Belfast City experience was not completely representative because the base course used there was HDM, which has a coarser texture than Marshall Asphalt. At Luton, Marshall Asphalt base course was used and the lowest recorded friction on the ungrooved surface was 0.63 with self-wetting (with a GripTester where the MFL is 0.55). The friction of the ungrooved base course at BIA was never measured in controlled self-wetting conditions with a Mu-meter or GripTester, so a direct comparison with Luton cannot be made. However, the Mu-meter runs in natural wet and damp conditions indicated that the ungrooved base course at BIA was probably below the Mu-meter MFL of 0.50. This investigation was unable to determine the reason for the lower measured friction of the BIA base course compared to the Luton base course. An independent visual examination of the BIA base course did not reveal any anomalies.

Due to the identified uncertainty concerning the friction characteristics of ungrooved Marshall Asphalt base course, particularly in wet conditions, airport operators and runway surfacing contractors should take this into account when planning future resurfacing works. A cautious approach should be employed until more data is obtained about the friction characteristics of ungrooved Marshall Asphalt base course in wet conditions.

Therefore, the AAIB recommends that:

> The Civil Aviation Authority should inform airport operators about the potential hazards of operating aircraft on sections of ungrooved Marshall Asphalt base course during wet and windy conditions and require that these hazards be controlled during any runway resurfacing programme. (Safety Recommendation 2008-075)

2.2 Hydroplaning

A number of pilots reported that they thought their aircraft was 'aquaplaning' when it hit the central ungrooved 'patch' area of the runway. When pilots refer to 'aquaplaning' they are usually describing the phenomenon of dynamic hydroplaning which results in a significant loss of both friction and controllability as a result of the hydrodynamic force lifting the tyres. This occurs only when the water depth and the aircraft's speed are sufficient. According to the literature on dynamic hydroplaning, the minimum water depth required is 0.25 mm for worn tyres and 0.76 mm for new tyres. The minimum speed required is based on tyre pressure as detailed in section 1.18.6.1.

In the events described in this report, the aircraft were landing on a surface that was described as 'WET' and therefore would have had a reflective surface but with a water depth of less than 3 mm. The conditions, therefore, may have been conducive to dynamic hydroplaning. Of the events for which there is recorded data, it was the two involving G-XLAC which provided the best information regarding braking action effectiveness over the length of the runway. On both landings, there was a significant reduction in deceleration as the aircraft passed over the ungrooved 'patch'. The ground speeds at which this initiated, 120 kt for the 3 January 2007 event and 110 kt for the 29 December 2006 event, were just below the 127-128 kt predicted minimum hydroplaning speed based on the main gear tyre pressures. This predicted minimum hydroplaning speed, based on the $9\sqrt{p}$ equation, is not precise and therefore dynamic hydroplaning cannot be ruled out as a factor in the two G-XLAC events.

In the G-BWDA event the loss of directional control began at a groundspeed of approximately 62 kt which was 10 kt below the predicted minimum hydroplaning speed for the nose gear. For this event it is again difficult to definitively rule in or out dynamic hydroplaning as a factor.

In the G-EMBO event the loss of directional control began at a groundspeed of approximately 67 kt which was 13 to 16 kt below the predicted minimum hydroplaning speed for the nose gear. Therefore, in this event dynamic hydroplaning was unlikely as a factor but still could not be definitely ruled out.

The CAA guidance in AIC 15/2006 (Pink 92) on the topic of *'Risks and factors associated with operations on runways affected by snow, slush, or water'*, states:

> *'Depths of water or slush, exceeding approximately 3 mm, over a considerable proportion of the length of the runway, can have an adverse effect on landing performance. Under such conditions aquaplaning is likely to occur…'*

However, the scientific literature on dynamic hydroplaning states that dynamic hydroplaning can occur at water depths as low as 0.25 mm. Therefore, when a runway surface is merely 'WET' (i.e. less than 3 mm depth), it should not be assumed that hydroplaning will not occur.

2.3 Operation of the aircraft

2.3.1 G-XLAC

The flight crews of G-XLAC experienced difficulties in reducing speed after landing, but not directional control difficulties. Both flight crews selected appropriate landing flap setting and autobrake settings for the circumstances of their landings. The available information, including the FDR data, indicated that the piloting technique used was correct and the difficulties experienced by the flight crews were a consequence of the reduced friction available from the ungrooved runway surface. These difficulties could only have been avoided had a decision been taken not to land at BIA in the conditions prevalent at the times of landing. The flight crews had not been provided with any information or guidance to suggest this decision was necessary; indeed on both events, the crews were passed information from ATC that the braking action was 'GOOD'.

2.3.2 G-BWDA

The difficulties experienced by the flight crew of G-BWDA arose from a number of sources.

2.3.2.1 Aircraft loading

The operations manual provided by the operator advised that the aircraft should be loaded with a forward centre of gravity for operations in strong crosswinds. The commander of G-BWDA (and others in the company) were not aware of this and as a result of this incident, the operator issued Flying Staff Memo General 14 2007 on 20 December 2007. This memo highlighted the operations manual advice and asked that pilots *'consider adopting this procedure in strong crosswind condition'*.

2.3.2.2 Crosswind component

The maximum crosswind component permitted for ATR-72 operations on a wet runway, according to the operations manual, was 25 kt. The final wind report broadcast by the tower controller before touchdown was 190°/34 kt, which gives a crosswind of almost 34 kt, considerably beyond the limit. Both pilots recalled hearing a final wind check of 190°/24 kt, which suggests that they either mis-heard the last broadcast or missed the last three broadcasts.

This factor should serve to highlight to flight crews the need for great care in accurately determining the crosswind prior to takeoff or landing.

2.3.2.3 Runway condition

Directional control was lost shortly after the landing, and this occurred as the aircraft ran onto the 'patch'. Reduced friction in this area affected directional control and braking as described earlier.

2.3.2.4 Effects of aileron handling and reverse thrust

The operations manual provided to the flight crew warned that correct positioning of the ailerons in crosswind conditions was essential to avoiding directional control difficulties, which could occur if the airframe 'listed' away from the wind. Analysis of the FDR data showed that G-BWDA did list after landing, and that the ailerons were moved, albeit not immediately, to the fully deflected position.

The investigation also considered the effect of reverse thrust upon the aircraft during the landing roll. Although reverse thrust has the potential to shorten the landing roll, the runway at BIA is considerably longer than the normal landing distance required by the ATR-72. Reverse thrust causes a relatively turbulent airflow to exist behind the propellers and this airflow is influenced by any crosswind. Its influence on the tail would be to reduce the aerodynamic effect of the rudder, causing directional control to become more difficult and, possibly, to alter the aerodynamic effect of the elevator during the landing roll. This could reduce the weight on the nose landing gear with similar effect.

The operations manual provided to the flight crew stated that if directional control problems occurred, reverse thrust should be reduced, or ground idle should be selected.

Correct operational and piloting technique is essential for safe operation of aircraft and the operating company is now highlighting the use of reverse thrust, especially in crosswind landings, during company pilot training.

2.3.2.5 NOTAMs

The software which filtered NOTAMs for inclusion in their pre-flight brief, filtered out any NOTAMs more than 15 days old. Therefore, the flight crew of G-BWDA were unaware that the runway at BIA was notified as 'may be slippery when wet'. As a result of this incident, the NOTAM filtering software has been amended: the 'cut off' period has been increased to three months and there is additional overview by the company ATR flight manager.

2.3.3 G-EMBO

The commander of G-EMBO experienced difficulties in directional control of his aircraft after landing. These difficulties were consistent with the effects of the poor friction of the ungrooved base course runway surface.

2.4 Runway state reporting

The two reports from landing aircraft on 14 November 2006 were the first indication to the airport authority that flight crew had experienced difficulties with the temporary runway surface. The investigation considered whether a 'survey run' to assess the friction characteristics of the temporary surface would have had a beneficial effect upon subsequent events. Such assessment might have enabled the airport authority to identify what action could be taken to improve the friction characteristics. The action taken on 15 November 2006, when the airport authority notified that the runway 'may be slippery when wet', would have been the appropriate action had a calibration assessment found that the surface friction fell below the MFL. This action was in accordance with instructions set out in CAP 683, for runways with surfaces which fail to meet the relevant minimum friction level.

The subsequent decision, on 30 December 2006, to notify that the runway *'WILL BE SLIPPERY WHEN WET'* appeared to reflect a desire to remove doubt from the minds of operators and flight crews, and to communicate clearly that when wet, the friction available would require consideration.

Advice and instruction on operations on runways notified as 'may be slippery when wet' has been published in a variety of documents. However, at the time of the incidents, the only advice to operators regarding operations in wet conditions on runways notified as 'may be slippery when wet' was in FODCOM 19/2006.

The advice in FODCOM 19/2006 stated:

> *'Braking action is assumed to be poor on a wet runway that is notified as one that may be slippery when wet'*

This advice was not communicated to the flight crews involved in these incidents. The advice was not reflected in the AIP entries concerning Runway Surface Condition Reporting or Runway Friction Assessment. If operators had assumed that the 'slippery when wet' runway at BIA would provide poor braking action, it is conceivable that the landings discussed in this report would not have been attempted.

The FODCOM also stated:

> *'Operators should ascertain from aerodrome operators the location and dimension of the part of the runway that has fallen below the minimum friction, 'slippery when wet' trigger level, in order that they can assess whether aeroplane performance is affected.'*

However, aircraft manufacturers have not provided data or information to indicate how aircraft may be expected to perform and, without such data, operators are unable to make such assessments.

Since these incidents, the CAA has published FODCOM 28/2007 '*Guidance For Operations On a Runway that is Notified as 'May Be Slippery When Wet'*'. This FODCOM recommends that:

> *'operators should ensure that flight crews are provided with guidance material on dealing with a runway that is notified as 'may be slippery when wet.'*

The AAIB concurs with this recommendation and makes the further Safety Recommendation that:

> The European Aviation Safety Agency should require operators to ensure that flight crews are provided with guidance material on aircraft performance when operating on a runway that is notified as 'may be slippery when wet', or has sections thereof notified as 'may be slippery when wet'. (Safety Recommendation 2008-076)

2.5 FODCOMs as a means of promulgating operational safety information

The advice contained in FODCOM 19/2006 was correct and included safety-critical information. Operators incorporating it into their operations manual would have then enabled their flight crews to understand that slippery when wet runways, in wet conditions, should be *'assumed'* to give poor braking action. Although in the circumstances at BIA, this assumption was contradicted by the advice from ATC, it may have acted to warn flight crews that braking action was questionable.

However, the operators were not required to do this and did not act upon the advice and information in the FODCOM. FODCOMs are not sent to pilots and operators do not routinely instruct pilots to read them. Therefore, when operators do not incorporate FODCOM advice into their operations manuals (whether as advice or instruction), pilots cannot be expected to act upon that information.

Recently issued FODCOMs have covered topics such as, '*Training for Ground De-icing and Anti-icing of Aircraft, Changes to Airborne Collision Avoidance System (ACAS) 'Resolution Advisory' Phraseology, Smoke Drills and Aircraft Loading'*.

They have included safety critical information but currently no system exists to ensure that the information in them is communicated to flight crews. Their effectiveness is also limited by distribution only to UK companies holding Air Operators Certificates.

Therefore, the following Safety Recommendation is made:

> The Civil Aviation Authority should review the manner in which it transmits FODCOM information to ensure that safety critical information is effectively transmitted to private and commercial operators flying in the UK and that it is acted upon. (Safety Recommendation 2008-077)

2.6 CFME and wet runways

A number of documents stated that CFME was not to be used on a runway *'contaminated with water'*. This meant a runway with water, or water patches, more than 3mm deep over more than 25% of its surface area. However, it was the understanding of the CAA that CFME should not be used at all on a wet runway. This was because CFME is considered unreliable in such conditions and no table existed for interpretation of results into braking action other than the snow and ice table, which was, by definition, not applicable. The CAA instruction to the airport on 5 January 2007 clearly instructed that braking action information should not be given when the runway was wet.

However, the statement in the MATS Part 2 at BIA confused the issue :

> *'Contamination by water*
>
> *'The measurement of the runway friction value will not normally be required but if requested by a pilot this value will be measured by mu-meter (MATS Part 1 Section 9 Chapter 3 pages 2-3 refer).'*

Also, the NOTAM issued on 15 November 2006 stated that braking action co-efficients would be available if required, and this reflected a general understanding amongst operations personnel at the airport that CFME could be used effectively and legitimately on a wet runway surface, and that the results would be relevant and useful to aircraft operators.

Although it is understood by the CAA that braking action assessments by CFME are not appropriate on a wet runway, there is no specific stipulation in the relevant documentation. Therefore, the following Safety Recommendation is made:

> The Civil Aviation Authority should clarify to airport authorities, pilots, aircraft operators and air navigation service providers, that Continuous Friction Measuring Equipment must not be used to assess braking action on runways which are wet, although it may be used in the wet for assessing the relative friction of different runway sections for maintenance purposes. (Safety Recommendation 2008-078)

2.7 ATC

The instructions to air traffic controllers in MATS Part 1 stated that:

> *'In conditions of slush or thin deposits of wet snow, friction measuring devices can produce inaccurate readings. The snow and ice table below applies only in conditions of compacted snow or ice.'*

However, from 15 November 2006, air traffic controllers at BIA used this table to interpret friction readings taken on wet runways.

Whilst in part the use of the snow and ice table must be a consequence of the relative infrequency of operations on contaminated or 'slippery when wet' runways in the UK, it should also be recognised that these circumstances are potentially hazardous and it might be expected that training and provision of information to those involved should have equipped them to deal with the circumstances correctly.

Several of the flight crews that had experienced braking problems on landing reported this to ATC. Subsequent CFME runs in the wet conditions gave friction readings that ATC controllers interpreted as a 'GOOD' braking action. ATC then passed the braking action to following landing traffic as 'good' without adding any of the problems that previous landing traffic had encountered.

The pilot reports of poor deceleration constituted essential aerodrome information and according to MATS Part 1, controllers should have continued passing them on. The presence of the 'GOOD' braking action information should not have served as reason to dismiss the pilot reports. However, this is likely to have caused confusion to the pilots of arriving aircraft, who would have received contradictory information.

If, as required, the information from the Mu-meter had not been converted into braking action and passed to pilots, it is likely that the pilot braking action reports would have been correctly transmitted in their place.

2.8 Braking coefficient

The plots of aircraft deceleration versus runway position in Figure 8 show how the deceleration varied with runway surface condition. However, the total deceleration cannot be used to ascertain an aircraft's braking effectiveness on a given runway surface. This is because deceleration depends on several factors aside from brake effectiveness.

The braking action reported to the flight crew of G-XLAC by ATC prior to landing on 29 December 2006 was 'GOOD'. The longitudinal deceleration and braking coefficient with respect to runway position, suggests that a significant variation in braking capability existed along the runway length. This variation is likely to have led to the commander sensing that the wheels had *'locked up'*, and the belief that braking action report of 'GOOD' was misleading. Had the braking coefficient data been available during this event and compared to braking coefficient data recorded from landings in better conditions, the braking action assessment of 'GOOD' may have been challenged.

Runway surface condition reports are created using a number of sources including runway friction measurement devices, pilot reports and runway visual observations. Runway conditions can change quickly due to weather conditions, runway usage, application of surface treatments, etc.

Using braking coefficient data, it should be possible to add to these sources of information to build a bigger picture of the runway condition. The complex avionics systems installed on modern aircraft are typically interconnected by databuses carrying vast quantities of aircraft information. With such data available, it should possible to calculate dynamically a braking coefficient for the aircraft, with respect to runway position, either in real-time or shortly after each landing.

If braking coefficient data could be transmitted from landing aircraft, it could enable the landing conditions for subsequent aircraft to be better determined; this information could be shared to prevent landing incidents and accidents. It is therefore recommended that:

> The European Aviation Safety Agency should research the technical and operational feasibility of developing equipment and procedures to measure aircraft braking friction with respect to runway position, using on-board aircraft data from landings. As part of this research the European Aviation Safety Agency should develop appropriate standards of recording and methods for sharing this information, and its tolerances, in a timely manner, with interested parties. (Safety Recommendation 2008-079)

The NTSB report into the accident to N471WN at Chicago Midway International Airport made a similar recommendation and, as a consequence, work was undertaken by both the FAA and the airline to start developing the required technology.

2.9 Communications

The only communications difficulties which occurred during the period involved radio communication between the RFFS, ATC, and aircraft. The action taken by the airport authority to resolve the technical problem which existed between ATC and RFFS was, according to RFFS managers, prompt and effective. The longer-term plan to install a new communication system throughout the airport offers the opportunity to introduce a system much improved upon that in use during the events described in this report.

2.9.1 Safety action

BIA has begun a programme for replacement of all radio equipment used by the RFFS, and others, with the aim of resolving the communications difficulties experienced by RFFS staff and pilots on 29 December 2006.

3 Conclusions

3.1 Findings

3.1.1 The aircraft

1. There was no evidence of the aircraft involved in the incidents having experienced a technical fault.

2. The only damage was to G-BWDA, which suffered damage to its left propeller.

3. The tread depths and pressures of the tyres on the incident aircraft were, as far as could be determined, within allowable limits.

3.1.2 The runway

4. The runway resurfacing work at Bristol Airport was complex because it involved an attempt to reshape parts of the runway prior to resurfacing.

5. Several separate areas of the runway had a temporary ungrooved base course Marshall Asphalt surface.

6. The runway resurfacing work was undertaken at night and during the winter to avoid disrupting flight schedules.

7. The longest stretch of ungrooved base course was the central runway portion and was 295 m long and covered the full width.

8. Marshall asphalt is not porous and, when used as a surface course, is usually grooved to allow water to drain to the side of the runway.

9. The surface friction of the ungrooved base course had not been assessed using a Mu-meter with self-wetting in dry conditions predominantly due to the prevailing weather. There was a dry period on 8 December 2006 but no staff were available to conduct the runs.

10. Mu-meter runs carried out in wet conditions revealed that the ungrooved base course had significantly less friction than the grooved runway sections.

11. Mu-meter runs of the central ungrooved section, undertaken in natural wet and damp conditions, indicated that the friction of the ungrooved base course was probably below the Minimum Friction Level (MFL) of 0.50.

12. The airport operator's risk assessment plan had not adequately addressed the hazards presented to aircraft operating on the temporary surfaces in wet and windy weather.

13. Runway surface contractors believed that temporary ungrooved base course did not represent a significant risk and were more concerned about limiting the length of ungrooved surface course to 100 m; no length limitation was specified for the ungrooved base course.

14. The information promulgated by NOTAM, that braking action information would be available during wet conditions, was incorrect.

15. Following the incidents investigated in this report, the airport operator closed the runway on 7 January 2007 and cut temporary grooves in the ungrooved base course.

16. The runway was re-opened on 8 January 2007; no further runway excursion or braking difficulty reports were received after this date.

17. The instruction in CAP 683 concerning friction assessment for resurfaced runways did not clearly include portions of runways which have been resurfaced.

18. The 295-metre full width section of runway surface covered with ungrooved base course asphalt did not provide adequate friction for safe operations when the runway surface was wet.

19. The airport authority was aware of the poor braking action provided by the ungrooved base course asphalt but did not take steps to increase the braking action available until 3 January 2007.

3.1.3 Flight operations

20. A significant number of flight crews experienced difficulties decelerating the aircraft after landing.

21. The flight crews of two aircraft were unable to prevent their aircraft leaving the paved surface while landing in strong crosswinds.

22. The operators of aircraft involved in the four principal events described in this report had not provided guidance concerning operations on runways notified *'slippery when wet'* to their flight crews.

23. During the landing roll of G-BWDA, the use of reverse thrust did not comply with the handling advice in the FCOM for operations in crosswind conditions.

24. The final wind information passed to G-BWDA was in excess of the wet crosswind limit for that aircraft.

3.1.4 Air traffic control

25. The instruction to air traffic controllers in the MATS Part 2, that they should provide runway friction value information based on Mu-meter measurements in wet conditions, was incorrect.

26. The use, by air traffic controllers, of the snow and ice table for conversion of mu-meter reading into braking action in wet conditions, was incorrect.

27. The passing of braking action reports based on CFME readings on a wet runway, ceased on 5 January 2007.

3.2 Causal Factors

The investigation identified the following causal factors:

1. Reduced friction on the wet ungrooved base course sections of the runway caused flight crews to experience reduced braking action and reduced lateral controllability on landing in strong crosswinds.

2. The Flight Operations Department Communication (FODCOM) advice published by the CAA regarding operations on runways notified 'slippery when wet', in wet conditions, was not communicated by operators to flight crews.

3. The passing, by ATC, of braking action reports based on Mu-meter friction assessments, gave flight crews a false confidence in the braking action available on the wet runway.

3.3 Contributory Factor

The investigation identified the following contributory factor:

1. G-BWDA landed in a crosswind outside the operator's published limits and the subsequent use of reverse thrust was contrary to the advice contained in the company's Operations Manual.

4 Safety Recommendations

4.1 **Safety Recommendation 2008-075:** The Civil Aviation Authority should inform airport operators about the potential hazards of operating aircraft on sections of ungrooved Marshall Asphalt base course during wet and windy conditions and require that these hazards be controlled during any runway resurfacing programme.

4.2 **Safety Recommendation 2008-076:** The European Aviation Safety Agency should require operators to ensure that flight crews are provided with guidance material on aircraft performance when operating on a runway that is notified as 'may be slippery when wet', or has sections thereof notified as 'may be slippery when wet'.

4.3 **Safety Recommendation 2008-077:** The Civil Aviation Authority should review the manner in which it transmits FODCOM information to ensure that safety critical information is effectively transmitted to private and commercial operators flying in the UK and that it is acted upon.

4.4 **Safety Recommendation 2008-078:** The Civil Aviation Authority should clarify to airport authorities, pilots, aircraft operators and air navigation service providers, that Continuous Friction Measuring Equipment must not be used to assess braking action on runways which are wet, although it may be used in the wet for assessing the relative friction of different runway sections for maintenance purposes.

4.5 **Safety Recommendation 2008-079:** The European Aviation Safety Agency should research the technical and operational feasibility of developing equipment and procedures to measure aircraft braking friction with respect to runway position, using on-board aircraft data from landings. As part of this research the European Aviation Safety Agency should develop appropriate standards of recording and methods for sharing this information, and its tolerances, in a timely manner, with interested parties.

K Conradi
Principal Inspector of Air Accidents
Air Accidents Investigation Branch
Department for Transport
December 2008

Appendix A

BIA Runway Condition at 29 December 2006

Appendix B

Additional Mu-meter Friction Measurements

The Mu-meter manufacturer provided the AAIB with some 2D colour-coded plots of measured friction for 5 January 2007 (Figure B1) and the survey runs on 10 January 2007 (Figure B2) at BIA. The runs on 5 January were done prior to the temporary grooving and were done under damp conditions without self-wetting. They were also undertaken for training purposes so cannot be used as a controlled CAP 683 survey. However, the data still clearly illustrates the lower friction values of the ungrooved portions of runway compared to the grooved portions (see Figure B1). Figure B2 shows all the Mu-meter data from the survey runs carried out on 10 January after the base course was grooved. These runs were undertaken in dry conditions using self-wetting in accordance with CAP 683. This figure shows a more uniform and consistent friction characteristic along the entire length of the runway with the temporary grooves installed.

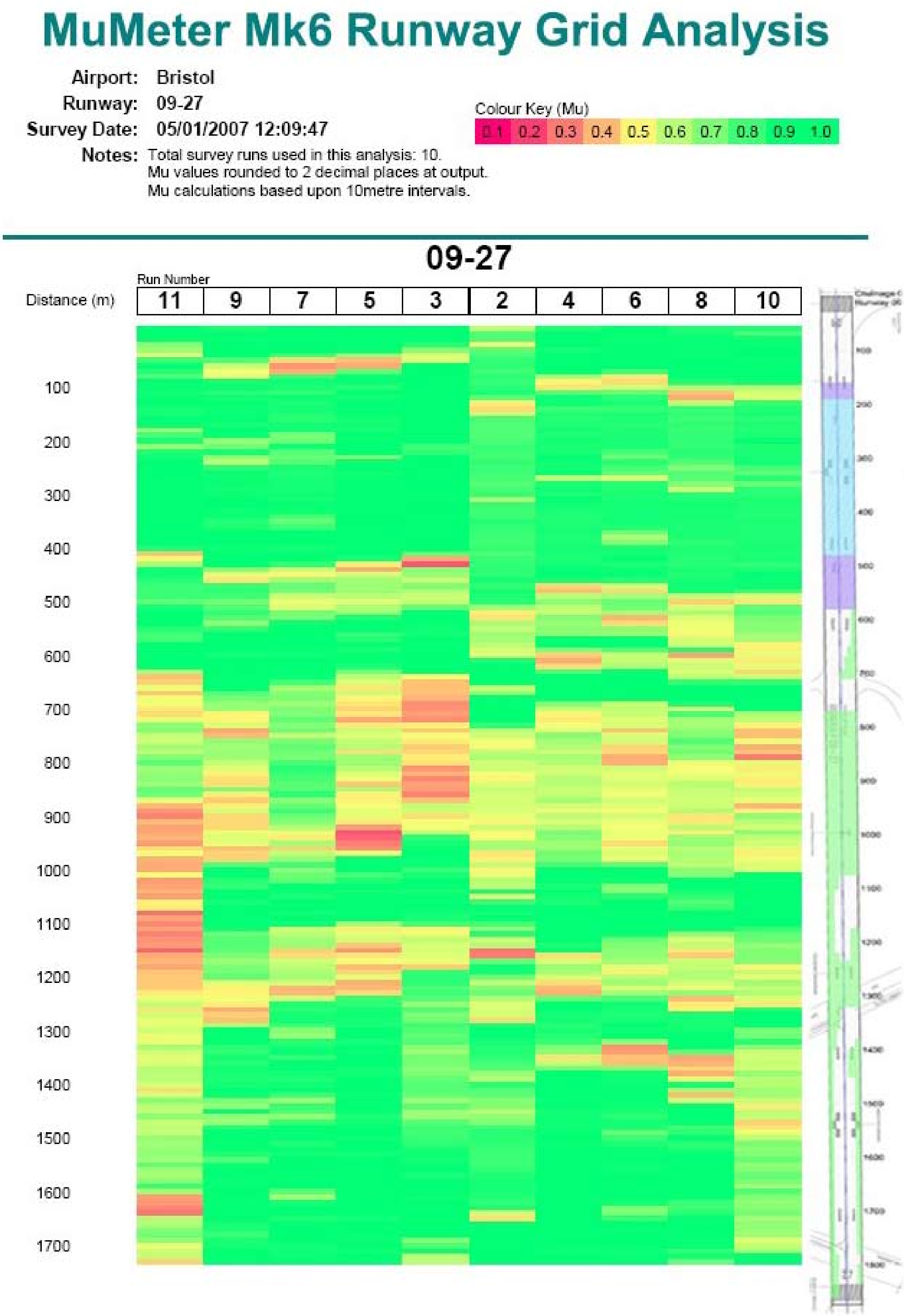


Figure B1

Friction measurement runs carried out on 5 January 2007 prior to temporary grooving, on a damp surface without self-wetting. Each 10 m portion of runway is depicted by a colour representing its friction value

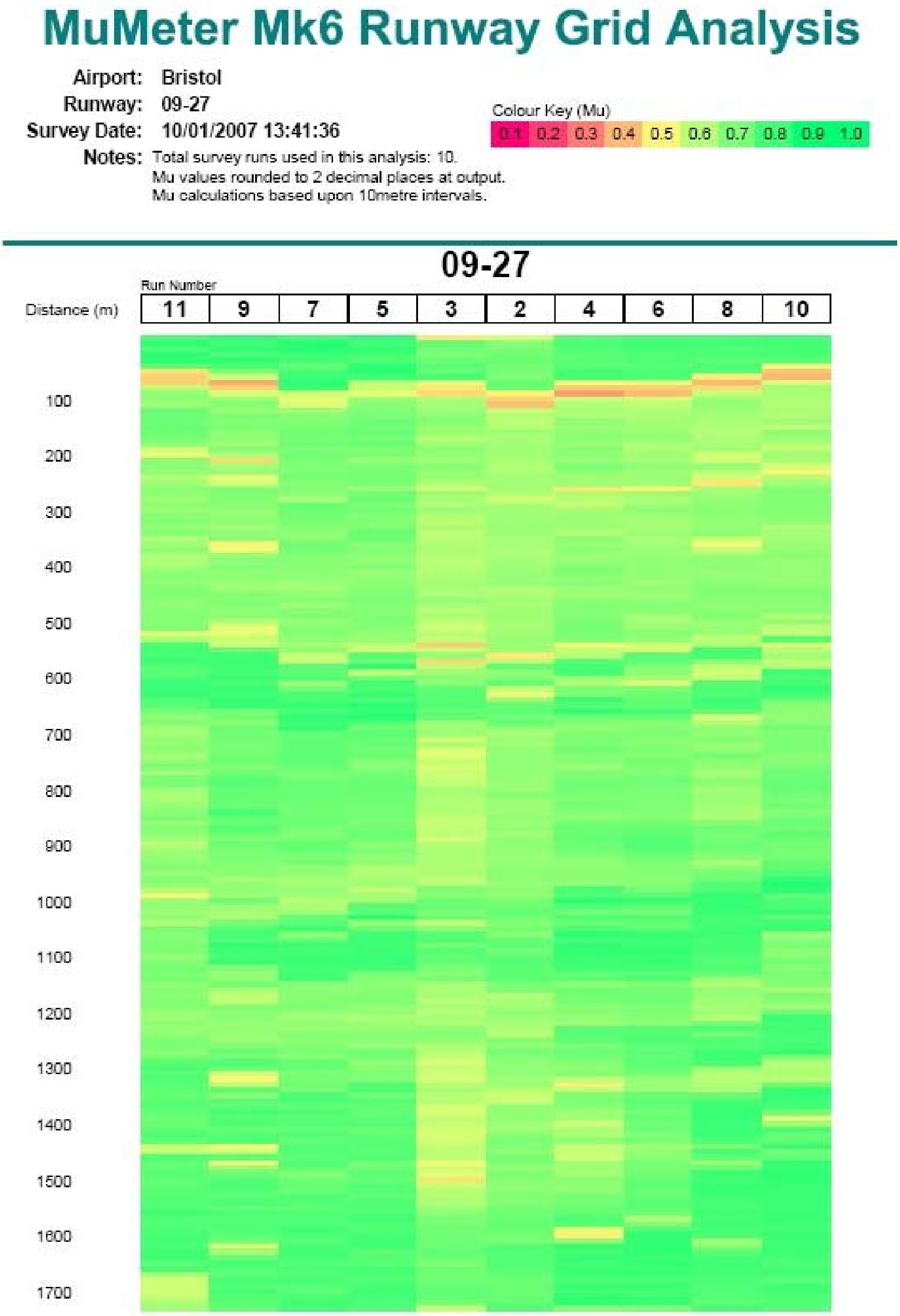


Figure B2

Friction measurement runs carried out on 10 January 2007 after base course grooving, on a dry surface with self-wetting. Each 10 m portion of runway is depicted by a colour representing its friction value

Additional Figures from FDR Data

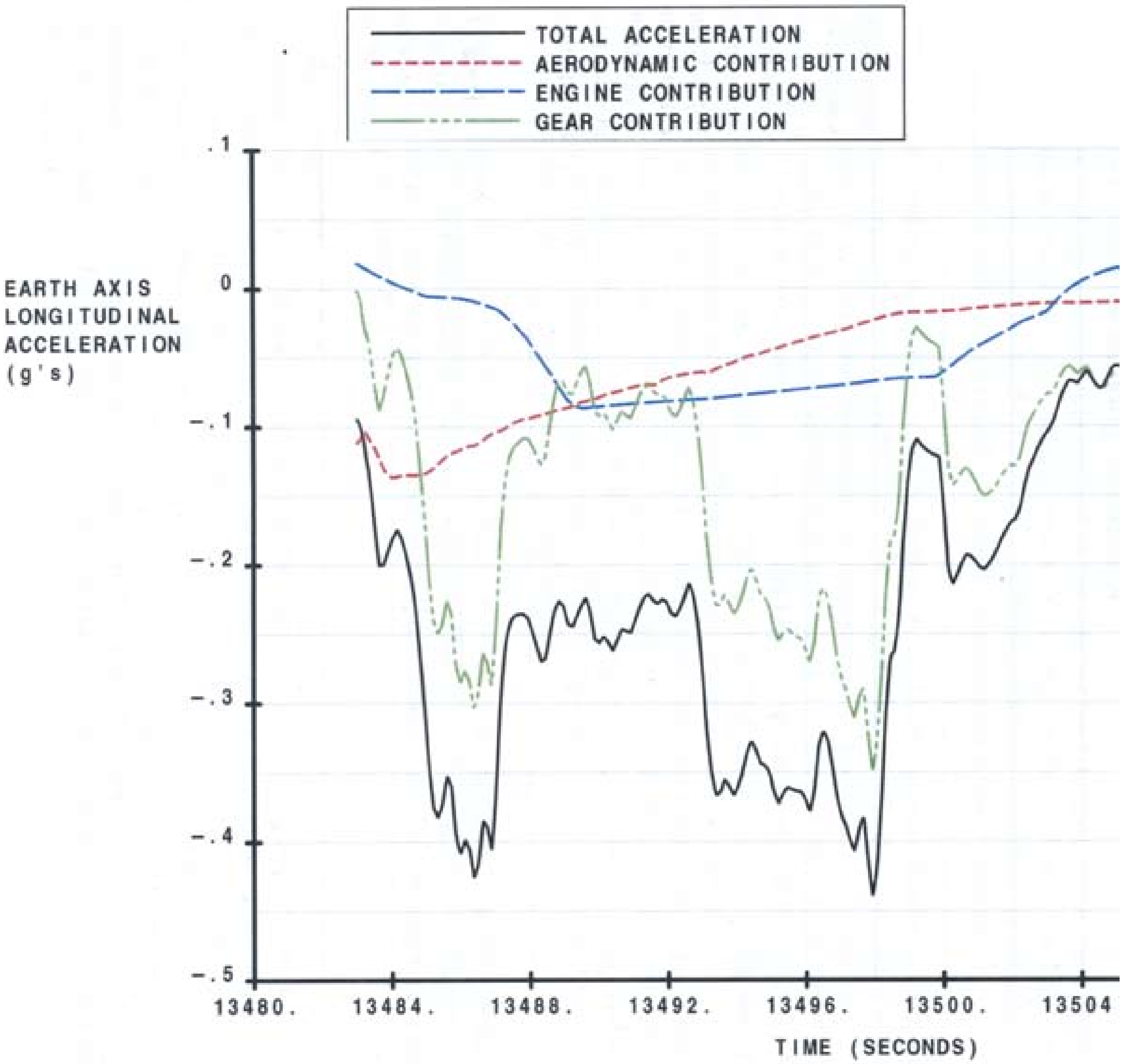


Figure C1

G-XLAC component deceleration contributions
3 January 2007
(Reproduced courtesy of Boeing)

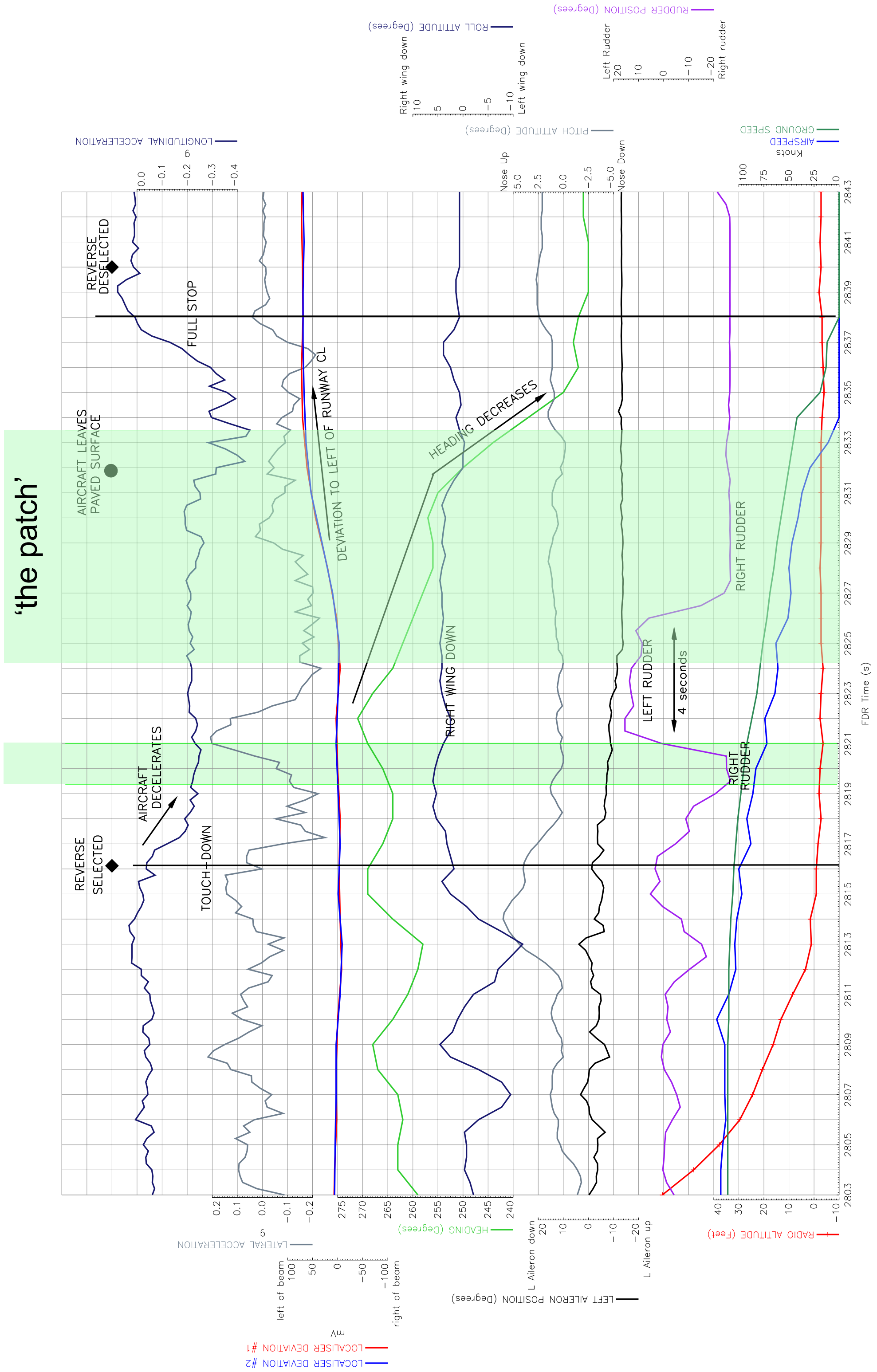


Figure C2

G-BWDA landing Runway 27, 29 December 2006

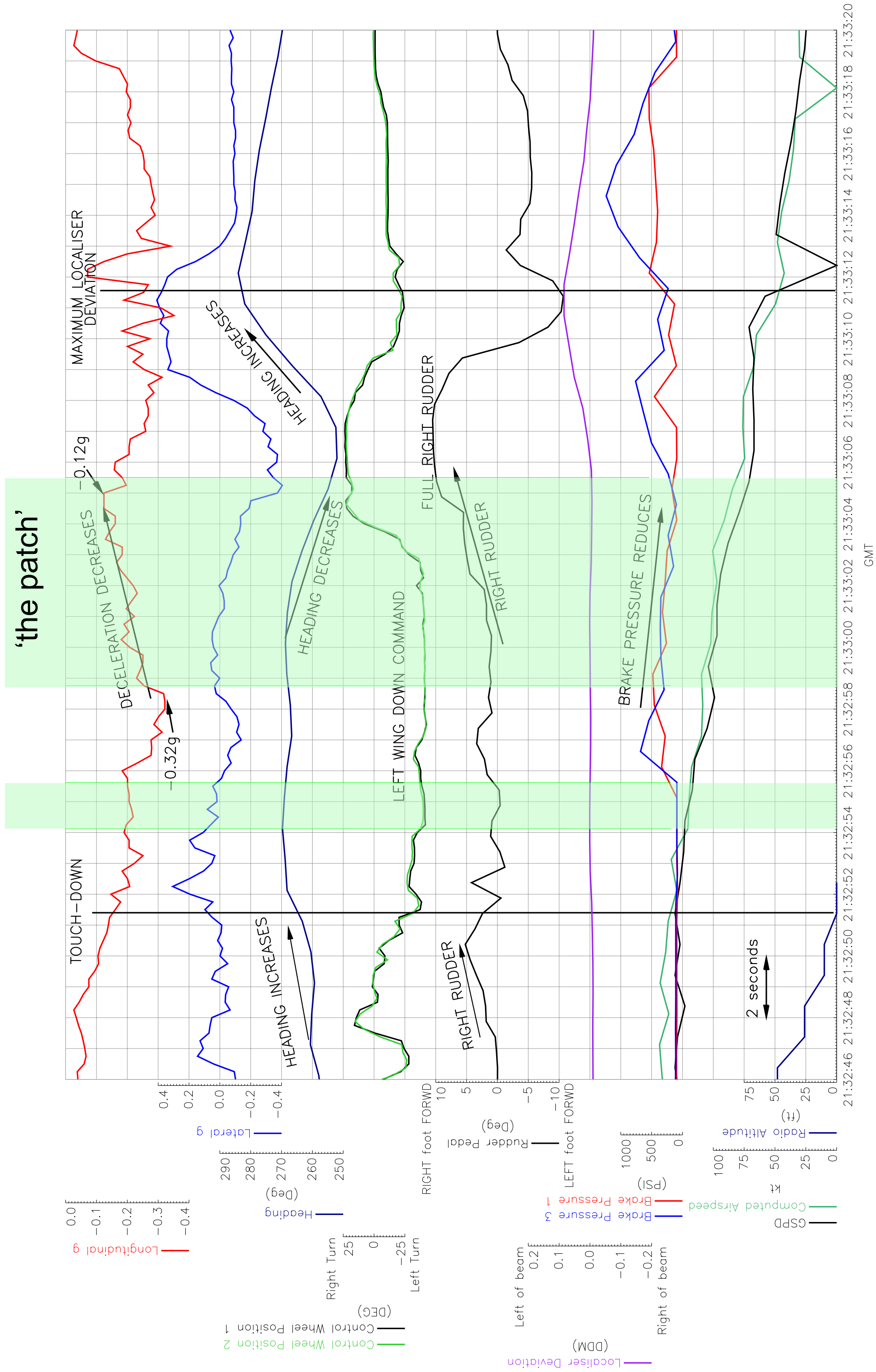


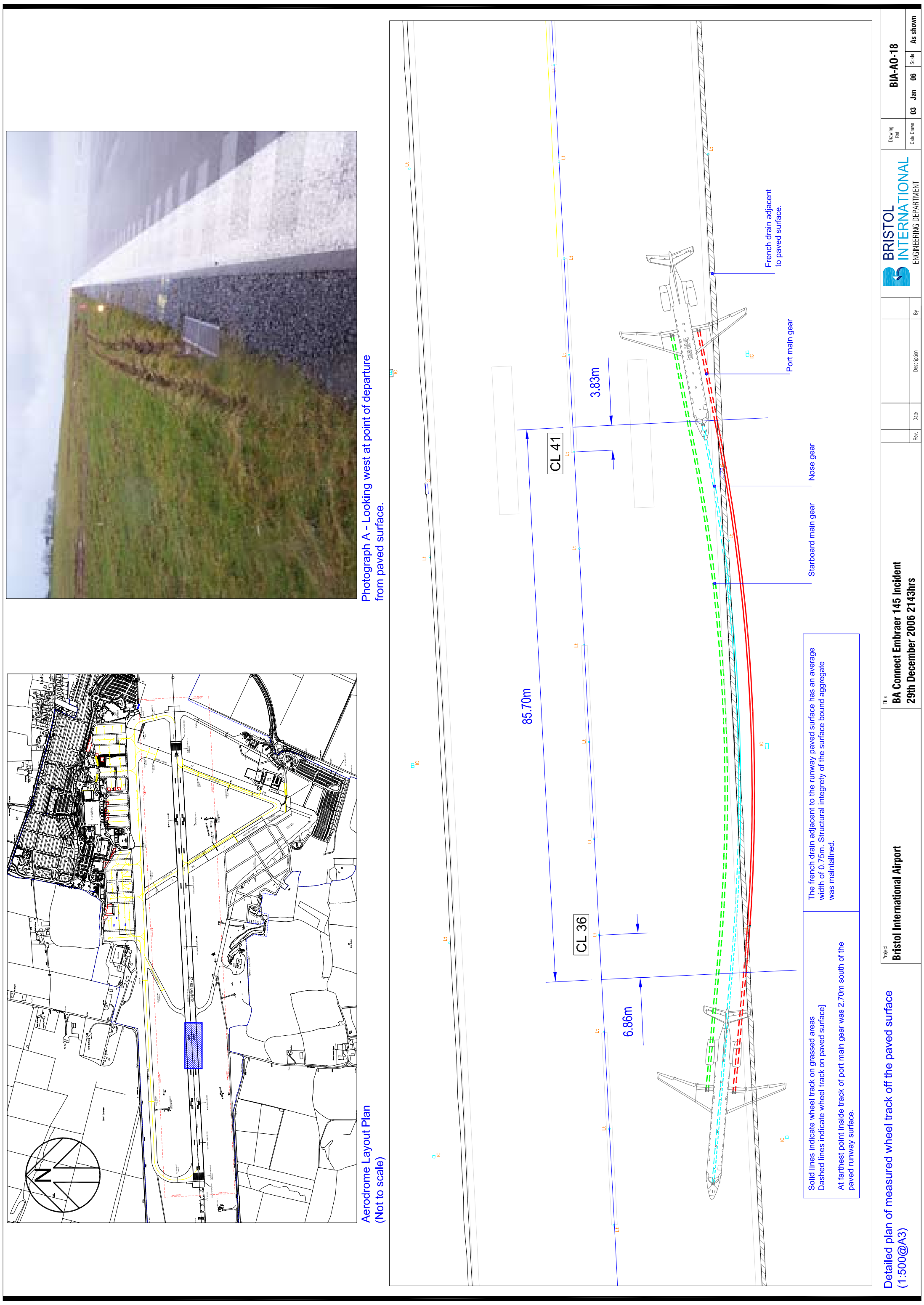
Figure C3

G-EMBO landing Runway 27, 29 December 2006

Appendix D

Diagrams of G-BWDA and G-EMBO Runway Excursions

G-BWDA Position at BIA, 29 December 2006



G-EMBO Position at BIA, 29 December 2006

FLIGHT CREW DETAILS

Flight Crew G-XLAC 29 December 2006

Commander	Male aged 47 years	
Licence	Airline Transport Pilot's Licence	
Type ratings	Boeing 737-200 to -900 inclusive	
Instrument Rating	Valid to 31 March 2007	
Licence Proficiency check	Valid to 31 March 2007	
Operator's Line check	Valid to 9 November 2007	
Medical Certificate	Class One, valid to 23 February 2007, required to wear correcting lenses with a spare pair available	
Flying experience	Total all types	8,474 hours
	Total on type	5,464 hours
	Last 28 days	34 hours
	Last 24 hours	4 hours
Previous rest period	Off duty 1800 hours on 28 December 2006	
	On duty 0600 hours on 29 December 2006	

Flight crew G-BWDA 29 December 2006

Commander	Male aged 57 years	
Licence	Airline Transport Pilot's Licence	
Type ratings	ATR 72, SF 340	
Instrument Rating	Valid to 31 March 2007	
Licence Proficiency check	Valid to 31 March 2007	
Operator's Line check	Valid to 12 February 2007	
Medical Certificate	Class One, valid to 2 May 2007 required to wear correcting lenses with a spare pair available	
Flying experience	Total all types	5,000 hours
	Total on type	1,000 hours
	Last 28 days	88 hours
	Last 24 hours	10 hours
Previous rest period	Off duty 1305 hours on 28 December 2006	
	On duty 0605 hours on 29 December 2006	

Flight crew G-EMBO 29 December 2006

Commander	Male aged 56 years	
Licence	Airline Transport Pilot's Licence	
Type ratings	Embraer 145	
Instrument Rating	Valid to 16 October 2007	
Licence Proficiency check	Valid to 16 October 2007	
Operator's Line check	Valid to not known	
Medical Certificate	Class One, valid to 31 March 2007	
Flying experience	Total all types	9,500 hours
	Total on type	3,000 hours
	Last 28 days	33 hours
	Last 24 hours	4 hours
Previous rest period	Off duty 2105 hours on 21 December 2006	
	On duty 1615 hours on 29 December 2006	

Flight crew G-XLAC 3 January 2007

Commander	Male aged 38 years	
Licence	Airline Transport Pilot's Licence	
Type ratings	Boeing 727, Boeing 737-300 to -900 inclusive	
Instrument Rating	Valid to 30 April 2007	
Licence Proficiency check	Valid to 30 April 2007	
Operator's Line check	Valid to 6 March 2007	
Medical Certificate	Class One, valid to 27 September 2007	
Flying experience	Total all types	5,464 hours
	Total on type	3,545 hours
	Last 28 days	56 hours
	Last 24 hours	8 hours
Previous rest period	Off duty 1945 hours on 2 January 2007	
	On duty 0800 hours on 3 January 2007	

SNOW AND ICE TABLE		
Measured or calculated coefficient of friction	**Estimated braking action**	**MOTNE METAR Code**
0.40 and above	Good	95
0.39 - 0.36	Medium/Good	94
0.35 - 0.30	Medium	93
0.29 - 0.26	Medium/Poor	92
0.25 and below	Poor	91
If for any reason the reading is considered unreliable.	—	99

The 'Snow and Ice Table'