Transportation Safety Board of Canada
Bureau de la sécurité des transports du Canada

AVIATION INVESTIGATION REPORT A15Q0075

Runway overrun

WestJet
Boeing 737-6CT, C-GWCT
Montréal/Pierre Elliott Trudeau International Airport, Quebec
05 June 2015

Canada

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Summary

On 05 June 2015, a WestJet Boeing 737-6CT (registration C-GWCT, serial number 35112) was operating as flight 588 on a scheduled flight from Toronto/Lester B. Pearson International Airport, Ontario, to Montréal/Pierre Elliott Trudeau International Airport, Quebec. At 1457 Eastern Daylight Time, the aircraft touched down in heavy rain showers about 2550 feet beyond the threshold of Runway 24L and did not stop before reaching the end of the runway. The aircraft departed the paved surface at a ground speed of approximately 39 knots and came to rest on the grass, approximately 200 feet past the end of the runway. There were no injuries to the 107 passengers or 5 crew members and no damage to the aircraft. The 406-megahertz emergency locator transmitter did not activate. The incident occurred at 1458, in daylight.

Le présent rapport est également disponible en français.

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1.0 Factual information

1.1 History of the flight

WestJet flight 588 (WJA588) departed Toronto/Lester B. Pearson International Airport (CYYZ), Ontario, on a scheduled flight to Montréal/Pierre Elliott Trudeau International Airport (CYUL), Quebec. The captain was the pilot flying (PF) and the first officer was the pilot not flying (PNF). While en route, the PNF uploaded the applicable standard arrival procedure and the Runway 24L approach to the flight management system before completing the approach briefing. The calculated landing distance obtained from the aircraft communications addressing and reporting system (ACARS) was 7784 feet with flaps set to 30° and the autobrake system set to 1. Because the gate where the aircraft was to park was close to the end of the 9600-foot-long runway, the PF planned to exit at the far end of Runway 24L, and the crew set up for a landing with flaps set to 30° and the autobrake system set to 1.

During descent, the crew obtained automatic terminal information service (ATIS) information Lima, issued at 1418,[1] which was as follows: weather at 1412, wind 240° magnetic (M) at 8 knots, visibility 15 statute miles (sm) in light rain showers, broken towering cumulus clouds at 4500 feet above ground level (AGL), another broken layer at 7500 feet AGL and overcast at 24 000 feet AGL, temperature 23°C, dew point 16°C, altimeter 29.91 inches of mercury, instrument flight rules approach instrument landing system (ILS) Runway 24L and ILS Runway 24R, visual flight rules Runway 24L. Based on this information, the PF planned to carry out a visual approach to Runway 24L with the ILS approach as back-up.

While being vectored for the approach, the crew observed on the aircraft weather radar that there was moderate to heavy rain activity north-northwest of the field. Once on a heading of 330°M, on the left base leg for Runway 24L, the crew observed that the weather radar showed heavy rain on the approach path, but no turbulence or hail. At 1453, when it was approximately 8.8 nautical miles (nm) from the runway, the aircraft was configured for landing: flaps extended to 30°, landing gear extended, and speedbrakes armed.

At 1455, WJA588 called the tower controller to advise that the aircraft was established on the ILS for Runway 24L. Shortly thereafter, WJA588 received clearance to land and was told to expect to exit at the end of the runway. The wind reported to the crew was 350°M at 17 knots with gusts to 22 knots. At that time, the aircraft was flying through heavy rain showers. The wipers were selected on.

The following information was retrieved from the flight data recorder (FDR). The ILS approach was coupled with the autopilot and autothrust (A/T) engaged. The A/T was in SPEED MODE, and the initial selected speed on the mode control panel (MCP) was

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1 All times are Eastern Daylight Time (Coordinated Universal Time minus 4 hours).

130 knots. However, it was increased to a final value of 140 knots[2] while the aircraft was descending through 740 feet AGL. The recorded landing reference speed (V_{REF}) was 125 knots; therefore, the final selected speed was V_{REF} + 15.

The autopilot was disengaged as the aircraft descended through approximately 280 feet AGL. The aircraft began to deviate above the glideslope and crossed the threshold at 52 feet AGL at a speed of 145 knots[3] (V_{REF} + 20) at 1457:48 (Appendix A). Ten seconds later, the aircraft touched down on its right main landing gear about 2550 feet beyond the threshold at a speed of 133 knots. The speedbrakes automatically deployed. The aircraft briefly bounced after final touchdown, and, at 1458:01, the autobrakes activated and both thrust reverser levers were brought to idle detent.

Figure 1. C-GWCT after coming to a stop

At 1458:08, at a speed of 103 knots, with 4940 feet of runway remaining, the PF manually stowed the speedbrakes, which disarmed the autobrakes. Nine seconds later, at 1458:17, the PF applied manual braking; the speed was 92 knots, with 3320 feet of runway remaining. Full brake pressure was obtained while the aircraft was at a speed of 85 knots, with 2270 feet of runway remaining. At 83 knots, the PF applied maximum reverse thrust. At that point, the PF had steered the aircraft to the right of the runway centreline to avoid the runway end lights and the approach lighting system for the opposite runway. Full reverse thrust (83% N1[4]) was obtained 10 seconds later.[5] At that point, the aircraft speed was 55 knots, with 550 feet of runway remaining. At 1458:43, at a ground speed of approximately 39 knots, the aircraft departed the paved surface of the runway and travelled approximately 200 feet into the grass before coming to a stop 200 feet to the right of the runway centreline at 1458:48 (Figure 1).

No one was injured (Table 1), and all passengers and crew deplaned by a mobile staircase placed at the front right door.

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2 All speeds are calibrated airspeed unless otherwise noted.

3 The ground speed was 151 knots. The recorded winds were from approximately 339° true (T) at 14 knots, corresponding to a tailwind of 6 knots and a crosswind component of 13 knots.

4 Low-pressure compressor revolutions per minute.

5 Ten seconds is the normal spool time (amount of time it normally takes to achieve full reverse thrust).

1.2 Injuries to persons

Table 1. Injuries to persons

	Crew	Passengers	Others	Total
Fatal	0	0	–	0
Serious	0	0	–	0
Minor/None	5	107	–	112
Total	5	107	–	112

1.3 Damage to aircraft

The aircraft was not damaged.

1.4 Other damage

Following the runway overrun, the tires of the landing gear dug into the soft, grassy surface of the runway end safety area (RESA), leaving traces up to 12 inches deep.

1.5 Personnel information

Table 2. Personnel information

	Captain	First officer
Pilot licence	Airline transport pilot licence (ATPL)	Airline transport pilot licence (ATPL)
Medical expiry date	01 July 2016	01 January 2016
Total flying hours	9000	13 898
Flight hours on type	7500	3360
Flight hours in the last 7 days	20.2	16.2
Flight hours in the last 30 days	83.3	66.4
Flight hours in the last 90 days	139.7	177.1
Flight hours on type in the last 90 days	139.7	177.1
Hours on duty prior to occurrence	2.0	2.0
Hours off duty prior to work period	62.0	22.5

The captain was certified and qualified for the flight in accordance with existing regulations. The captain had completed an initial Boeing 737 pilot proficiency check (PPC) on 23 February 2007 as first officer and upgraded to a Boeing 737 captain on 07 March 2014. The PPC was valid until 01 October 2015. The captain's last line check was completed on 08 April 2015 and was valid until 01 May 2016.

The first officer was certified and qualified for the flight in accordance with existing regulations. The first officer had completed an initial Boeing 737 PPC as first officer on

25 October 2010. The PPC was valid until 01 May 2016. The first officer's last line check was completed on 08 May 2015 and was valid until 01 August 2016.

The crew had been on duty for approximately 2 hours at the time of the occurrence. An analysis of the sleep-wake data provided by the crew was conducted to identify whether 6 risk factors[6] known to increase the probability of fatigue-related performance effects were present at the time of the occurrence. The analysis showed that neither crew member was in a fatigued state at the time of the occurrence.

1.6 Aircraft information

Table 3. Aircraft information

Manufacturer	Boeing
Type, model, and registration*	Boeing 737-6CT, C-GWCT
Year of manufacture	2006
Serial number	35112
Certificate of airworthiness issue date	11 August 2006
Total airframe time	26 573.25 hours
Engine type (number of engines)	CFM International CFM56-7B22 CFM International CFM56-7B22/3 (1)
Maximum allowable take-off weight	145 502.45 pounds
Recommended fuel types	Kerosene Jet A, Jet A-1, JP-5 JP-8
Fuel type used	Jet A

* The primary reference for the type and model is the type specification; a secondary reference is International Civil Aviation Organization Document 8643/22.

1.6.1 General

Records indicate that the aircraft was certified and maintained in accordance with existing regulations and approved procedures, and that there were no recorded deficiencies before the occurrence flight. Following the occurrence, all deceleration and stopping devices[7] were checked and no faults were found. All systems successfully passed their respective operational tests and were found to be serviceable according to the aircraft manufacturer's maintenance manual.

6 The 6 risk factors are acute sleep disruption; chronic sleep disruption; continuous wakefulness; circadian rhythm effects; sleep disorders; and medical and physiological conditions, illnesses, and drugs.

7 Deceleration and stopping devices include brakes, antiskid systems, autobrakes, speedbrakes, and thrust reversers.

1.6.2 Deceleration devices

1.6.2.1 Speedbrakes

When armed, speedbrakes usually deploy automatically upon main gear touchdown and provide 2 distinct aerodynamic effects: they increase aerodynamic drag, which contributes to the aircraft's deceleration, and they reduce the lift, which increases the load on the wheels, thereby increasing wheel brake efficiency.

According to the landing roll procedure in WestJet's Boeing 737NG *Flight Operations Manual* (FOM),[8] there are 2 methods of disarming the autobrake: smoothly applying brake pedal force "until the autobrake system disarms,"[9] or stowing the speedbrake handles. The FOM states, "Stowing the speedbrake handles is permitted when the aircraft has decelerated below 80 [knots] and stopping distance within the remaining runway is assured."[10] By way of guidance as to which procedure is preferable, the landing roll procedure stipulates that the use of pedal brakes is the desired procedure when "disarming MAX autobrake,"[11] while the stowing of speedbrakes "should only be used when decreased braking is desired."[12]

In this occurrence, the speedbrakes automatically deployed after touchdown, but were then stowed, thereby disarming the autobrake system, while the aircraft was decelerating through 103 knots, with 4940 feet of runway remaining.

1.6.2.2 Thrust reversers

Thrust reversers provide a deceleration force that is independent of the runway condition; they are more effective at high airspeed. According to the FOM, the usage of the thrust reversers during the landing roll is as follows:

> Without delay, raise the reverse thrust levers to the interlocks, hold light pressure until the interlocks release, then apply reverse thrust, as below;
>
> - When required to minimize stopping distance and/or for operations on contaminated runways, use maximum reverse thrust,
> - When conditions allow, limit reverse thrust to the number 2 detent,
> - To comply with noise abatement requirements, idle reverse thrust may be used.[13]

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8 WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 026 (13 February 2015), Section 4, p. 100.

9 Ibid.

10 Ibid.

11 Ibid.

12 Ibid.

13 Ibid., p. 99.

In this occurrence, thrust reversers were deployed to reverse idle nearly 3 seconds after the initial touchdown and maintained in this position for approximately 25 seconds. Full reverse was commanded at 83 knots. However, due to the engine spool-up time, maximum reverse thrust was not obtained until 10 seconds later, at 55 knots, with 550 feet of runway remaining.

1.6.2.3 Autobrake system

The autobrake system uses hydraulic system B pressure to provide maximum deceleration in the event of a rejected takeoff, and automatic braking at preselected deceleration rates immediately after touchdown. The system operates only when the normal brake system is functioning, and antiskid system protection is provided during autobrake operation.

Four levels of deceleration can be selected for landing.[14] After landing, autobrake application begins when both forward thrust levers are retarded to IDLE and the main wheels spin up.

To maintain the selected landing deceleration rate, autobrake pressure is reduced as other controls, such as thrust reversers and spoilers, contribute to total deceleration. The deceleration level can be changed (without disarming the system) by rotating the selector. The autobrake system brings the aircraft to a complete stop unless the pilot disarms the system.

Pilots can disarm the autobrake system by moving the selector switch to the OFF position or by doing any of the following:

- moving the speedbrake lever to the down detent;
- advancing the forward thrust lever(s), except during the first 3 seconds after touchdown for landing; or
- applying manual brakes.

In this occurrence, the autobrake system was disarmed when the PF manually stowed the speedbrake lever at 103 knots. Manual braking was initially applied at 92 knots, with 3320 feet of runway remaining. Maximum brake pressure was commanded with 2270 feet of runway remaining.

According to the FOM,

> The AUTOBRAKE system setting should be consistent with desired stopping distance and runway length available. On landing, override the autobrake and apply required manual braking if deceleration is not suitable for stopping within the desired distance.[15]

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14 The 4 autobrake settings are autobrake 1, 2, 3, and MAX.

15 WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 026 (13 February 2015), section 4, p. 81.

To determine the most desirable autobrake setting for the available field length, the crew can "refer to the ACARS Landing Distance Report, the TLR [takeoff and landing report] Landing Report or reference Landing Distance Charts in QRH [Quick Reference Handbook]."[16]

In this occurrence, the autobrake was set to 1, based on the ACARS calculated landing distance of 7784 feet. The ACARS landing distance calculator will be discussed later in the report.

Each brake assembly features a wear indication pin that protrudes from a guide cast as part of the brake assembly's main housing. The wear indication pin retracts into the guide as brake wear increases. Maximum brake wear is reached when, under normal brake hydraulic pressure, the wear indication pin's outer end is flush with the guide. The brake wear status was verified and all of the brake assemblies were found to be within their in-service wear limits (Table 4).

Table 4. Brake wear indication pin protrusion dimensions on the occurrence aircraft

Brake position	1	2	3	4
Pin protrusion, in inches (minimum: 0.00)	0.300	1.095	0.537	0.770

1.6.3 Antiskid protection

Antiskid protection is provided by the normal and alternate brake systems. The normal brake hydraulic system provides each main gear wheel with individual antiskid protection. When the system detects a skid, the associated antiskid valve reduces brake pressure until skidding stops. The alternate brake hydraulic system is similar to the normal system; however, antiskid protection is applied to main gear wheel pairs instead of individual wheels. Both the normal and alternate brake systems provide protection against skids, locked wheels, and hydroplaning. Antiskid protection is available even with loss of both hydraulic systems.

The brake/antiskid system is friction-limited when the commanded brake pressure is greater than or equal to the brake pressure governed by the antiskid valve. The antiskid system adapts to the runway conditions by sensing an impending skid condition and adjusting the brake pressure to each wheel for maximum braking. In this occurrence, as maximum manual brake pressure was applied, the longitudinal acceleration recorded on the FDR remained constant, which is consistent with the antiskid system removing brake pressure in order to avoid slippage and tire lock.

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16 Ibid.

1.6.4 Main wheel tires

Examination of the tires revealed no damage. Tire pressures were measured shortly after the occurrence (Table 5) and were found to be within the acceptable range specified in the maintenance manual: 205 (± 5) psig.[17] One main tire was found to be 1 psig over the specified pressure range, but this was deemed negligible and is not considered to have had any effect on the occurrence.

Tire wear was also assessed (Table 5) and was found to be acceptable, as all the tires displayed a groove depth above the minimum value defined in the maintenance manual. All of the main tires displayed light circumferential scoring and no evidence of reverted rubber was found, nor were there any discernable flat spots other than 5 localized areas of chevron cuts, which likely resulted from the occurrence. The tires' groove depth was measured around the whole tire, giving a depth range; the minimum depth was 0.031 inches.

Table 5. Tire pressure and groove depth measured shortly after the occurrence

Tire position	#1 main	#2 main	Left nose	Right nose	#3 main	#4 main
Tire pressure (psig)	210	208	210	210	210	211
Tire groove depth range (inches)	0.190–0.210	0.305–0.330	0.195–0.210	0.175–0.180	0.075–0.140	0.140–0.170

1.6.5 Landing performance

Before departure, the crew received a flight-release package from company dispatch. The package contained all information pertinent to the flight, including current and forecasted weather, winds aloft, notices to airmen (NOTAMs), and airport/runway analysis data. A remark in the package indicated "WET RUNWAY" at CYUL.

The flight-release package also depicts performance data in the form of aircraft weight for takeoff or landing, and any additional restrictions that may apply. On the day of the occurrence, the planned landing weight for CYUL was 115 400 pounds. However, the aircraft departed with less payload, and the actual landing weight was approximately 113 500 pounds.

1.6.5.1 Landing distance calculation

According to the FOM,

> Pilots shall determine the required landing distance using established procedures outlined in QRH - Performance Inflight - General section in conjunction with: the ACARS Landing Distance Calculator, the Takeoff and

[17] Psig: pounds per square inch gauge.

Landing Report (TLR) landing data, and/or the performance tables in QRH - Performance Inflight.[18]

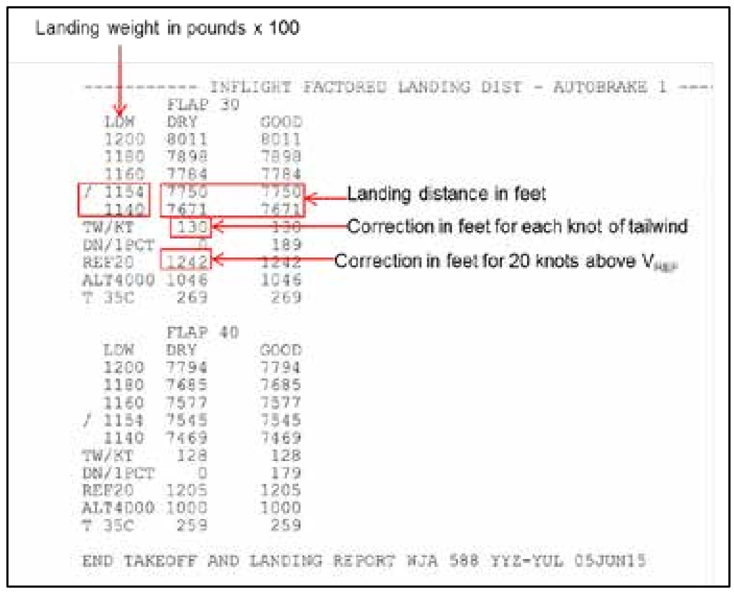
Landing can be carried out with flaps at 30° or 40°. Setting the flaps to 40° reduces the factored landing distance by approximately 2.8%. The FOM states, "Runway length and conditions must be taken into account when selecting a landing flap position."[19]

1.6.5.1.1 Takeoff and landing report

The TLR included in the flight-release package provided the crew with "inflight factored landing distances"[20] based on aircraft weight, flap configurations of 30° and 40°, runway surface condition,[21] and autobrake setting, and included credit for normal reverse thrust.

According to the TLR, the factored landing distance was 7750 feet for the dispatch-planned landing weight of 115 400 pounds, with the autobrake system set to 1 and the flaps at 30° (Figure 2). The lowest landing weight indicated on the TLR was 114 000 pounds—500 pounds over the actual landing weight. At that weight, the TLR indicated a factored landing distance of 7671 feet. These landing distances were valid for dry runways and for wet runways with a braking action report (BAR) of good. If the BAR were medium, an autobrake setting of 2, 3, or MAX was to be used; if the BAR were poor, an autobrake setting of 3 or MAX was to be used.

Figure 2. Takeoff and landing report included in the flight-release package (Source: WestJet, with TSB annotations)

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------------ INFLIGHT FACTORED LANDING DIST - AUTOBRAKE 1 ---
            FLAP 30
   LDW      DRY        GOOD
   1200     8011       8011
   1180     7898       7898
   1160     7784       7784
 / 1154     7750       7750
   1140     7671       7671
 TW/KT       130        130
 DN/1PCT       0        189
 REF20      1242       1242
 ALT4000    1046       1046
 T 35C       269        269

            FLAP 40
   LDW      DRY        GOOD
   1200     7794       7794
   1180     7685       7685
   1160     7577       7577
 / 1154     7545       7545
   1140     7469       7469
 TW/KT       128        128
 DN/1PCT       0        179
 REF20      1205       1205
 ALT4000    1000       1000
 T 35C       259        259

 END TAKEOFF AND LANDING REPORT WJA 588 YYZ-YUL 05JUN15
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The TLR also indicated that 130 feet should be added for each knot of tailwind, and 1242 feet for 20 knots above the V_{REF}. Given that the aircraft crossed the threshold at V_{REF} + 20 with a tailwind component of 6 knots, the landing distance without the 15% safety margin, at a landing weight of 114 000 pounds, would have been approximately 8692 feet.[22] However,

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18 WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 026 (13 February 2015), section 4, p. 73.

19 Ibid., p. 93.

20 The landing distance includes a 15% safety margin.

21 Dry, wet, or contaminated.

22 7671 feet/1.15 + 1242 feet + 780 feet.

this assumes a touchdown at 1500 feet from the threshold. In this occurrence, the aircraft touched down 1050 feet beyond the 1500-foot reference point. Therefore, the landing distance would have been approximately 9742 feet, 142 feet past the end of the runway.

Because the TLR is prepared before departure, it is not based on actual data at the time of arrival, and pilots must manually apply corrections for wind, runway slope, temperature, and speed if they are using the TLR figures instead of the ACARS landing distance calculator. In this occurrence, the flight crew used the ACARS landing distance calculator.

1.6.5.1.2 Landing distance tables

The QRH contains landing distance tables that indicate the landing distances required based on flap settings and braking configuration, and any adjustments necessary based on weight, altitude, wind, slope, temperature, and speed. The reference distance in the table, to which adjustments are made, is for "sea level, standard day, no wind or slope and two engine detent reverse thrust plus a 15% margin of safety."[23] The distance indicated is the distance required for the aircraft to come to a stop after crossing the runway threshold at 50 feet AGL and touching down 1500 feet past the threshold (Appendix B).

Based on the table for a landing with flaps set to 30°, the landing distance required with the autobrake set to 1 on a dry runway at a landing weight of 110 000 pounds is 7354 feet, which includes a 15% safety margin. If the safety margin is removed, the landing distance is 6395 feet.[24] After applying the required adjustments for weight, altitude, actual tailwind component, runway slope, temperature, and approach speed, the landing distance (still without the safety margin) is 8624 feet, if the aircraft touches down 1500 feet past the runway threshold. However, in this occurrence, the aircraft touched down 1050 feet past that 1500-foot reference touchdown point. Therefore, based on the table, the aircraft would have overrun the runway end by approximately 74 feet compared to 142 feet, based on the TLR.

For wet or contaminated runways, the tables in the QRH do not provide landing distances with the autobrake set to 1; however, they do provide landing distances for braking configurations with the autobrakes set to 2, 3, or MAX. These tables are based on flap settings and the reported braking action. Calculations made using the appropriate tables show that, on a wet runway with good reported braking action, with the autobrake set to 2 and a touchdown 1050 feet beyond the normal touchdown point of 1500 feet past the runway threshold, the aircraft would have stopped approximately 590 feet before the end of the runway. By comparison, an aircraft in the same configuration but landing on a wet runway with medium reported braking action would have come to a stop 351 feet before the end of the runway.

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23 WestJet, *737 Quick Reference Handbook*, Revision 1 (14 November 2013), PI-737-600.10A.16.

24 7354 feet/1.15.

In this occurrence, the crew were aware that the runway would be wet prior to landing, but did not know the actual level of braking action because there were no BARs made by aircraft that had landed before them. The QRH states the following:

> If the surface is affected by water, snow or ice, and the braking action is reported as GOOD, conditions should not be expected to be as good as on clean dry runways. The value GOOD is comparative and is intended to mean that airplanes should not experience braking or directional control problems when landing. The performance level to calculate GOOD data is consistent with wet runway testing done on early Boeing jets.[25]

1.6.5.1.3 Aircraft communications addressing and reporting system landing distance calculator

According to the WestJet FOM,

> The ACARS data server uses the same Boeing performance information to complete the ACARS landing distance calculations as the landing distance tables in the QRH - Performance Inflight.[26]

To obtain ACARS landing distance calculations, the crew must enter data such as the airport identifier, landing runway, reported braking action,[27] magnetic surface wind, outside air temperature, barometric pressure, engine anti-ice ON or OFF, flap setting of 30° or 40°, and the actual aircraft weight.

Once the server has completed the landing distance calculations, a text message will provide the crew with the landing distances for the airport conditions that were sent.

The FOM provides several notes about the ACARS landing distance calculator, including the following:

> - ACARS landing distances are based on a 50 foot threshold crossing, 3 degree descent slope, firm touchdown at 1500 feet, spoilers deployed at touchdown, and autobrakes engaged until stopped.
> - **If the autobrake system disengages, pilots must immediately apply appropriate manual braking as required for the remaining runway available**. Pilots shall not intentionally disarm the Autobrake until the landing distance is assured or maximum manual braking is required. [...]
> - For WET runways, select GOOD in the Braking Action Report line.[28]

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25 WestJet, *737 Quick Reference Handbook*, Revision 1 (14 November 2013) PI-737-600.10A.18.

26 WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 025 (14 February 2013), section 5, p. 38.

27 Good, medium, or poor.

28 WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 026 (13 February 2015), section 5, p. 41.

On the day of the occurrence, the ACARS landing distance calculation was 7784 feet, based on the crew selecting GOOD in the BAR line of the ACARS. The QRH contains a landing distance flow chart (Appendix C) and a runway condition and BAR equivalency table (Appendix D) to assist pilots in determining which landing performance data to select. The flow chart and equivalency table provide criteria for when to use data for good, medium, or poor braking action. These tables specify that good braking action may be expected for a wet runway when there is less than ⅛ inch of standing water and a BAR of good has been received. In this occurrence, the crew did not receive any BARs from other aircraft that had landed on Runway 24L before them.

1.6.6 *Runway condition definitions*

The following is a list of runway conditions as defined in the QRH:

Dry Runway:	A runway with dry pavement and no contaminants or a runway with dry spots showing on a drying runway with no standing water.
Wet Runway:	A runway that has a shiny appearance due to a thin layer of water less than ⅛" or 3mm covering 100% of the runway surface. [...]
Contaminated Runway:	A […] runway where more than 25% of the runway length, within the width being used, is covered by standing water or slush more than ⅛" or 3mm deep or that has an accumulation of snow or ice. A runway is also considered to be contaminated with less than 25% coverage if the contaminant is located prior to the midpoint of the runway.[29]

1.6.7 *Landing on wet, slippery, or contaminated runways*

As stated earlier, the QRH provides crews with a landing distance calculation flow chart to help them make decisions when non-dry runway conditions exist. One of the rules to follow when using the flow chart is that "[p]recipitation in any form constitutes an active condition."[30] In such cases, "the Captain shall be satisfied that the landing calculations are based on valid conditions or landing is prohibited."[31] Valid conditions can be obtained from a BAR, a runway surface condition report, or a Canadian Runway Friction Index (CRFI) report. In this occurrence, none of these were available. Therefore, the flow chart would have been of no use to the crew even if they had consulted it.

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29 WestJet, *737 Quick Reference Handbook*, Revision 1 (14 November 2013), PI-General.10.3–10.4.

30 Ibid., PI-General.10.1.

31 Ibid.

1.6.8 Boeing Commercial Aircraft performance calculations

To better understand the factors involved during the ground roll phase of the landing, the aircraft manufacturer, Boeing Commercial Aircraft (Boeing), was requested to perform an aerodynamic airplane performance analysis based on the FDR data. The following information is taken from an analysis report prepared by Boeing for the TSB.

Boeing defines airplane braking coefficient as follows:

> the ratio of the deceleration force from the wheel brakes relative to the normal force acting on the wheels. The deceleration force from the wheel brakes is calculated from the total airplane deceleration minus aerodynamic drag and thrust components, and the normal force acting on the wheels is essentially weight minus lift. The airplane braking coefficient is an all-inclusive term that incorporates effects due to the runway surface, contaminants, and airplane braking system (e.g., antiskid efficiency, brake wear, tire condition, etc.). Therefore, airplane braking coefficient [...] is not equivalent to the tire-to-ground friction coefficient [runway friction] that would be measured by an airport ground vehicle.
>
> In simple terms, the airplane braking coefficient represents the braking capability of the airplane, and only represents the runway characteristics when the brake/antiskid system is friction-limited. The brake/antiskid system is friction-limited when the commanded brake pressure is greater than or equal to the brake pressure governed by the antiskid valve. The antiskid system adapts to the runway conditions by sensing an impending skid condition and adjusting the brake pressure to each individual wheel for maximum braking. When not friction-limited, the airplane braking coefficient represents the level of braking applied. [...]
>
> Results show the airplane's braking became friction limited starting at 6750 feet beyond the threshold [2850 feet of runway remaining] and lasted for the duration of the rollout until the airplane departed the runway [...].[32]

Based on the FDR data, "[a]s maximum manual brakes were applied, longitudinal acceleration remained constant."[33] This is "consistent with the antiskid system removing brake pressure in order to avoid slippage and tire-lock (friction-limited condition). During this period of friction-limited braking, it can be assumed [that the airplane braking coefficient] represents the runway surface condition."[34]

Boeing has associated pilot-reported braking action with airplane braking coefficient levels. The airplane braking coefficient-to-braking action was chosen to be conservative. The

32 Boeing, WestJet 737-600 C-GWCT Runway During Landing at Montreal—05 June 2015, Revision B (15 April 2016).

33 Ibid.

34 Ibid.

airplane braking coefficients in the table below (Table 6) are used to generate the advisory landing distance information for reported braking actions in WestJet's QRH.

Table 6. Airplane braking coefficients[35]

Pilot-reported braking action	Airplane braking coefficient ($\mu_{airplane}$)
Dry	~0.40
Good	0.20
Medium	0.10
Poor	0.05

Based on the FDR data,

> the initial portion of maximum manual braking shows the runway surface condition was between Medium ($\mu_{airplane} = 0.10$) and Poor ($\mu_{airplane} = 0.05$). As the airplane approached the end of the runway, the surface gradually improved to Medium.[36]

1.6.8.1 *Effect of speedbrakes and reverse thrust*

Boeing ran engineering simulations to quantify the effects of the early speedbrake stowage on the stopping distance. The results show the importance of speedbrakes and their effects on stopping the airplane as the runway condition deteriorates. Based on the FDR data, "the crew-commanded brake pressure remained approximately at levels commanded by the autobrakes"[37] once disarmed; however, the deceleration decreased by one half. According to Boeing, this can be primarily attributed to the stowage of the speedbrakes.[38]

On a runway surface with medium reported braking action, the landing distance would have been 9873 feet if the speedbrakes had been deployed for the entire landing roll, with the reverser thrust used during the occurrence. This takes into account the occurrence touchdown point and the use of autobrake setting 1 until the aircraft came to a complete stop. On a runway surface with poor reported braking action, with the same conditions as above, the landing distance with speedbrakes deployed during the entire landing roll would have been approximately 10 178 feet.

Given that there was additional reverse thrust available during the landing roll, additional calculations were also performed to quantify the effects of using maximum reverse thrust for the entire landing roll with the speedbrake used during the occurrence. On a medium reported braking runway surface, if maximum reverse thrust had been used for the entire

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35 Ibid.

36 Ibid.

37 Ibid.

38 Ibid.

landing roll, the landing distance would have been approximately 9498 feet. On a poor reported braking runway surface, with the same conditions as above, the landing distance with maximum reverse thrust during the entire landing roll would have been 9563 feet.

Therefore, "[r]egardless of the runway condition, usage of maximum reverse thrust would have allowed the airplane to remain on the runway"[39] with the autobrake set to 1, even with the speedbrake used during the occurrence and a touchdown 1050 feet beyond the normal 1500-foot touchdown point.

1.7 Meteorological information

The following meteorological information is taken from a meteorological analysis report prepared by Environment Canada for the TSB.[40]

During the morning of 05 June 2015, the skies partially cleared out at CYUL and in the area west of CYUL, allowing the surface temperature to rise with the daytime heating. In addition, a moderate south to southwesterly flow allowed low-level moisture to increase, which resulted in convective development in the form of cumulus clouds.

These convective cells continued to grow and became towering cumulus by 1300. The first mention of precipitation was reported at 1400. At 1451, about 7 minutes before WJA588 landed, an aerodrome special meteorological report (SPECI) was issued for CYUL and read as follows: wind 330° true (T) at 18 knots, variable from 250°T to 340°T, visibility 15 sm in rain showers, few clouds at 1200 feet, broken towering cumulus clouds at 2500 feet, overcast at 7500 feet, temperature 20°C, dew point 18°C, altimeter 29.92 inches of mercury, with remarks indicating stratus fractus clouds 2/8, towering cumulus clouds 5/8, altocumulus clouds 1/8, visibility from the southwest to the north 2½ sm, pressure rising rapidly, sea level pressure 1013.1 hectopascals, density altitude 700 feet. The SPECI information was broadcasted on ATIS information Mike at 1458 when the aircraft was already on the runway. Therefore, the crew had not been informed of the SPECI before landing.

The 1500 hourly aerodrome routine meteorological report (METAR) reported heavy showers with reduced visibility of 1½ sm and wind from 310°T at 12 knots with gusts up to 23 knots. The ceilings during this precipitation event remained at or above 2200 feet AGL. This METAR was issued approximately 2 minutes after the aircraft landed. ATIS information November was issued at 1509 to reflect the 1500 METAR observation. By 1513, precipitation had tapered off to a light shower over the station, with a prevailing visibility of 3 sm. The METARs did not mention the presence of thunderstorms in the area from 1400 to 1513.

Based on the radar images from 1300 to 1500, the precipitation band was estimated to be moving east-southeast at a speed of 15 to 20 knots. The highest reflectivities were over CYUL

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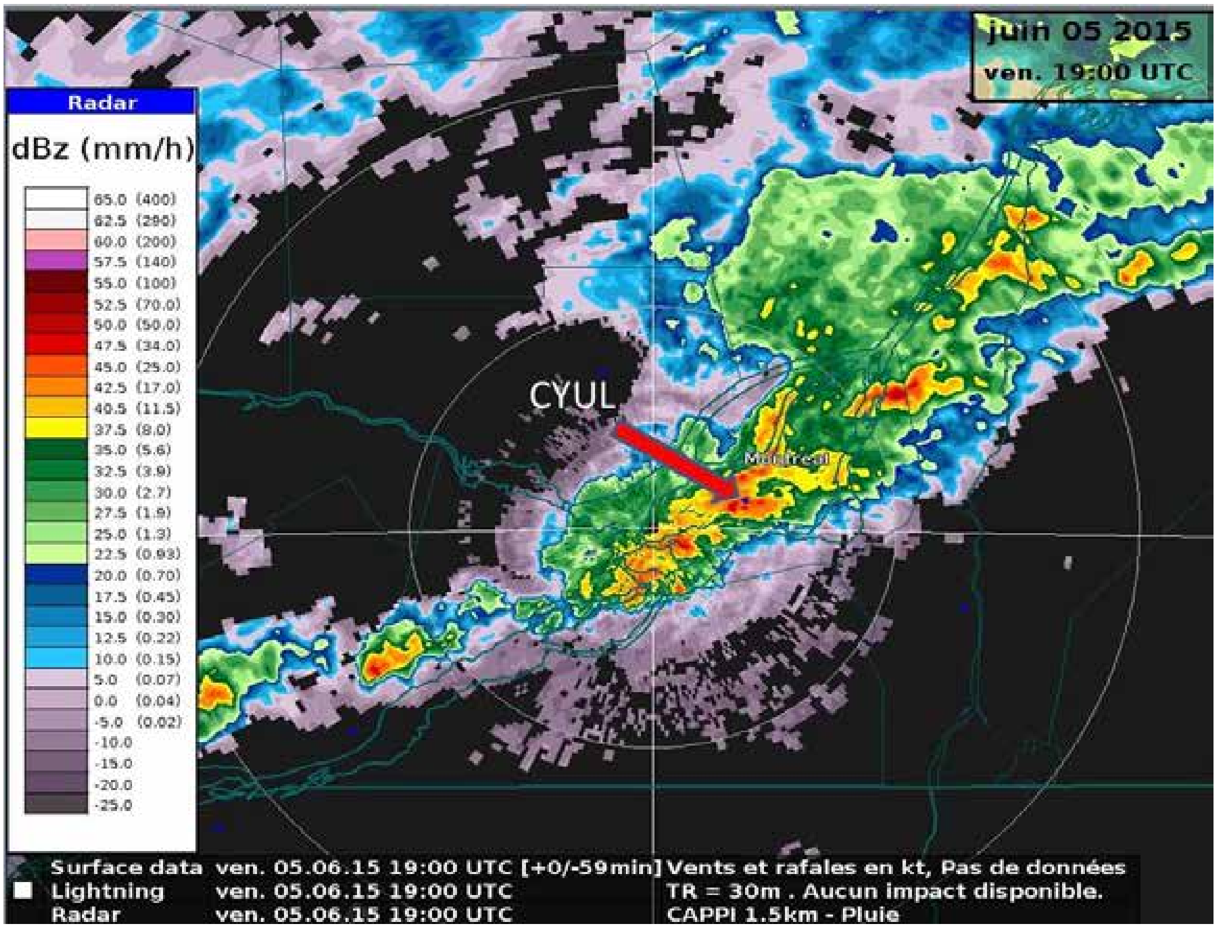
39 Ibid.

40 Environment Canada, Meteorological Service of Canada, Weather and Environmental Prediction and Services, *Meteorological Assessment – June 5th, 2015 – Montreal, QC* (11 June 2015).

between 1450 and 1510. (CYUL is denoted by a blue dot as indicated by the red arrow in Figure 3.) A dBZ[41] value of approximately 45 was observed in the vicinity of CYUL at 1500, which gives an approximate precipitation rate of 25 mm per hour.

Figure 3. Radar image showing precipitation band less than 2 minutes after the occurrence (Source: Environment Canada, with TSB annotations)



The rain gauge AU8 at the WTQ[42] automated station recorded 5 mm of precipitation between 1400 and 1505. However, 4.2 mm of the 5 mm was recorded between 1455 and 1505, giving a precipitation rate of 25.2 mm per hour. The estimated rain rate from the radar is consistent with the amount observed on the ground. According to the Environment Canada *Manual of Surface Weather Observations* (MANOBS),[43] this precipitation rate corresponds to heavy rain intensity. The quantity of precipitation recorded from 1455 until the aircraft departed the paved surface at 1458:43 was approximately 1.6 mm, which also corresponds to heavy rain intensity.

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41 dBZ refers to decibel and can be converted to rainfall rates.

42 WTQ is a Meteorological Service of Canada automated station located at CYUL.

43 Environment Canada, *Manual of Surface Weather Observations* (MANOBS), Seventh Edition, Amendment 19 (April 2015).

1.8 Aids to navigation

There were no reported outages of navigation aids at the time of WJA588's approach and landing on Runway 24L.

1.9 Communications

1.9.1 General

At approximately 1455, the WJA588 flight crew contacted the controller and advised that they were on final approach for landing on Runway 24L. They were instructed to continue and were told that they were number 2 on approach for landing following a Cessna 441 ahead of them, also on approach for landing on Runway 24L.

Immediately after the Cessna 441 landed, WJA588 was cleared to land and told to plan on exiting at the end of the runway. After WJA588 touched down, based on the aircraft's speed and the amount of water spraying from it as it approached the end of the runway, air traffic control sounded the crash alarm to signal aircraft rescue and fire-fighting (ARFF) services before the aircraft went off the end of the runway.

1.9.2 Previous landings

From 1451 to 1513, when the reported precipitation was variously moderate rain showers, heavy rain, and light showers, a total of 9 aircraft landed at CYUL: 3 on Runway 24L[44] and 6 on Runway 24R.[45]

A DHC-8-400 landing on Runway 24L was initially cleared to exit at the end of the runway. However, once on the ground, the DHC-8-400 was instructed to exit at Taxiway A2, located approximately 5200 feet from the threshold. A Cessna 441, which landed just before WJA588, was also instructed to exit at Taxiway A2. At the time, the controller could barely see Taxiway A2, which is approximately 1 sm from the tower. The controller did not ask flight crews for a BAR, as both aircraft had been able to exit as instructed without difficulty, and neither pilot reported braking issues. Therefore, there was no BAR available for WJA588. Furthermore, a runway inspection on 24L had been carried out at 1440, approximately 18 minutes before WJA588 landed, and there was no indication that the runway surface condition might prevent a safe landing.

The 6 aircraft that landed on Runway 24R during the same period were all instructed to exit at Taxiway B2, located approximately 7400 feet from the threshold, except for a King Air, which was instructed to exit on Taxiway E, located approximately 5500 feet from the threshold. All of the aircraft were able to exit the runway as instructed. The first time the controller requested a BAR from a crew was at approximately 1508, following the landing of

44 A DHC-8-400, a Cessna 441, and the occurrence aircraft.

45 A Boeing 737, an Airbus 310, two Airbus 320s, a King Air, and a Beechcraft 1900.

an Airbus 320. The pilot reported braking action as medium. Subsequently, an Airbus 310 crew reported it as good to fair, and a Boeing 737 crew reported it as medium.

1.10 *Aerodrome information*

1.10.1 General

Aéroports de Montréal is a private, not-for-profit, and financially independent corporation responsible for the management, operation, and development of CYUL. CYUL has 3 runways: Runway 10/28, which is 7000 feet long and 200 feet wide with an asphalt surface; Runway 06L/24R, which is 11 000 feet long and 200 feet wide with an asphalt/concrete surface; and Runway 06R/24L, which is 9600 feet long and 200 feet wide with a textured[46] concrete surface.

1.10.2 Runway 24L physical description

An engineering drawing[47] indicates that Runway 24L has a downward longitudinal slope of approximately 0.20% for the majority of its length, except for the last 820 feet, where the slope increases to 0.51% for approximately 328 feet and then decreases to approximately 0.25% for the last 492 feet. These gradients fall within established standards contained in the Transport Canada (TC) *Aerodrome Standards and Recommended Practices* (TP312),[48] which require that the longitudinal slope not exceed 1.5%, and, for the first and last quarter of the length of the runway, the longitudinal slope not exceed 0.8% for Code 3 and 4 runways.[49]

To promote rapid drainage, TP312 recommends that a runway's surface be cambered, if practicable. The transverse slope should not exceed 1.5% and should not be less than 1% except at taxiway and runway intersections where flatter slope may be necessary. An engineering drawing[50] indicates that the transversal gradients on Runway 24L fall within established requirements. Runway 24L also includes storm drains. A video taken approximately 40 minutes after the occurrence during light rain showed a wet runway with a shiny appearance, but no evidence of standing water.

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46 Runway 06R/24L was rebuilt and textured using the wire-combing technique in 2004. According to Federal Aviation Administration (FAA) Advisory Circular 150/5320-12C, the wire-combing technique uses rigid steel wires to form a deep texture in the plastic concrete pavement. The grooves provide parallel transverse channels in the pavement.

47 Aéroports de Montréal (Trudeau), Drawing Q142YECAR146 (28 January 2016).

48 Transport Canada, TP312, *Aerodrome Standards and Recommended Practices*, 4th Edition (March 1993), Chapter 3: Physical characteristics.

49 The length of a Code 3 runway is from 1200 m up to but not including 1800 m; the length of a Code 4 runway is 1800 m and over.

50 Aéroports de Montréal (Trudeau), Drawing A142Y912C0002 (28 January 2016).

1.10.3 Runway 24L lighting and markings

The approach lighting for Runway 24L is a simplified short approach light system with runway alignment indicator lights, which is a high-intensity approach lighting system that provides a visual landing path for aircraft. Runway 24L is also equipped with runway edge lights, uniformly spaced at 200-foot intervals, with 5 intensity settings. At the time of the occurrence, the runway edge lights were on setting 5, which is the maximum setting.

Unlike Runway 24R, Runway 24L is not equipped with centreline runway lights. When installed, these lights are white up to a point 3000 feet from the runway end. They then alternate red and white up to a point 1000 feet from the runway end, and are red for the last 1000 feet. Runway 24L had white runway markings consistent with an instrument approach runway of over 5000 feet in length. The runway markings were the following:

- threshold markings made up of a series of vertical bars marking the threshold;
- runway indication markings, consisting of the runway number;
- touchdown zone markings, made up of a repeating series of vertical bars on either side of the centreline, every 500 feet within the first 3000 feet of the runway;
- aiming point markings at 1500 feet from the threshold; and
- centreline markings made up of a dashed line indicating the centreline of the runway.

All of the relevant markings and lighting on Runway 24L meet the standards for runway marking and lighting as per TP312.[51]

Touchdown zone markings are intended to identify the preferred touchdown zone, and the separation between them varies depending on the runway length. The aircraft's orientation on the runway may be assessed using centreline markings, centreline lighting, runway edges, and runway edge lights.

The runway was not equipped with distance-remaining signage, nor was it required to be by Canadian regulations or International Civil Aviation Organization (ICAO) standards.

1.10.4 Runway friction

It is essential that the surface of a paved runway be constructed so as to provide optimal friction characteristics when the runway is wet. Adequate runway friction characteristics are required for aircraft deceleration, directional control, and wheel spin-up at touchdown. Serious reductions of friction coefficients can result from rubber deposits, especially when the runway is wet.

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51 Transport Canada, TP312, *Aerodrome Standards and Recommended Practices*, 4th Edition (March 1993), Chapter 5: Visual aids for navigation.

Tradewind Scientific performed a runway friction test at CYUL on 13 May 2015. The following is taken from Tradewind Scientific's summary report:

> [A] trailer-mounted version of the ICAO listed and FAA[52]/Transport Canada approved SARSYS SFT[53] friction measurement instrument [was used]. This equipment type has been used to conduct the Transport Canada national test programs for more than 30 years.
>
> As per the most recent Transport Canada Advisory Circular AC 302-017[54] standard test condition specifications for the SFT equipment, the normal friction tests with this device were conducted at 65 km/h using a smooth-tread ASTM[55] 1551 test tire at 200 kPa[56] inflation pressure under self-watering conditions at **1.0 mm** water depth. Full-length tests at 6m L&R offsets [i.e., left and right of the runway centreline] on Runway 06R-24L were conducted as per Transport Canada recommendations for runways serving wide-body aircraft.
>
> Transport Canada/TP 312 guidelines for tests under these conditions indicate that remedial action should be programmed for a facility when the overall Runway average Friction Index falls below ***60*** or any 100m section falls below ***40***.[57]

Table 7, below, represents the friction index values measured on 13 May 2015.

Table 7. Results of runway friction test carried out on 13 May 2015[58]

Runway	Average runway friction index	Minimum 100 m runway friction index
06R/24L (3 m)	56	48
06R/24L (6 m)	58	43
06R/24L (22 m)	64	54

As indicated in the table, much of the length of Runway 06R/24L had friction values below 60 at both 3 m and 6 m left and right of the runway centreline, which is the TC maintenance planning level. Some evidence of rubber contaminant buildup/texture loss near both touchdown zones of Runway 06R/24L was also observed.

52 FAA: U.S. Federal Aviation Administration.

53 SARSYS SFT: Scandinavian Airport and Road Systems surface friction test.

54 Transport Canada, Advisory Circular (AC) 302-017, *Runway Friction Measurement*, Issue No. 01 (15 December 2014).

55 ASTM: American Society for Testing and Materials.

56 kPa: kilopascals.

57 Tradewind Scientific, *Runway Friction Testing Summary Report: Trudeau International Airport* (21 May 2015).

58 Ibid.

Based on these results, Tradewind Scientific's report indicated that "[f]ollow up friction tests on Runway 06R/24L should be scheduled immediately after the runway rubber contaminant removal and maintenance activities are completed."[59]

Rubber removal took place on 02 June 2015, just 3 days before the occurrence. Following the rubber removal, friction tests were carried out on 16 July 2015.

Table 8. Results of runway friction test carried out on 16 July 2015[60]

Runway	Average runway friction index	Minimum 100 m runway friction index
06R/24L (3 m)	73	62
06R/24L (6 m)	61	51
06R/24L(22 m)	N/A	N/A

As indicated in Table 8, much of the length of Runway 06R/24L had friction values above 60 at both 3 m and 6 m left and right of the runway centreline, and all 100 m sections were above 40.

1.10.5 Grooving of runway

Grooving reduces the potential for both dynamic and viscous hydroplaning by providing a place (i.e., grooves) where water can escape from underneath tires. Grooving is applied to both the macrotexture and microtexture of the runway surface. Runway grooving is not a requirement for new or existing runway pavement in Canada. Although there is no specific definition for runway grooving, it is normally understood by the aviation community that a grooved runway refers to grooves cut using the technique and configuration (depth, width, and spacing) given in Advisory Circular (AC) 300-008.[61] Wire-combing technique uses rigid steel wires to form a deep texture in the plastic concrete pavement and is not considered equivalent to grooving as per AC 300-008.

1.10.6 Runway end safety area

In June 2009, the Australian Transport Safety Bureau (ATSB) published a safety report[62] on runway excursions, which states, in part:

> Runway end safety areas [RESAs] are designed to reduce the risk of damage to an aircraft that:
>
> - undershoots the runway (touches down before the runway threshold);

59 Ibid.

60 Tradewind Scientific, *Runway Friction Testing Summary Report: Trudeau International Airport* (20 July 2015).

61 Transport Canada AC 300-008 Issue No. 2, effective date 08 April 2013.

62 Australian Transport Safety Bureau, ATSB Transport Safety Report: Runway excursions, Part 2: Minimising the likelihood and consequences of runway excursions (June 2009).

- aborts a takeoff and overruns the runway end; or
- cannot stop following a landing and overruns the runway end.

A RESA achieves this by assisting aircraft to decelerate in a controlled manner.

Surface materials used for RESAs vary widely, from natural surfaces to pavement. Common RESA surface materials include compact gravel pavement, pulverised fuel ash (PFA), grass, pavement quality concrete (PQC), compacted earth, or a combination of these. In all cases, the bearing strength of the RESA must be able to support movement of airport rescue and fire fighting (ARFF) vehicles, and be resistant to blast erosion from jet engine exhaust from aircraft in day-to-day operations.

[…]

The provision of RESAs at airports was initiated by an FAA study of overrun and undershoot accidents between 1975 and 1987. This study showed that approximately 90 per cent of aircraft that overrun stop within 1,000 ft (approximately 330 m) of the runway end. Half of overrunning aircraft stopped within 300 ft (90 m), and 80 per cent stopped within 700 feet (approximately 210 m) […].[63] It also found that most overrunning aircraft do not deviate very far from the extended runway centreline [...].[64]

1.10.6.1 Runway end safety area requirements

Table 9 shows ICAO's and TC's standard runway strip lengths and standard and recommended RESA lengths.

Table 9. Runway end safety area (RESA) standard and recommended lengths

For Code 3 and 4 runways	Standard runway strip	Standard RESA	Recommended RESA
ICAO Annex 14[65]	60 m	90 m	240 m
TP312 4th Edition[66]	60 m	N/A	90 m

Runway 24L has a runway strip that extends 60 m beyond the runway end and a RESA that is 240 m long by 152 m wide. These dimensions meet ICAO's standard and recommendation. However, not all Code 4 runways in Canada have RESAs of such dimensions or a means of stopping aircraft that provides an equivalent level of safety.

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63 This figure was re-confirmed in a 2009 study by the Australian Transport Safety Bureau.

64 Federal Aviation Administration, Advisory Circular 150/5220-22A – *Engineered Materials Arresting Systems (EMAS) for Aircraft Overruns*, Washington, D.C. (2005).

65 International Civil Aviation Organization (ICAO), Annex 14 to the Convention on International Civil Aviation – *Aerodromes*, Volume 1 – *Aerodrome Design and Operations*, 5th Edition (July 2009).

66 Transport Canada, TP312, *Aerodrome Standards and Recommended Practices*, 4th Edition (March 1993).

Following the TSB's investigation into a runway overrun accident[67] at Toronto/Lester B. Pearson International Airport, the Board recommended that

> the Department of Transport require all Code 4 runways to have a 300 m runway end safety area (RESA) or a means of stopping aircraft that provides an equivalent level of safety.
>
> **TSB Recommendation A07-06**

Since TSB Recommendation A07-06 was issued, TC has provided several responses[68] following the TSB's assessments of its initial responses.

In its most recent response, in November 2015, TC agreed with the intent of the recommendation and stated the following:

> In early 2014, TC commissioned an independent risk assessment (RA) to establish implementation criteria for RESAs across all airport types in Canada. The risk assessment has been completed. On the basis of that RA, TC is in the process of developing options for the implementation of RESA. TC will then undertake a full cost/benefit analysis along with additional stakeholder consultation, before proceeding with drafting an updated Notice of Proposed Amendment (NPA) and revised regulatory language.

TC has not included any information in its latest update to address the TSB's March 2015 concern that TC's independent risk assessment (RA), entitled *Risk Assessment for Runway End Safety Area at Canadian Airports* (T8080-120164), would not include a study of 300 m RESAs on Code 4 runways.

Furthermore, TC's update does not provide any details of the RA's findings, merely stating that the RA is complete. Without such particulars, it is impossible to assess whether or not TC's stated plan to implement changes to RESA regulatory requirements will include options that specifically address the deficiency identified in Recommendation A07-06.

Consequently, as TC implements its plan to develop options, undertakes a cost/benefit analysis, consults with stakeholders, and drafts an NPA, it is still not known whether these efforts will include a discussion about the possibility of 300 m RESAs on Code 4 runways.

Given that TC's latest update provides no specific information, action plan or timeline to provide for 300 m RESAs on Code 4 runways at Canadian airports, the Board assessed TC's response as Unsatisfactory.

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67 TSB Aviation Investigation Report A05H0002.

68 Transport Canada responded to TSB Recommendation A07-06 in February 2008, April 2009, February 2010, January 2011, April 2011, September 2011, December 2012, November 2013, January 2015, and November 2015.

1.11 Flight recorders

The aircraft was equipped with an FDR (Honeywell Solid State, Model SSFDR), which contained approximately 26.5 hours of data. The data consisted of the occurrence flight and 18 previous flights. As previously mentioned, on the occurrence flight, the speedbrakes were manually stowed at 103 knots, 23 knots above the 80-knot limit stated in the FOM. A review of the FDR data found that the speedbrakes had been stowed at a significantly higher speed on the occurrence flight than on the 18 previous flights. In the previous landings reviewed, the speedbrakes were stowed at speeds between 9 knots and 88 knots. A review of the systems data did not find any failures that would have degraded the aircraft's stopping performance.

The aircraft was also equipped with a cockpit voice recorder (CVR) (Honeywell Solid State, Model SSCVR, part number 980-6022-001, serial number CVR120-12629) on which the entire flight from CYYZ was captured, including the runway overrun. The recording ended when the CVR circuit breaker was pulled post-occurrence.

1.12 Wreckage and impact information

Not applicable.

1.13 Medical and pathological information

Not applicable.

1.14 Fire

There was no fire either before or after the aircraft departed the runway end.

1.15 Survival aspects

1.15.1 Aircraft evacuation

Once the aircraft was stopped, the captain made a public-address announcement asking all passengers to remain seated with their seatbelts fastened. The auxiliary power unit was started and both engines were shut down at 1505:02. All passengers deplaned from the right front main door via a mobile staircase, boarded a passenger transfer vehicle, and were driven to the main terminal.

1.15.2 Aircraft rescue and fire-fighting

The fire hall at CYUL is located northeast of the terminal in an open area between the runways. According to ground radar data, ARFF left the fire hall and headed to the site at 1500, and arrived at the aircraft at 1501:51, approximately 3 minutes after the occurrence.

1.16 Tests and research

1.16.1 Turbojet braking performance on wet runways

On 31 August 2006, the FAA issued Safety Alert for Operators (SAFO) 06012. This SAFO urgently recommended that operators of turbojet airplanes develop procedures for flight crews to assess landing performance based on various conditions actually existing at the time of arrival, rather than the conditions presumed at the time of dispatch. Those conditions included weather, runway conditions, the airplane's weight, and braking systems to be used. Once the actual landing distance is determined, an additional safety margin of at least 15% should be added to that distance.

The results of an analysis of the stopping data from several recent runway landing incidents/accidents[69] indicated that "the braking coefficient of friction in each case was significantly lower than expected for a wet runway."[70] The FAA subsequently issued SAFO 15009 on 11 August 2015. The SAFO

> warns airplane operators and pilots that the advisory data for wet runway landings may not provide a safe stopping margin under all conditions. […]
>
> The data indicates that applying a 15% safety margin to wet runway time-of-arrival advisory data as, [*sic*] recommended by SAFO 06012, may be inadequate in certain wet runway conditions. [...]
>
> The root cause of the wet runway stopping performance shortfall is not fully understood at this time; however issues that appear to be contributors are runway conditions such as texture (polished or rubber contaminated surfaces), drainage, puddling in wheel tracks and active precipitation. Analysis of this data indicates that 30 to 40 percent of additional stopping distance may be required in certain cases where the runway is very wet, but not flooded.
>
> For non-grooved or non-PFC [porous friction course] runways, experience has shown that wheel braking may be degraded when the runway is very wet. If active <u>moderate or heavy</u> precipitation exists, the operator should consider additional conservatism in their time-of-arrival assessment.
>
> For grooved or PFC runways, experience has shown that wheel braking is degraded when the runway is very wet. If active <u>heavy</u> precipitation exists; the operator should consider additional conservatism in their time-of-arrival assessment.[71]

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[69] The incidents and accidents studied had "occurred on both grooved and un-grooved or non-Porous Friction Course overlay (PFC) runways." (Federal Aviation Association (FAA), Safety Alert for Operators (SAFO) 15009, Turbojet Braking Performance on Wet Runways, 11 August 2015.)

[70] Ibid.

[71] Federal Aviation Administration (FAA), Safety Alert for Operators (SAFO) 15009, Turbojet Braking Performance on Wet Runways (11 August 2015).

1.16.2 Runway overruns

To provide pilots and operators with a way "to identify, understand, and mitigate risks associated with runway overruns during the landing phase of flight,"[72] the FAA issued AC 91-79A on 17 September 2014. Intended for use in the development of standard operating procedures (SOPs) that mitigate such risks, the AC states

> A study of FAA and NTSB [U.S. National Transportation Safety Board] data indicates that the following hazards increase the risk of a runway overrun:
>
> - Unstabilized approach;
> - High airport elevation or high-density altitude, resulting in increased groundspeed;
> - Effect of excess airspeed over the runway threshold;
> - Airplane landing weight;
> - Landing beyond the touchdown point;
> - Downhill runway slope;
> - Excessive height over the runway threshold;
> - Delayed use of deceleration devices;
> - Landing with a tailwind; and
> - A wet or contaminated runway.[73]

According to the AC, specific SOPs are "a primary risk mitigation tool" and should "[a]s a minimum" contain the hazards listed above. Furthermore, it is "imperative" that these SOPs be executed faithfully by flight crews. An effective runway overrun mitigation training program provided by operators is also a tool that provides flight crews with "academic knowledge and skill to increase the pilot's awareness of the factors that can cause a runway overrun."[74]

1.16.3 Studies of factors contributing to runway overruns

1.16.3.1 Flight Safety Foundation

An analysis of a 14-year period of runway overrun data by the Flight Safety Foundation (FSF)[75] found that runway overruns were usually the result of one or more factors involving weather, aircraft performance, crew technique and decision making, or aircraft systems. Of relevance to this occurrence, the review found that the following were frequent contributors:

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72 Federal Aviation Administration (FAA), Advisory Circular (AC) 91-79A, Mitigating the Risks of a Runway Overrun Upon Landing (17 September 2014).

73 Ibid.

74 Ibid.

75 Flight Safety Foundation (FSF), Reducing the Risk of Runway Excursions: Report of the Runway Safety Initiative (May 2009), pp. 157–160.

- Unanticipated runway conditions (i.e., worse than anticipated);
- Extended flare leading to a long touchdown; and
- Late braking.

The FSF's recommended mitigations for these included

- Defined policies prohibiting landing outside the touchdown zone;
- Inclusion of standard calls of runway remaining based on runway lighting, distance-to-go markers or known landmarks;
- Published procedures for adverse runway conditions; and
- Published procedures for optimum use of autobrake and reverse thrust on contaminated runways.

1.16.3.2 Boeing

Boeing published *AERO* magazine quarterly from 1998 to 2014, providing operators with supplemental technical information to promote continuous safety and efficiency in their daily fleet operations. The following information is a summary of an article published in the magazine about reducing runway landing overruns:

> Data collected and analysed from 2003 to 2010 shows the factors contributing to landing overruns occur at the following frequencies:
>
> - 68 percent occurred after stable approaches.
> - 55 percent touched down within the touchdown zone.
> - 90 percent landed on an other-than-dry runway.
> - 42 percent landed with a tailwind of 5 knots or greater.[76]

A review of runway overrun occurrences by Boeing showed that a runway overrun is typically caused by multiple factors and, as a result, a multi-faceted approach to reducing the incidence of runway overruns was required. Breaking down the contributing factors by phase of flight, the study found that the most frequent contributors to runway excursions were

- Approach phase:
  - Unstable approaches
  - Tailwinds
- Touchdown phase:
  - Long landing
  - High touchdown speed

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76 M. Jenkins and R. F. Aaron, Jr., "Reducing Runway Landing Overruns," *AERO*, QTR_03 (2012), pp. 15–20. Available at http://www.boeing.com/commercial/aeromagazine/articles/2012_q3/3/ (last accessed 24 August 2016).

  - Speedbrakes late or not deployed
- Deceleration phase:
  - Reverse thrust level too low or reduced too soon
  - Reversers deployed late or not deployed
  - Runway contaminated, limited friction
  - Speedbrakes deployed late or not deployed
  - Autobrake setting too low.

As well, a frequent contributor to these events is a lack of recognition of the actual conditions:

> Runway overrun event data suggests that a number of runway overruns can be avoided if the flight crew has a more thorough understanding of the interrelationship between the landing environment and the potential risks existing that day (e.g. weather, winds, runway conditions, minimum equipment list items, airplane weights).[77]

Mitigations recommended by Boeing to reduce runway overruns focus on increasing crew awareness:

- Calculating the runway distance using real-time data before landing;
- Determining a go-around point by which the aircraft must be established on the runway;
- Including additional thrust reverser callouts in SOPs to ensure thrust reversers are deployed early and remain engaged until the aircraft is at a slow speed; and
- Training and guidance to ensure pilots understand the importance of using deceleration devices early in the landing, particularly on wet or contaminated runways.

1.16.4 TSB laboratory reports

The TSB completed the following laboratory reports in support of this investigation:

- LP115/2015 – DFDR [digital flight data recorder] Download
- LP114/2015 – CVR Download and Transcription

1.17 Organizational and management information

WestJet is a Canadian air operator and an approved maintenance organization that holds operating certificates for operations under *Canadian Aviation Regulations* (CARs) subparts 705 and 573. WestJet is also an approved training organization.

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77 Ibid.

The current fleet operated by WestJet consists of approximately 104 B737-600, -700, and -800 series aircraft. WestJet has 3 B737-700NG pilot training simulators located in Calgary, Alberta. Initial and recurrent classroom training takes place at the company's facility in Calgary.

1.17.1 *WestJet flight data monitoring*

Following the occurrence, WestJet used flight data monitoring information to examine cases where speedbrakes were stowed in excess of 80 knots. Table 10 shows the number of cases identified, broken down by runway, at various airports from January to September 2015.

Table 10. WestJet cases of speedbrakes stowed at speeds in excess of 80 knots at various airports, by runway, from January to September 2015

Landing runway	Number of flights	Number of cases	Percentage
CYYC* - 35L	4815	583	12
CYEG** - 30	4408	166	4
CYYZ - 05	5098	151	3
CYEG - 20	2236	138	6
CYYC - 17L	5454	109	2
CYUL - 24L	771	108	14
CYVR*** - 26R	4992	78	2
CYYC - 35R	4690	73	2
CYUL - 24R	1923	70	4
CYVR - 08L	3957	63	2

* Calgary International Airport, Alberta.
** Edmonton International Airport, Alberta.
*** Vancouver International Airport, British Columbia.

The table shows that the 2 runways with the largest proportions of these events are Runway 24L at CYUL and Runway 35L at Calgary International Airport (CYYC), Alberta. These 2 runways have similar configurations: the terminal is located at the departure end of the runway, and aircraft are frequently instructed to exit at the end to keep parallel taxiways free for the use of departing aircraft taxiing to the opposite end of the runway.

1.18 *Additional information*

1.18.1 *Approach and landing*

According to WestJet's FOM,[78] when the auto-throttle is disconnected, which was the case in this occurrence, the approach "target speed is calculated as follows: Add ½ the reported

[78] WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 026 (13 February 2015), section 4, p. 76.

steady headwind component plus the gust increment above the steady wind to V_{REF}."[79,80] The target speed should not be less than V_{REF} + 5 knots and should not exceed V_{REF} + 20 knots. The "gust correction should be maintained until touchdown while the steady wind correction should be bled off as the aircraft approaches touchdown."[81] A common error noted by WestJet check pilots when this procedure was applied was to add half of the total wind rather than half of the headwind component.

The occurrence aircraft landing weight was 113 500 pounds and the calculated V_{REF} with flaps at 30° was 125 knots. The wind reported to the crew while on final approach was 350°M at 17 knots, gusting to 22 knots. Therefore, there was no headwind component and only the gust increment of 5 knots above the steady wind should have been added to the V_{REF}, which would give a target speed—the speed that should be maintained until touchdown—of 130 knots. In this occurrence, the PF initially set 130 knots as the target speed in the MCP, but increased it to 140 knots after the tower controller reported the above-stated wind condition. Based on the FDR data, the aircraft crossed the threshold at 145 knots—20 knots above V_{REF}. The speed was bled off during the flare, and the aircraft touched down at 133 knots.

1.18.2 Stabilized approach

According to WestJet's FOM,

- A stabilized approach is defined as:
  - Aircraft in the final landing configuration;
  - Power setting appropriate for aircraft configuration;
  - Airspeed no greater than target + 20 knots and trending towards target;
  - On glidepath, gradient path or assumed 3° glidepath.
- Descent rates above 1,000 [feet per minute] should be avoided;
- Avoid any tendency to 'duck under' the profile approaching the threshold;
- If the approach is not stabilized at 1,000 feet above field elevation or the approach becomes unstable below 1,000 feet, a go-around must be executed.[82]

Based on these criteria, the occurrence approach was considered stable: the landing configuration was with flaps set at 30°, the power setting was appropriate for the aircraft

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79 V_{REF} is the reference landing approach speed based on aircraft landing weight and flaps configuration for landing.

80 WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 026 (13 February 2015), section 4, p. 76.

81 Ibid.

82 WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 026 (13 February 2015), section 4, p. 80.

configuration, the airspeed did not exceed target + 20 (150 knots), and the aircraft was on the glide path. However, the target speed of 140 knots was too high for the wind conditions.

WestJet normal procedures require a go-around to be initiated if a landing cannot be made in the touchdown zone.[83] However, there is no requirement for the crew to pre-determine criteria that would trigger the recognition that the aircraft cannot be landed in the touchdown zone.

1.18.3 Wet runway operations

Runway friction values are currently not provided during the summer when it is raining. The *Transport Canada Aeronautical Information Manual* (TC AIM) states the following:

> Notwithstanding the fact that friction values cannot be given for a wet runway and that hydroplaning can cause pilots serious difficulties, it has been found that the well-drained runways at most major Canadian airports seldom allow pooling of sufficient water for hydroplaning to occur. The wet condition associated with rain may produce friction values [in] the order of a CRFI of 0.3 on a poorly maintained or poorly drained runway, but normally produces a value of 0.5. These figures can be used as a guide in conjunction with pilot and other reports.[84]

Section AIR 1.6.6 of the TC AIM provides tables that contain recommended landing distances according to the reported CRFI and are based on the following:

- The aircraft crossing the runway threshold when at 50 feet AGL;
- Stabilized approach at V_{REF};
- Firm touchdown;
- Minimum delay time to deployment of ground spoilers; and
- Application of brakes and sustained maximum antiskid braking until stopped.[85]

The landing distance tables associated with CRFI are not applicable to operations on a wet runway. TC has advised that the reference in the TC AIM will be amended to clarify this in a future publication cycle.

Using the actual aircraft landing weight at the time of the occurrence, the unfactored landing distance using maximum autobrake on a dry runway with flaps set at 30° is approximately 3700 feet[86] based on a touchdown 1500 feet from the runway threshold. Based on Table 1 (without discing or reverse thrust) of the TC AIM, the recommended landing distance with a reported CRFI of 0.3 is 8200 feet, and 6665 feet with a reported CRFI of 0.5 (Appendix E).

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83 Ibid., section 4, p. 95.

84 Transport Canada, TP14371, *Transport Canada Aeronautical Information Manual* (TC AIM), 02 April 2015, AIR 1.6.5.

85 Ibid., AIR 1.6.6, Table 1.

86 WestJet, *737 Quick Reference Handbook*, Revision 1 (14 November 2013), PI-737-600.10A.A6.

1.18.4 Runway assessment and condition reporting

In 2008, ICAO established the Friction Task Force (FTF), which is made up of international experts and stakeholders from key industry groups who review, update, and recommend changes to existing safety-related provisions. The FTF has focused on addressing shortcomings in current standards and recommended practices related to methods used to assess and report runway friction characteristics, the use of measured friction values for flight operation purposes, and the removal of contaminants in a timely manner.

The FTF developed a global reporting format (GRF) for runway surface conditions. The concept relies on a runway condition assessment matrix (RCAM), which uses a set of criteria to assess the runway surface condition and assign a corresponding runway condition code. This methodology is based on recommendations from the FAA Aviation Rulemaking Committee's takeoff and landing performance assessment initiative.

Following a Boeing 737 runway overrun accident at Chicago Midway International Airport, United States, in December 2005, the FAA and industry developed a new methodology to communicate actual runway conditions to pilots in terms that directly relate to expected aircraft performance. On 15 August 2016, the FAA issued SAFO 16009 to notify operators, pilots, training providers, and other personnel of changes in runway condition reporting when a runway is anything other than dry. This change in reporting the runway surface condition has been in effect in the United States since 01 October 2016.

SAFO 16009 states the following:

> The FAA is implementing the use of the Runway Condition Assessment Matrix (RCAM) which will be used by airport operators to perform assessments of runway conditions and by pilots to interpret reported runway conditions. The RCAM is presented in a standardized format, based on airplane performance data supplied by airplane manufacturers, for each of the stated contaminant types and depths. The RCAM replaces subjective judgments of runway surface conditions with objective assessments tied directly to contaminant type and depth categories.
>
> The airport operator will use the RCAM to assess paved runway surfaces, report contaminants present, and through the assistance of the Federal NOTAM System, determine the numerical Runway Condition Codes (RwyCC) based on the RCAM. The RwyCCs apply to paved runways and may be the same or vary for each third of the runway depending on the type(s) of contaminants present. RwyCCs will replace Mu reports which will no longer be published in the NOTAM system. Additionally, contaminant coverage will be expressed in percentage terms for each third of the runway, beginning at the Runway end from which it was assessed. This is typically the runway end primarily in use.
>
> Pilot braking action reports will continue to be solicited and will be used in assessing braking performance. Effective October 1, 2016, the terminology "Fair" will be replaced by "Medium" and pilot braking action reports will now describe conditions as Good, Good to Medium, Medium, Medium to

> Poor, or NIL. This will harmonize the NAS [National Aircraft Standards] with ICAO standards.
>
> Additionally, it will no longer be acceptable for a federally obligated airport to report a NIL braking action condition. NIL conditions on any surface require the closure of that surface. These surfaces will not be opened until the airport operator is satisfied that the NIL braking condition no longer exists.[87]

Following the issuance of SAFO 16009, TC issued Civil Aviation Safety Alert (CASA) No. 2016-08, "United States Implementation of Takeoff and Landing Performance Assessment (TALPA)," to alert Canadian pilots, flight dispatchers, air operators and private operators to the changes affecting flight operations in the United States. TC's objective is to implement the GRF by November 2020.

1.18.5 Hydroplaning

Hydroplaning occurs when a layer of water builds up between the aircraft's tires and the runway surface, leading to loss of traction and thus preventing the aircraft from responding to control inputs such as steering or braking. Hydroplaning is a function of the water depth, tire pressure, and speed. Both smooth runway surfaces and smooth tread tires will induce hydroplaning with shallower water depths.

There are 3 types of hydroplaning: dynamic, viscous, and reverted rubber. Dynamic hydroplaning can occur during the higher speeds of landing and take-off ground roll and

> is the result of the hydrodynamic forces developed when a tire rolls on a water covered surface. […] Dynamic hydroplaning is influenced by tire tread, water layer thickness and runway macrotexture. […] When there is sufficient macro texture on the surface and / or the tire has proper tread, total dynamic hydroplaning will usually not occur. However, hydroplaning can occur when the water depth is high enough so that both tire tread and runway macro texture cannot drain the water quick [*sic*] enough.[88]

Additionally, according to ICAO, "As little as 0.5 mm of water has been found to be sufficient to support dynamic hydroplaning."[89] Dynamic hydroplaning seldom leaves any physical evidence on tires or runway surfaces.

Viscous hydroplaning occurs when a tire is unable to puncture the thin water film (1/1000 of an inch in depth is sufficient) on the pavement and rolls on top of the water film. This can occur at a much lower speed than dynamic hydroplaning, but requires a very smooth

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87 Federal Aviation Administration (FAA), Safety Alerty for Operators (SAFO) 16009, Runway Assessment and Condition Reporting, Effective October 1, 2016 (15 August 2016).

88 G. W. H. van Es, "Hydroplaning of modern aircraft tires," National Aerospace Laboratory NLR, May 2001, p. 4.

89 International Civil Aviation Organization, *Airport Services Manual*, *Part 2: Pavement Surface Conditions*, Document 9137, 2002.

runway surface, such as an area that has been subjected to polishing by traffic or other means. Viscous hydroplaning is associated with damp or wet runways and, once begun, can persist down to very low speeds. As is the case with dynamic hydroplaning, viscous hydroplaning also seldom leaves physical evidence on tires or runway surfaces.

Reverted rubber hydroplaning occurs when a locked wheel skids. In such a case, the heat generated by friction produces steam and begins to melt the rubber on a portion of the tire (i.e., the rubber "reverts" to its original, uncured state). The tires will show clear evidence of rubber reversion and the runway surface will be clearly marked with the path of the wheels as a result of steam pressure cleaning beneath the tires. No such evidence was observed either on the tires or on the runway following the occurrence.

1.18.6 Threat and error management

The threat and error management (TEM) model is a conceptual framework that can be used to describe how flight crews manage the situations they encounter that increase the risks associated with a given flight and to diagnose how situations developed following an occurrence. Included in the model are threats, errors, and undesired aircraft states. The model also outlines countermeasures that have been shown to be effective in managing such situations.[90]

Threats are conditions that are beyond the control of the crew and increase the risk.They may include environmental threats such as adverse weather, runway contamination, or challenging air traffic control clearances. If threats are identified and actively managed, they can be of little consequence. However, threats often lead to crew errors and to undesired aircraft states.

Errors include actions or inactions by the crew, which lead to deviations from organizational or crew expectations. These may include aircraft-handling errors such as the incorrect use of automation, procedural errors such as completing checklists from memory or omitting briefings, or communication errors such as missed callouts or incorrect air traffic control readbacks. Errors can result from the mismanagement of a threat, or they may occur spontaneously. The key to error management is detection and action.

Undesired aircraft states are situations where the aircraft is placed in a position of increased risk, most often due to the mismanagement of a threat or error. They may include aircraft-handling issues such as altitude or speed deviations, ground navigation issues, or instances of incorrect aircraft configuration such as incorrect automation settings or late configuration for landing.

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90 D. Maurino, "Threat and Error Management," presented at the Canadian Aviation Safety Summit, Vancouver, British Columbia (18 to 20 April 2005).

TEM advocates the careful analysis of potential hazards and taking appropriate steps to avoid, trap, or mitigate threats and errors before they lead to an undesired aircraft state. In other words, TEM stresses anticipation, recognition, and recovery as the key principles.[91]

1.18.7 Situational awareness, mental models, and decision making

Situational awareness (SA) describes the extent to which information within the operating environment is perceived and its significance is understood, both at the present time and for the future. The most widely used model[92] of SA breaks down the construct into 3 levels and states that effective performance requires crews to

1. Perceive information in the operating environment (Level 1 SA).
2. Comprehend the significance of this information to the current situation (Level 2 SA).
3. Use this information to anticipate future states (Level 3 SA).[93]

Breakdowns can occur at any of the 3 levels, leading to situations where critical information is not perceived, the current situation is misunderstood, or future situations are not anticipated.

SA is developed and maintained through a continual process of situational reassessment. In some circumstances, this can be triggered by information being presented in the operating environment. In these cases, the salience of the information being presented will be a critical determinant of whether information is attended to and assimilated into an individual's mental model of the situation.

In highly practised environments, however, attentional resources are more often driven by the individual's existing mental model of the situation, since previous experience will dictate what information is most relevant at any given time. In this mode of goal-directed processing, "SA is affected by the aircrew's goals and expectations, which influence how attention is directed, how information is perceived and how it is interpreted."[94] Such processing is critical to effective performance in dynamic environments because it reduces attentional demands, but it can also lead to errors where an inaccurate mental model leads to critical information not being perceived or the significance of this information not being understood.[95]

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91 A. Merritt and J. Klinect, "Defensive Flying for Pilots: An Introduction to Threat and Error Management," The University of Texas Human Factors Research Project: The LOSA Collaborative (Austin, TX: 2006), p. 16.

92 M. R. Endsley, "Situation Awareness in Aviation Systems," in J. A. Wise, V. D. Hopkin and D. J. Garland, *Handbook of Aviation Human Factors* (Boca Raton, FL: Taylor and Francis, 2010), p. 12-3.

93 Ibid.

94 Ibid., p. 12-7.

95 Ibid., p. 12-12.

Situation assessment may be triggered by cues available in the operating environment or by the decision-maker's expectations of how the situation will unfold.[96] Because of this, efforts to ensure timely situation assessments can focus on making the information that will trigger a situation assessment more salient or on increasing the likelihood of a reassessment through training or procedures.[97]

1.18.8 TSB Watchlist

The Watchlist identifies the key safety issues that need to be addressed to make Canada's transportation system even safer.

Runway overruns are a 2016 Watchlist issue. As this occurrence demonstrates, runway overruns continue to occur at Canadian airports.

Runway overruns will remain on the TSB Watchlist until

- pilots receive timely information about runway surface conditions to calculate the landing distance required, no matter the season;
- TC requires appropriate RESAs at Canadian airports to reduce risks when a runway overrun occurs; and
- major airports provide adequate RESAs or other engineered systems and structures to safely stop aircraft that overrun.

The TSB database shows that, in the 10-year period from 06 June 2005 to 06 June 2015, there were 80 runway overruns in Canada that occurred during the landing phase. Of these, 3 resulted in fatalities and 20 caused serious injuries. Five[98] of the 80 runway overruns involved a Boeing 737. Of those 5, none were fatal or caused serious injuries. The last runway overrun at CYUL before this occurrence was in 2006, after a landing on Runway 06R, and involved a Learjet 35A.[99]

1.19 Useful or effective investigation techniques

Not applicable.

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96 C. D. Wickens and J. G. Hollands, *Engineering Psychology and Human Performance*, 3rd edition (New Jersey: Prentice Hall, 2000), p. 296.

97 Ibid., pp. 324-330.

98 TSB aviation investigation reports A08O0035, A12W0004, and this occurrence, and TSB aviation occurrences A07P0340 and A10P0250.

99 TSB Aviation Investigation Report A06Q0190.

2.0 Analysis

2.1 Introduction

Records indicate that the aircraft was certified, equipped, and maintained in accordance with existing regulations and approved procedures. The aircraft was not found to have any mechanical discrepancies. An examination of the aircraft's deceleration devices was completed, and no anomalies were found.

The flight crew were certified and qualified for the flight in accordance with existing regulations and there were no indications that the flight crew's performance was in any way degraded as a result of physiological factors, such as fatigue. As a result, this analysis will focus on the management of the operational threats the crew were facing, as well as the use of the available decelerating devices.

2.2 Operational threats

2.2.1 General

Before operational threats can be effectively managed by a crew, they must be identified and their potential impact—for the current situation and in the future—must be accurately assessed. Information available in the operating environment is perceived and assessed in the context of a crew's mental model of the situation.

2.2.2 Runway condition expectation

When planning the arrival at Montréal/Pierre Elliot Trudeau International Airport (CYUL), the crew were anticipating a visual approach to a wet runway. This was based on the weather information provided by automatic terminal information service (ATIS) information Lima, which was reporting 15 statute miles (sm) visibility in light rain showers and a broken ceiling at 4500 feet above ground level (AGL) with towering cumulus present. In this weather, and anticipating the normal practice of exiting at the end of Runway 24L, the crew briefed a visual approach, backed up by the instrument landing system (ILS), and planned to use an autobrake setting of 1 and a flap setting of 30°.

Guidance material available to assist crews in these situations equates a wet runway with good braking performance. The landing distance flow chart and stopping distance equivalency tables contained in WestJet's *Flight Operations Manual* (FOM) specify that, unless a braking action report (BAR) from a similar type of aircraft has been received to indicate poor or medium braking or the crew expect there to be more than ⅛ inch of standing water on the runway, landing distance calculations for good braking conditions may be used.

These procedures rely on information that may not always be available to the crew. Based on the information obtained from ATIS information Lima, which reported light rain, the crew had no reason to expect that the runway would be more than just wet or contaminated by water (more than 3 mm, or ⅛ inch, of standing water). Therefore, in order to obtain aircraft communications addressing and reporting system (ACARS) landing distance calculations, the crew selected GOOD in the BAR line. The ACARS calculated landing distance with flaps set to 30° and autobrake set to 1 was 7784 feet. Given that this distance included a 15% safety margin and that the runway landing distance available was 9600 feet, the crew had no reason to reconsider their decision to use a higher autobrake setting or use a flap setting of 40° for landing.

The use of the takeoff and landing report (TLR) and landing distance tables would have provided similar landing distances to the flight crew. As stated in the *Transport Canada Aeronautical Information Manual* (TC AIM), a wet runway can produce friction values that would equate to a Canadian Runway Friction Index (CRFI) of 0.3 on a poorly maintained or poorly drained runway. However, even if the crew had consulted the recommended landing distances table, this would also have provided a landing distance well below the landing distance available, even without the use of the thrust reverser.

2.2.3 *Actual runway condition*

Runway 24L was maintained in accordance with the standards established in *Aerodrome Standards and Recommended Practices* (TP312) published by Transport Canada (TC). Rubber removal took place on 02 June 2015 (3 days before the occurrence) and friction tests carried out on 16 July 2015 (more than a month after the occurrence) show that friction index values were within the TP312 standards. Therefore, there is no reason to believe that friction index values would have been less on the day of the occurrence.

Although the friction index values were within the TP312 standards, it is likely that viscous hydroplaning occurred when the aircraft was approaching the end of the runway, as shown by the lack of deceleration once maximum braking was applied. It is normal to have some rubber contaminant buildup and texture loss near both touchdown zones of a runway even after rubber removal, especially when the runway is wet. Combined with the downslope, this reduced the possibility of stopping on the runway.

Runway 24L is a textured runway and, as such, provides channels for water to escape and increases braking coefficient in wet conditions. However, according to the Federal Aviation Administration (FAA) Safety Alert for Operators (SAFO) 15009, experience has shown that wheel braking on a grooved runway is degraded when the runway is very wet, and operators should therefore consider being more conservative in their time-of-arrival assessments. If operators do not consider making more conservative time-of-arrival assessments when active heavy precipitation exists, then there is a risk of runway overrun.

Runway 24L longitudinal and transversal slope gradients fall within the established standards of TP312 and nothing indicates that runway drainage was inadequate. Based on the rainfall gauge located at CYUL, only 1.6 mm of precipitation was recorded from 1455 until the aircraft departed the paved surface at 1458. Although the rainfall amount for this period seems small, the rate at which it fell was significant and equivalent to heavy rain according to the criteria in Environment Canada's *Manual of Surface Weather Observations* (MANOBS). Therefore, the runway was not contaminated, per se, but was likely more than just wet with a shiny appearance. Furthermore, the amount of water observed being sprayed from the aircraft as it was approaching the end of the runway is consistent with some level of water accumulation.

Pilots must calculate the landing distance required, and they need timely and accurate runway surface condition information to make correct calculations, given that snow, rain, or ice can affect landing distance. However, during periods of rain, water depth on a runway may change rapidly; therefore, there is no formal procedure for reporting runway surface conditions as there is with other runway contaminants such as snow and ice. Unless another aircraft has already landed and reported poor braking, the crew have little information with which to develop an expectation of runway performance. As shown in this occurrence, the 2 aircraft that had landed on Runway 24L before WestJet flight 588 (WJA588) had no problems exiting the runway as instructed. However, neither of these aircraft provided a BAR to the controller, nor were they asked to provide one.

During the period of moderate and heavy rain, 6 aircraft landed on Runway 24R. None of them provided a BAR, nor were they asked to provide one. It was only approximately 10 minutes after the occurrence that the controller began asking crews to provide BARs in order to pass the information on to subsequent aircraft landing at CYUL.

The global reporting format (GRF) for runway surface conditions implemented by the FAA is a concept that relies on a runway condition assessment matrix (RCAM), which uses a set of criteria to assess the runway surface condition and assign a corresponding runway condition code. This new methodology is used to assess and communicate actual runway conditions to pilots in terms that directly relate to expected aircraft performance. This information will certainly improve crew's ability to properly assess landing conditions, especially during non-winter months. However, the GRF for runway surface conditions has not yet been implemented in Canada. Therefore, if there is no specific guidance on how to assess and report runway surface conditions during non-winter months, then there is a risk that crews will be unable to properly assess landing conditions.

The runway inspection conducted about 18 minutes before WJA588 landed did not raise any issues that could have prevented safe landings. However, the runway inspection was carried out before the beginning of moderate and heavy rain showers. The video recording of the runway inspection completed after the occurrence during light rain showed a wet runway with a shiny appearance but no water accumulation. However, this runway inspection took place 40 minutes after the occurrence.

2.2.4 Approach and landing in heavy rain

The fact that rain or even heavy rain is occurring will not automatically prompt a crew to anticipate poor braking, because a wet runway is expected to provide good braking action and the runway is assumed to be adequately drained. Unless reports of standing water on the runway are received, pilots are unlikely to consider rain or even heavy rain as threats to their ability to stop the aircraft. This expectation is supported by information contained in the TC AIM, which states that "the well-drained runways at most major Canadian airports seldom allow pooling of sufficient water for hydroplaning to occur."[100] Therefore, the crew's initial plan for the arrival, using autobrake setting 1 and thrust reverser to provide minimal deceleration, was consistent with existing guidance that a wet runway should provide good braking action.

An aerodrome special meteorological report (SPECI) was issued at 1451, 7 minutes before WJA588 landed, and was reporting a visibility of 15 statute miles (sm) in moderate rain. At that time, WJA588 was being vectored for Runway 24L and was not aware of this SPECI. However, once on the approach, the crew became aware that weather conditions were worse than anticipated: they noted heavy precipitation on the aircraft's weather radar and flew through heavy rain on their final approach. The knowledge that precipitation was intensifying at the airport did not prompt the crew to expect that the runway could be contaminated rather than just wet, and, as a result, they continued to expect good braking performance on a wet runway. The SPECI information was broadcasted on ATIS information Mike at 1458. At that time, the aircraft was already on the runway.

In August 2015, the FAA published a SAFO following an analysis of landing performance in a number of runway overrun occurrences suggesting that the accepted assumption that a wet runway will allow for good braking may not adequately mitigate the risks of wet runways. The SAFO stated that the braking coefficient of friction was significantly lower than expected for a wet runway and warned operators that 30% to 40% of additional stopping distance may be required on runways that are wet but not flooded.[101]

Given the information contained in the FAA's SAFO, operators should be more conservative when making landing distance assessments in situations where moderate or heavy precipitation is occurring on non-grooved or non-porous friction course (PFC) runways and where heavy precipitation is occurring on grooved or PFC runways. If procedures and guidance do not prompt flight crews to anticipate less-than-good braking conditions on wet runways, then there is a risk that landing distance and aircraft management will be inadequate to provide for safe stopping performance.

2.2.5 Approach, flare, and touchdown point

A stabilized approach provides the basis for a good landing. In this occurrence, all the criteria stated in the WestJet FOM for a stable approach were met; however, the aircraft still overran the runway. As shown by data collected and analyzed from 2003 to 2010, 68% of landing overruns occur after stable approaches.[102]

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100 Transport Canada, *Transport Canada Aeronautical Information Manual* (TC AIM), TP14371, 02 April 2015, AIR 1.6.5.

101 Federal Aviation Administration (FAA), Safety Alert for Operators (SAFO) 15009, Turbojet Braking Performance on Wet Runways (11 August 2015).

102 M. Jenkins and R. F. Aaron, Jr., "Reducing Runway Landing Overruns," *AERO*, QTR_03 (2012), available at http://www.boeing.com/commercial/aeromagazine/articles/2012_q3/3/ (last accessed 24 August 2016).

A review of runway overrun occurrences by Boeing demonstrated that a runway overrun is typically caused by multiple factors. One of these factors is the approach target speed. As per the WestJet FOM, the target speed is calculated by adding half of the reported steady headwind component plus the gust increment above the steady wind to V_{REF}. The target speed should not be less than V_{REF} + 5 knots and should not exceed V_{REF} + 20 knots. A common error noted by WestJet check pilots when this procedure was applied was to add half of the total wind rather than half of the headwind component.

The wind reported to the crew before landing was 350°M at 17 knots, gusting to 22 knots. This information did not prompt the crew to take into account the tailwind component for their target speed calculation. In fact, following the landing clearance, the target speed in the mode control panel (MCP) was increased from 130 knots to 140 knots.

In this occurrence, the crew calculated an inaccurate target approach speed and crossed the threshold 15 knots faster than recommended. Combined with a tailwind and a slightly high flare, this resulted in the aircraft touching down beyond the normal touchdown zone, thus reducing the amount of runway available for stopping. However, it was not sufficient to prompt either crew member to contemplate a go-around before touching down. It is likely that the crew were unaware of how far beyond the touchdown zone the aircraft was.

There are no clear cues to indicate to the crew how far outside the touchdown zone the aircraft has landed, as distance-to-go markers are not provided at Canadian civil airports. One recommended means of mitigating the tendency to continue with a landing outside the touchdown zone is to include a requirement to brief a definite point, such as a taxiway or physical landmark, at which point a go-around will be initiated if the aircraft is not on the ground.

Although WestJet's normal procedures require a go-around to be initiated if a landing cannot be made in the touchdown zone, there is no requirement for the crew to identify a trigger to help recognize when the aircraft has not landed in the touchdown zone. If pilots do not identify a point at which a go-around should be initiated if the aircraft is not on the ground, then there is a risk that the landing will result in a runway overrun.

2.3 Managing of deceleration devices

The fact that the crew had not recognized the longer-than-normal touchdown and was expecting good braking even in heavy rain is demonstrated by the handling of the aircraft following touchdown. The crew continued to implement their plan to use minimal deceleration because they were expecting to exit at the end of the runway. Reverse thrust was selected shortly after touchdown, but only idle reverse was selected for most of the landing roll. According to WestJet's standard operating procedures (SOPs), idle reverse may be used when required to comply with noise abatement requirements; otherwise, normal or maximum reverse is to be used, depending on the stopping performance required and landing performance data provided to crews.[103]

As shown by engineering simulations run by Boeing, if maximum reverse thrust had been used for the entire landing roll with the occurrence speedbrake usage and autobrake set to 1, the aircraft would have remained on the paved surface of the runway despite touching down 1050 feet beyond the normal 1500-foot touchdown point. In this occurrence, the captain delayed the selection of maximum thrust by approximately 25 seconds after touchdown. Consequently, the distance required to stop the aircraft increased.

In addition, the captain stowed the aircraft's speedbrakes above the speed of 80 knots specified in WestJet's SOPs, and they were not redeployed during the landing roll. This reduced the normal load on the gear and the aerodynamic drag. Consequently, the deceleration rate decreased, which increased the stopping distance.

The results of engineering simulations run by Boeing show the importance of speedbrakes and their role in stopping the airplane as the runway condition deteriorates. Based on the flight data recorder (FDR) data, the crew-commanded brake pressure remained approximately at levels commanded by the autobrakes once disarmed; however, the deceleration decreased by one half. According to Boeing, this can be primarily attributed to the stowage of the speedbrakes. However, in this occurrence, even if the speedbrakes had been kept deployed for the entire landing roll, the aircraft would still have overrun the end of the runway given the use of reverser thrust used during the occurrence.

According to WestJet's FOM,

> if the autobrake system disengages, pilots must immediately apply appropriate manual braking as required for the remaining runway available. Pilots shall not intentionally disarm the autobrake until the landing distance is assured or maximum manual braking is required.[104]

In this occurrence, the pilot flying (PF) intentionally disarmed the autobrake by retracting the spoilers at 103 knots and no manual brake application occurred until 16 seconds after touchdown. Therefore, it is reasonable to believe that the PF judged that there was sufficient runway remaining when the spoilers were retracted, based on the observed runway condition.

Runway 24L is not equipped with distance-to-go markers or centreline runway lights, nor is it required to be. However, these markers or lights could have provided clues to the crew when they were 3000 feet and 1000 feet from the runway end. This could have prompted the PF to apply maximum reversers and maximum braking earlier or redeploy the speedbrakes. If crews are not provided with clear clues to indicate how far from the end of a runway they

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103 WestJet, *Flight Operations Manual – Boeing 737NG*, Volume 1, Revision 026 (13 February 2015), section 4, p. 99.

104 Ibid., section 5, p. 41.

are, then there is a risk that deceleration devices will not be used in a timely manner to prevent a runway overrun.

2.4 Conclusion

As shown by a review of runway overrun occurrences by Boeing, a runway overrun is typically caused by multiple factors. High speed, tailwind, long landing, and delayed use of deceleration devices were factors that significantly contributed to this occurrence. Fortunately, the runway end safety area (RESA) allowed the aircraft to decelerate in a controlled manner; the aircraft was not damaged and no one was injured. However, not all Code 4 runways in Canada have a 300 m RESA or a means of stopping aircraft that provides an equivalent level of safety. Therefore, if Code 4 runways do not have a 300 m RESA or a means of stopping aircraft that provides an equivalent level of safety, then there is a risk of injuries to occupants in the event of a runway overrun.

Suggested best practices for preventing overruns include conducting a positive touchdown in the touchdown zone and making maximum use of deceleration devices early in the landing roll. This is particularly true of reverse thrust, which is more effective at higher speeds. As shown in this occurrence, the instruction to exit at the end of the runway contributed to the minimal use of deceleration devices early in the landing roll, as the crew were attempting to expedite their exit at the end of Runway 24L.

It is normal for landing aircraft that are going to the terminal to be instructed to exit at the end when landing on Runway 24L at CYUL. Having landing aircraft travel to the end of the runway facilitates traffic flow by leaving the single taxiway free for departing aircraft. In these circumstances, safety and best practices for preventing runway overruns would dictate that flight crews land with full use of available deceleration devices and then proceed to the instructed exit point at a normal taxi speed.

Flight data monitoring conducted by WestJet following the occurrence suggests that non-standard use of deceleration devices is more prevalent on runways where aircraft are typically instructed to exit at the end of the runway. These data support the assertion that, in these situations, pilots may be inclined to maintain speed and decelerate at the end of the runway rather than decelerating normally through the early application of all available deceleration devices and taxiing the aircraft to the end of the runway. If pilots limit the use of deceleration devices to comply with a real or perceived requirement to expedite exiting at the end of a runway, then there is a risk that the landing will result in a runway overrun.

3.0 Findings

3.1 Findings as to causes and contributing factors

1. The knowledge that precipitation was intensifying at the airport did not prompt the crew to expect that the runway could be contaminated rather than just wet, and, as a result, they continued to expect good braking performance on a wet runway.

2. The crew calculated an inaccurate target approach speed and crossed the threshold 15 knots faster than recommended. Combined with a tailwind and a slightly high flare, this resulted in the aircraft touching down beyond the normal touchdown zone, thus reducing the amount of runway available for stopping.

3. The captain delayed the selection of maximum thrust by approximately 25 seconds after touchdown. Consequently, the distance required to stop the aircraft increased.

4. The captain stowed the aircraft's speedbrakes above the speed of 80 knots specified in WestJet's standard operating procedures, and they were not redeployed during the landing roll. This reduced the normal load on the gear and the aerodynamic drag. Consequently, the deceleration rate decreased, which increased the stopping distance.

5. The instruction to exit at the end of the runway contributed to the minimal use of deceleration devices early in the landing roll, as the crew were attempting to expedite their exit at the end of Runway 24L.

6. It is likely that viscous hydroplaning occurred when the aircraft was approaching the end of the runway, as shown by the lack of deceleration once maximum braking was applied. Combined with the downslope, this reduced the possibility of stopping on the runway.

3.2 Findings as to risk

1. If operators do not consider making more conservative time-of-arrival assessments when active heavy precipitation exists, then there is a risk of runway overrun.

2. If there is no specific guidance on how to assess and report runway surface conditions during non-winter months, then there is a risk that crews will be unable to properly assess landing conditions.

3. If procedures and guidance do not prompt flight crews to anticipate less-than-good braking conditions on wet runways, then there is a risk that landing distance and aircraft management will be inadequate to provide for safe stopping performance.

4. If pilots do not identify a point at which a go-around should be initiated if the aircraft is not on the ground, then there is a risk that the landing will result in a runway overrun.

5. If crews are not provided with clear clues to indicate how far from the end of a runway they are, then there is a risk that deceleration devices will not be used in a timely manner to prevent a runway overrun.

6. If pilots limit the use of deceleration devices to comply with a real or perceived requirement to expedite exiting at the end of the runway, then there is a risk that the landing will result in a runway overrun.

7. If Code 4 runways do not have a 300 m runway end safety area or a means of stopping aircraft that provides an equivalent level of safety, then there is a risk of injuries to occupants in the event of a runway overrun.

3.3 Other findings

1. The crew's initial plan for the arrival, using autobrake setting 1 and thrust reverser to provide minimal deceleration, was consistent with existing guidance that a wet runway should provide good braking action.

2. The pilot flying intentionally disarmed the autobrake by retracting the spoilers at 103 knots and no manual brake application occurred until 16 seconds after touchdown. Therefore, it is reasonable to believe that the pilot flying judged that there was sufficient runway remaining when the spoilers were retracted, based on the observed runway condition.

4.0 Safety action

4.1 Safety action taken

4.1.1 WestJet

Following the occurrence, WestJet's chief pilot debriefed the flight crew, and all training pilots received a briefing on this incident. The briefing included reference to the speedbrake stowage above 80 knots.

The flight safety annual ground school now includes the following topics:

- Overrun characteristics
- WestJet flight 588 incident review
- Early speedbrake stowage statistics
- Federal Aviation Administration Safety Alert for Operators 15009
- National Transportation Safety Board video: "Procedural Compliance"
- Boeing Embraer video: "No Landing is Routine"
- Normalization of deviance

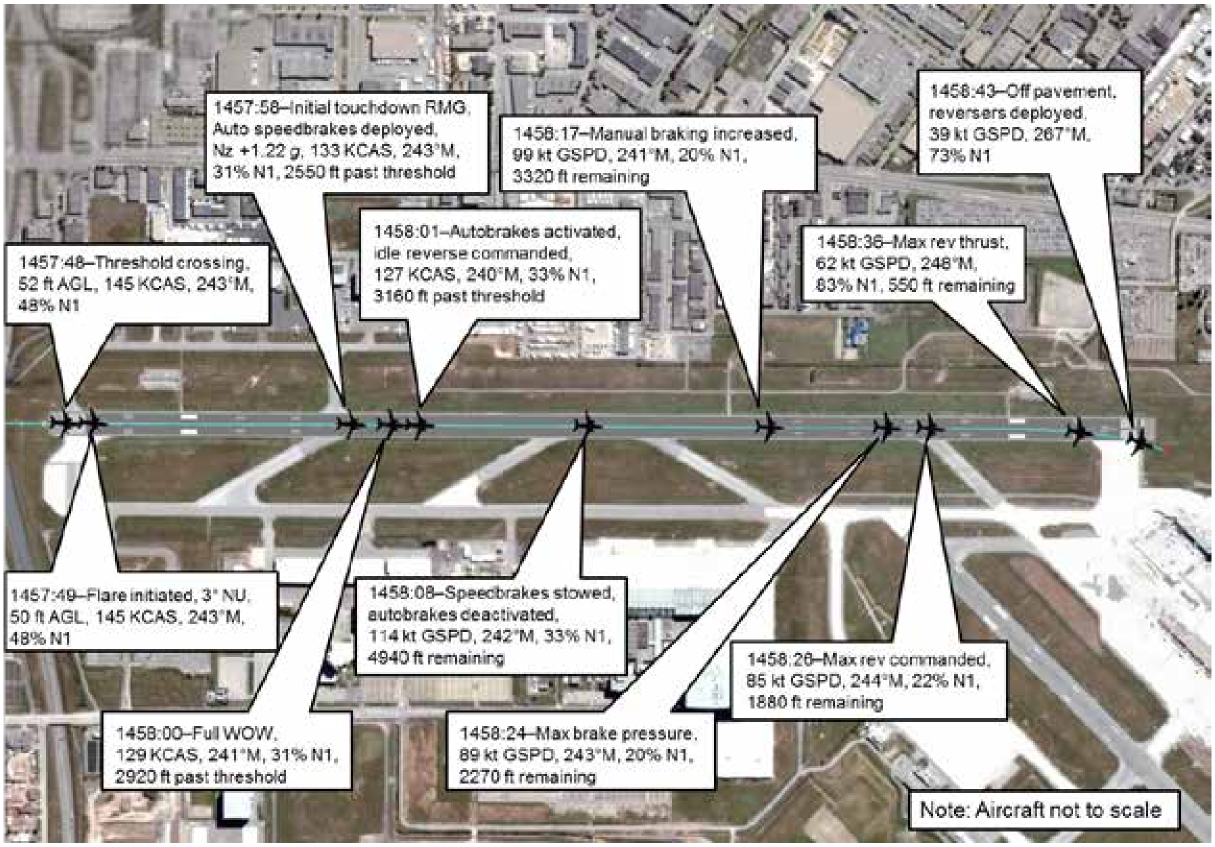
During flight training, speedbrake stowage above 80 knots and braking performance on wet runways are discussed. Recurrent simulator sessions now include wet runway landings with crosswind.

This report concludes the Transportation Safety Board's investigation into this occurrence. The Board authorized the release of this report on 29 March 2017. It was officially released on 16 May 2017.

Visit the Transportation Safety Board's website (www.tsb.gc.ca) for information about the TSB and its products and services. You will also find the Watchlist, which identifies the transportation safety issues that pose the greatest risk to Canadians. In each case, the TSB has found that actions taken to date are inadequate, and that industry and regulators need to take additional concrete measures to eliminate the risks.

Appendices

Appendix A – Sequence of events of WestJet flight 588



Source: Google Earth, with TSB annotations. Note: all times in this figure are Eastern Daylight Time (Coordinated Universal Time minus 4 hours)

Abbreviation	Meaning
AGL	above ground level
ft	feet
g	gravitational force
GSPD	ground speed
KCAS	knots calibrated airspeed
kt	knots
M	magnetic (degrees)
Max rev	maximum reverse
N1	low-pressure compressor revolutions per minute
NU	nose up
Nz	normal acceleration
RMG	right main gear
WOW	weight on wheels

Appendix B – WestJet landing distance tables

WESTJET

737 Flight Operations Manual

WestJet
Performance
737-600

Landing Distances - Dry Runway

Flaps 15
Brakes with Antiskid and Speedbrakes (Auto or Manual)

	Landing Distance and Adjustment (FT)									
	REFERENCE DISTANCE	WEIGHT ADJUSTEMENT	ALTITUDE ADJ	WIND ADJ PER 10 KTS		SLOPE ADJ PER 1 %		TEMP ADJ PER 10°C		VREF ADJ
BRAKING CONFIG	110,000 LB LANDING WEIGHT	PER 10,000 LB ABOVE/ BELOW 110,000 LB	PER 1000 FT ABOVE SEA LEVEL	HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	ABV ISA	BLW ISA	PER 10KTS ABOVE VREF 15
MAX AUTO	4364	224/-201	81	-150	495	0	0	81	-75	380
AUTOBRAKE 3	5756	362/-357	132	-242	817	0	0	132	-127	627
AUTOBRAKE 2	7147	518/-512	190	-316	1133	81	-92	190	-184	644
AUTOBRAKE 1	7826	604/-598	230	-374	1323	190	-224	213	-207	604

Reference distance is for sea level, standard day, no wind or slope and two engine detent reverse thrust plus a 15% margin of safety.
Distance is actual distance from 50 ft above runway threshold to stop, and includes 1500 ft of air distance.
Landing distance corrections are all in feet.
Assumes VREF 15 approach speed.

Flaps 30
Brakes with Antiskid and Speedbrakes (Auto or Manual)

	Landing Distance and Adjustment (FT)									
	REFERENCE DISTANCE	WEIGHT ADJUSTEMENT	ALTITUDE ADJ	WIND ADJ PER 10KTS		SLOPE ADJ PER 1 %		TEMP ADJ PER 10°C		VREF ADJ
BRAKING CONFIG	110,000 LB LANDING WEIGHT	PER 10,000 LB ABOVE/BELOW 110,000 LB	PER 1000 FT ABOVE SEA LEVEL	HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	ABV ISA	BLW ISA	PER 10KTS ABOVE VREF 30
MAX AUTO	4175	207/-201	81	-127	477	0	0	81	-75	362
AUTOBRAKE 3	5440	328/-322	115	-224	794	0	0	132	-127	587
AUTOBRAKE 2	6733	466/-460	173	-316	1081	81	-109	173	-167	569
AUTOBRAKE 1	7354	552/-546	213	-357	1265	190	-184	190	-184	552

Reference distance is for sea level, standard day, no wind or slope and two engine detent reverse thrust plus a 15% margin of safety.
Distance is actual distance from 50 ft above runway threshold to stop, and includes 1500 ft of air distance.
Landing distance corrections are all in feet.
Assumes VREF 30 approach speed.

Flaps 40
Brakes with Antiskid and Speedbrakes (Auto or Manual)

	Landing Distance and Adjustment (FT)									
	REFERENCE DISTANCE	WEIGHT ADJUSTEMENT	ALTITUDE ADJ	WIND ADJ PER 10 KTS		SLOPE ADJ PER 1 %		TEMP ADJ PER 10°C		VREF ADJ
BRAKING CONFIG	110,000 LB LANDING WEIGHT	PER 10,000 LB ABOVE/BELOW 110,000 LB	PER 1000 FT ABOVE SEA LEVEL	HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	ABV ISA	BLW ISA	PER 10KTS ABOVE VREF 40
MAX AUTO	4083	190/-184	81	-127	477	0	0	81	-75	362
AUTOBRAKE 3	5307	311/-305	115	-224	776	0	0	115	-109	569
AUTOBRAKE 2	6567	449/-443	173	-299	1081	81	-109	155	-150	552
AUTOBRAKE 1	7170	535/-512	213	-357	1248	190	-184	173	-167	529

Reference distance is for sea level, standard day, no wind or slope and two engine detent reverse thrust plus a 15% margin of safety.
Distance is actual distance from 50 ft above runway threshold to stop, and includes 1500 ft of air distance.
Landing distance corrections are all in feet.
Assumes VREF 40 approach speed.

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PI-737-600.10A.16 Revision: 1 - 14NOV13

Source: WestJet, *Flight Operations Manual—Boeing 737NG*

Appendix C – WestJet landing distance calculation flow chart

Performance — Section 10
General

Landing Distance Calculation Flow Chart

The following rules must be used in conjunction with the flow chart;

- For conditions to be non active there cannot have been precipitation in any form since the BAR/RSC/CRFI report was issued. Precipitation in any form constitutes an active condition.
- In active conditions, the Captain shall be satisfied that the landing calculations are based on valid conditions or landing is prohibited.
- Only Braking Actions Reports from similar type jet aircraft can be considered valid.
- CRFI reports greater than one hour old are invalid. Use the latest BAR/RSC report.
- If a valid CRFI report is available use the CRFI value to modify the latest, most restrictive, BAR/RSC braking value as indicated:

CRFI	BAR/RSC – VALUE	USE
0.3 – 0.25	GOOD	MEDIUM BRAKING
0.3 – 0.25	MEDIUM	MEDIUM BRAKING
< 0.25	GOOD	MEDIUM BRAKING
< 0.25	MEDIUM	POOR BRAKING

1 Choose one:

◆There **has** been an aircraft BAR after the RSC was taken:

►►**Go to step 2**

◆There **has not** been an aircraft BAR after the RSC was taken:

- Obtain the latest RSC report.
- Determine the appropriate braking action (Good, Medium or Poor) from the Runway Condition Equivalency Table.
- If available, use a valid CRFI report to modify the braking action value.
- Use the resulting braking action value to calculate the required landing distance.

►►**Go to step 3**

2 Choose one:

◆**Active Conditions**

- Obtain the latest RSC report and/or aircraft BAR.
- Determine the appropriate braking action (Good, Medium or Poor) from the Runway Condition Equivalency Table.
- Compare the BAR value with the value determined from the Runway Condition Equivalency Table.
- If available, use a valid CRFI report to modify the most restrictive braking action value.
- Use the resulting braking action value to calculate the required landing distance.

►►**Go to step 3**

◆**Non Active Conditions**

- Use the BAR to calculate the required landing distance (CRFI is not used as a modifier).

►►**Go to step 3**

3 Choose one:

◆Acceptable data is obtained

Landing may be conducted using the acceptable data and associated autobrake selection.

■■■■

◆Acceptable data is not obtained

Landing prohibited. Do Not Land.

■■■■

Source: WestJet, *Flight Operations Manual—Boeing 737NG*

Appendix D – WestJet runway condition and braking action report equivalency table

Runway Condition and Braking Action Report Equivalency Table

Pilots may use the Runway Condition and Braking Action Report Equivalency Table below to assist in determining an associated braking level with the reported conditions. This Equivalency Table can be especially helpful when the only reported information is the Runway Surface Condition Report. When multiple sources of runway conditions are provided conflicts between the reports are possible (i.e. runway is covered with a trace of Dry Snow, which would be the equivalent of GOOD but the last Braking Action Report was MEDIUM). When this occurs the most restrictive report will be used to determine the braking intensity.

Note: This is advisory information only and does not include all possible variations; pilots must use actual conditions to determine the suitability for each runway.

Braking Action Report PIREPs		Associated Runway Surface Condition
Term	Definition	
Dry		• Bare and dry
Good	Braking deceleration is normal for the wheel braking effort applied. Directional control is normal.	• Frost • Trace of dry or wet snow • Water/Slush depth less than 1/8"
Good to Medium	Braking deceleration and controllability is between Good and Medium.	• Compacted snow at or below 15°C
Medium	Braking deceleration is noticeably reduced for the wheel braking effort applied. Directional control may be slightly reduced.	• Wet runway with a "slippery when wet" report • Dry or wet snow greater than trace; below -3°C • Compacted snow above -15°C
Medium to Poor	Braking deceleration and controllability is between Medium and Poor. Potential for hydroplaning exists.	• Dry or wet snow greater than trace; at or above -3°C • Water/slush 1/8" or greater
Poor	Braking deceleration is significantly reduced for the wheel braking effort applied. Directional control may be significantly reduced.	• Ice (not melting)
Nil	Braking deceleration is minimal to non-existent for the wheel braking effort applied. Directional control may be uncertain.	• Ice melting

Where a Braking Report uses the term FAIR, it may be used interchangeably with the term MEDIUM. The terms GOOD to MEDIUM and MEDIUM to POOR represent an intermediate level of braking action between the defined terms. It does not refer to a braking action that varies along the length of the runway. When the Runway Condition and Braking Action Report Equivalency Table is used as the ***only*** source to determine braking action, the ***more restrictive*** value of the intermediate level shall be used for the ACARS or TLR landing distance calculation (GOOD to MEDIUM shall = MEDIUM and MEDIUM to POOR shall = POOR). If subsequent to the RSC report being taken, a similar type jet aircraft gives a Braking Action Report (GOOD or MEDIUM), that is equal to or greater than the better value of the intermediate level, the better value in the intermediate level may, at the Captain's discretion, be used for the landing distance calculation (GOOD to MEDIUM may = GOOD and MEDIUM to POOR may = MEDIUM).

Source: WestJet, *Flight Operations Manual—Boeing 737NG*

Appendix E – Canadian Runway Friction Index recommended landing distances (no reverse thrust)

Table 1—CRFI Recommended Landing Distances (No Discing/Reverse Thrust)

	Reported Canadian Runway Friction Index (CRFI)													
Landing Distance (Feet) Bare and Dry	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.27	0.25	0.22	0.20	0.18	Landing Field Length (Feet) Bare and Dry	Landing Field Length (Feet) Bare and Dry
Unfactored	Recommended Landing Distances (no Discing/Reverse Thrust)												60% Factor	70% Factor
1 800	3 120	3 200	3 300	3 410	3 540	3 700	3 900	4 040	4 150	4 330	4 470	4 620	3 000	2 571
2 000	3 480	3 580	3 690	3 830	3 980	4 170	4 410	4 570	4 700	4 910	5 070	5 250	3 333	2 857
2 200	3 720	3 830	3 960	4 110	4 280	4 500	4 750	4 940	5 080	5 310	5 490	5 700	3 667	3 143
2 400	4 100	4 230	4 370	4 540	4 740	4 980	5 260	5 470	5 620	5 880	6 080	6 300	4 000	3 429
2 600	4 450	4 590	4 750	4 940	5 160	5 420	5 740	5 960	6 130	6 410	6 630	6 870	4 333	3 714
2 800	4 760	4 910	5 090	5 290	5 530	5 810	6 150	6 390	6 570	6 880	7 110	7 360	4 667	4 000
3 000	5 070	5 240	5 430	5 650	5 910	6 220	6 590	6 860	7 060	7 390	7 640	7 920	5 000	4 286
3 200	5 450	5 630	5 840	6 090	6 370	6 720	7 130	7 420	7 640	8 010	8 290	8 600	5 333	4 571
3 400	5 740	5 940	6 170	6 430	6 740	7 110	7 550	7 870	8 100	8 500	8 800	9 130	5 667	4 857
3 600	6 050	6 260	6 500	6 780	7 120	7 510	7 990	8 330	8 580	9 000	9 320	9 680	6 000	5 143
3 800	6 340	6 570	6 830	7 130	7 480	7 900	8 410	8 770	9 040	9 490	9 840	10 220	6 333	5 429
4 000	6 550	6 780	7 050	7 370	7 730	8 170	8 700	9 080	9 360	9 830	10 180	10 580	6 667	5 714

Source: Transport Canada, TP14371, *Transport Canada Aeronautical Information Manual*, 02 April 2015, p. 421, with TSB annotations

Appendix F – Abbreviations and acronyms

A/T	autothrust
AC	Advisory Circular
ACARS	aircraft communications addresing and reporting system
AGL	above ground level
ARFF	aircraft rescue and fire-fighting
ASTM	American Society for Testing and Materials
ATIS	automatic terminal information service
ATPL	airline transport pilot licence
ATSB	Australian Transport Safety Bureau
BAR	braking action report
CARs	*Canadian Aviation Regulations*
CASA	Civil Aviation Safety Alert
CRFI	Canadian Runway Friction Index
CVR	cockpit voice recorder
CYEG	Edmonton International Airport, Alberta
CYUL	Montréal/Pierre Elliott Trudeau International Airport, Quebec
CYVR	Vancouver International Airport, British Columbia
CYYC	Calgary International Airport, Alberta
CYYZ	Toronto/Lester B. Pearson International Airport, Ontario
DFDR	digital flight data recorder
FAA	U.S. Federal Aviation Administration
FDR	flight data recorder
FOM	*Flight Operations Manual*
FSF	Flight Safety Foundation
FTF	Friction Task Force

GRF	global reporting format
ICAO	International Civil Aviation Organization
ILS	instrument landing system
M	magnetic (degrees)
MANOBS	*Manual of Surface Weather Observations*
MCP	mode control panel
METAR	aerodrome routine meteorological report
nm	nautical miles
NOTAM	notice to airmen
NPA	Notice of Proposed Amendment
PF	pilot flying
PFA	pulverized fuel ash
PFC	porous friction course
PNF	pilot not flying
PPC	pilot proficiency check
PQC	pavement quality concrete
psig	pounds per square inch gauge
QRH	Quick Reference Handbook
RA	risk assessment
RCAM	runway condition assessment matrix
RESA	runway end safety area
SA	situational awareness
SAFO	Safety Alert for Operators
SARSYS SFT	Scandinavian Airport and Road Systems surface friction test
sm	statute mile
SMS	safety management system

SOPs	standard operating procedures
SPECI	aerodrome special meteorological report
T	true (degrees)
TALPA	takeoff and landing performance assessment
TC	Transport Canada
TC AIM	Transport Canada *Aeronautical Information Manual*
TEM	threat and error management
TLR	takeoff and landing report
TP312	*Aerodrome Standards and Recommended Practices*
V_{REF}	landing reference speed