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

AVIATION INVESTIGATION REPORT
A11H0003

RUNWAY EXCURSION

TRANS STATES AIRLINES LLC
EMBRAER EMB-145LR, N840HK
OTTAWA/MACDONALD-CARTIER INTERNATIONAL AIRPORT, OTTAWA, ONTARIO
04 SEPTEMBER 2011

Canada

The Transportation Safety Board of Canada (TSB) investigated this occurrence for the purpose of advancing transportation safety. It is not the function of the Board to assign fault or determine civil or criminal liability.

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Summary

At 1529 Eastern Daylight Time, an Embraer EMB-145LR (registration N840HK, serial number 145341) operated by Trans States Airlines LLC as United Express Flight 3363 from Chicago O'Hare International Airport, Chicago, United States, landed on Runway 32 at the Ottawa/Macdonald-Cartier International Airport during heavy rain. Shortly after touching down, the aircraft skidded off the left side of the runway. There were no injuries to the 44 passengers and 3 crew members aboard. All of the occupants evacuated safely, using the main cabin door. During the runway excursion, both sides of the main landing gear collapsed, damaging the wing and causing a fuel leak. There was no fire, and the emergency locator transmitter did not activate.

Ce rapport est également disponible en français.

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1.0 Factual information

1.1 History of the flight

At 1406, [1] United Express Flight 3363 (LOF3363), operated by Trans States Airlines LLC (TSA), departed Chicago O'Hare International Airport, Chicago, United States. Before commencing the descent into Ottawa/Macdonald-Cartier International Airport (CYOW), Ontario, the flight crew obtained the automatic terminal information service (ATIS) information Yankee for CYOW issued at 1411. Based on the reported wind speed and direction, the flight crew calculated the approach speed [2] (V_{APP}) to be 133 knots indicated airspeed (KIAS).

Runway 25 was identified in ATIS information Yankee as the active runway. However, as a result of a previous overrun on Runway 07/25 in August 2010, TSA prohibited [3] its flight crews from landing or taking off on Runway 07/25 when the surface is reported as damp or wet. Because rain showers were forecast for CYOW and Runway 32 was the longest runway, the flight crew decided at 1506 to carry out an instrument landing system (ILS) approach to Runway 32.

At 1524, the CYOW terminal air traffic controller (ATC) advised the flight crew that it was starting to rain heavily at CYOW. About 2 minutes later, the aircraft intercepted the glideslope for the ILS to Runway 32. Final descent was initiated, the landing gear was extended, and the flaps were selected to 22°. Upon contacting the CYOW tower controller, the flight crew was advised that moderate rain had just started at the airport and the wind was reported as 310° magnetic (M) at 10 knots.

The aircraft crossed the GREELY (YYR) final approach fix at 4.3 nautical miles (nm), slightly above the glideslope at 174 KIAS. About 1528, the aircraft passed through 1000 feet above ground level (agl) at 155 knots. Moments later, the flaps were selected to 45°. The airspeed at the time was approximately 145 KIAS. The tower controller advised the flight crew that the wind had changed to 320°M at 13 knots gusting to 20 knots. To compensate for the increased wind speed, the flight crew increased the V_{APP} to 140 KIAS.

About 1 minute later, at 1529, the aircraft crossed the threshold of Runway 32 at about 45 feet agl, at an airspeed of 139 KIAS. As the aircraft crossed the runway threshold, the intensity of the rain increased, so the flight crew selected the windshield wipers to high. When the aircraft was about 20 feet agl, engine power was reduced and a flare was commenced.

Just before touchdown, the aircraft encountered a downpour sufficient to obscure the crew's view of the runway. Perceiving a sudden increase in descent rate, at approximately 5 feet agl,

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

2 V_{APP} was calculated using the reference speed (V_{REF}) + ½ the headwind component + the full gust, in accordance with the *Trans States Airlines EMB Standard Operating Procedures Manual*, Revision 43, section 4.1: Approach Speed Calculation.

3 See *1.18.3 Landing on Wet Runways* for additional information.

the captain applied maximum thrust [4] on both engines. The master caution light illuminated, and a voice warning stated that the flaps were not in a take-off configuration. [5] Maximum thrust was maintained for 7 seconds.

The aircraft touched down smoothly 2700 feet beyond the threshold at 119 KIAS; the airspeed was increasing, and the aircraft became airborne again. The aircraft touched down a second time at 3037 feet beyond the threshold, with the airspeed increasing through 125 KIAS. Airspeed on touchdown peaked at 128 KIAS as the nosewheel was lowered to the ground, and then the thrust levers were retarded to flight idle. The outboard spoilers almost immediately deployed, and about 8 seconds later, the inboard spoilers deployed. The aircraft was about 20 feet right of the runway centreline when it touched down for the second time.

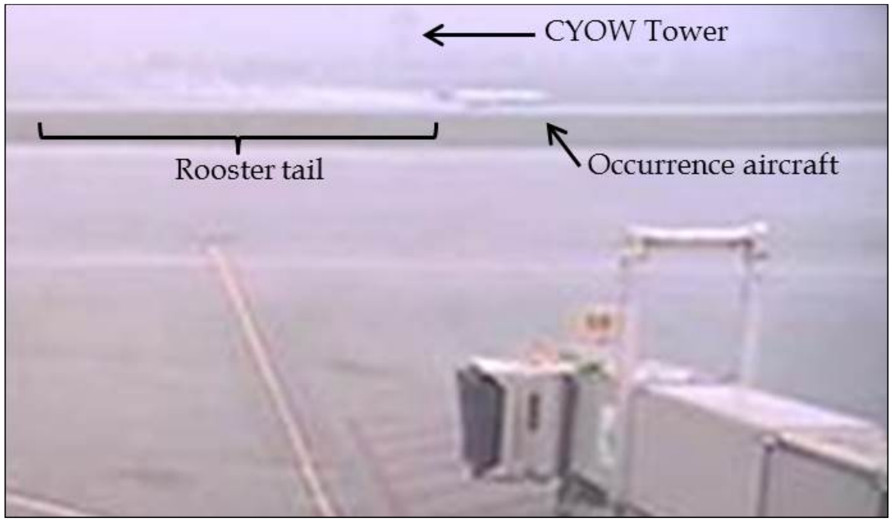

Photo 1. Surveillance video image of occurrence aircraft landing

Once the nosewheel was on the ground, the captain applied maximum brakes. The flight crew almost immediately noted that the aircraft began skidding. The captain then requested the first officer to apply maximum brakes as well. The aircraft continued to skid, and no significant brake pressure was recorded until about 14 seconds after the outboard spoilers deployed, when brake pressure suddenly increased to its maximum. During this time, the captain attempted to steer the aircraft back to the runway centreline.

As the aircraft skidded down the runway, it began to yaw to the left. Full right rudder was applied, but was ineffective in correcting the left yaw.

Sufficient water was present on the runway surface to cause the aircraft tires to send a spray of water, commonly known as a rooster tail, to a height of over 22 feet, trailing over 300 feet behind the aircraft (Photo 1).

At some point during the landing roll, the captain partially applied the emergency/parking brake (EPB), and when no braking action was felt, the EPB was engaged further. With no perceivable deceleration being felt, the EPB was stowed.

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4 The speed of the low-pressure rotor in the engine (N_1) increased to 88%.

5 This warning was due to the application of maximum thrust with the flaps selected at 45°.

The aircraft continued to skid down the runway until about 7500 feet from the threshold, at which point it started skidding sideways along the runway.

At 1530, the nosewheel exited the paved surface, 8120 feet from the threshold, at approximately 53 knots, on a heading of 271°M. The aircraft came to rest on a heading of 211°M, just off the left side of the paved surface. After coming to a stop, the flight crew carried out the emergency shutdown procedure as per the company *Quick Reference Handbook* (QRH), and consulted with the flight attendant on the status of everyone in the passenger cabin. The flight crew determined that there was no immediate threat and decided to hold the passengers on board.

When the aircraft exited the runway surface, the tower activated the crash alarm. The CYOW airport rescue and firefighting (ARFF) services responded, and were on scene approximately 3 minutes after the activation of the crash alarm. Once ARFF personnel had conducted a thorough exterior check of the aircraft, they informed the flight crew that there was a fuel leak.

The captain then called for an immediate evacuation of the aircraft. The passengers evacuated through the main cabin door, and moved to the runway as directed by the flight crew and ARFF personnel. The evacuation was initiated approximately 12 minutes after the aircraft came to a final stop.

After the evacuation was complete, the firefighters sprayed foam around the aircraft where the fuel had leaked.

1.2 Injuries to persons

Table 1. Injuries to persons

	Crew	Passengers	Others	Total
Fatal	–	–	–	–
Serious	–	–	–	–
Minor/none	3	44	–	47
Total	3	44	–	47

1.3 Damage to aircraft

The aircraft was substantially damaged when the main landing gear collapsed. The lower surface of the left wing was damaged, causing a fuel leak (Photo 2).

Photo 2. Occurrence aircraft off Runway 32

1.4 Other damage

ARFF contacted a hazardous material team to assess the fuel spill area. The groundwater drainage system alongside the runway was isolated, inspected, flushed, and drained of all contaminants to prevent a build-up of fuel and fumes in the drainage system.

1.5 Personnel information

Records indicate that the flight crew was certified and qualified for the flight in accordance with existing regulations. The flight crew consisted of a captain, a first officer, and a flight attendant.

The captain was the pilot flying (PF). This flight was the flight crew's fourth of 5 flight segments to be flown that day, and it was the third day of their assigned 6-day pairing.

The captain and the first officer had been employed by TSA for approximately 6½ years and 4 years, respectively. The flight attendant had been employed by TSA for approximately 1½ years.

Table 2. Personnel information

	Captain	First officer
Pilot licence	Airline Transport Pilot (ATP)	ATP
Last medical examination	25 March 2011	18 March 2011
Total flying hours	8000	4800
Hours on type	4000	3800
Hours, last 6 months	324	412
Hours on type, last 30 days	48	58
Hours on duty before occurrence	8	8
Days off duty before start of pairing	3	7

1.6 *Aircraft information*

1.6.1 *General*

Records indicate that the aircraft was certified, equipped, and maintained in accordance with existing regulations and approved procedures, and that there were no recorded deficiencies before the occurrence flight. Nothing was found to indicate that there was any airframe failure or system malfunction before or during the flight.

The investigation determined that the aircraft's weight and centre of gravity were within the prescribed limits.

The aircraft was equipped with a central maintenance computer (CMC), which stores maintenance-related messages and engine-related data. Although the download process was successfully completed, there were no data present in the memory unit. It could not be determined why there were no data recorded.

Table 3. Aircraft information

Manufacturer	Embraer S.A.
Type and model	EMB-145LR
Year of manufacture	2000
Serial no.	145341
Certificate of airworthiness	Issued 18 July 2004
Total airframe time/cycles	25 655 hours/23 335 cycles
Engine type (no.)	Rolls Royce AE3007A1 (2)
Maximum allowable take-off weight	48 501 pounds

1.6.2 Thrust reversers

Thrust reversers have been shown to play a significant role in reducing accelerate–stop distances on wet and contaminated runways, and provide a stopping force that is not dependent on runway friction. When landing on a runway with poor braking action, the effect of reverse thrust can make a dramatic difference and has positively contributed to the transport category airplane fleet's accelerate–stop safety record. [6,7]

A thrust reverser offers a number of operational advantages. Some of the advantages of using a thrust reverser are that it: [8]

- shortens landing runs,
- results in less wear and tear on aircraft brakes,
- permits safer landing in adverse weather conditions, and
- provides additional safety and control margins during rejected take-offs.

At the time of the accident, 14 of the 26 EMB-145s operated by TSA were equipped with thrust reversers. The occurrence aircraft was not equipped with thrust reversers.

1.6.3 Nosewheel steering system

The nosewheel steering system is electrically controlled and hydraulically actuated. The flight crew has the ability to command the nosewheel to turn 5° in either direction by pressing on the rudder pedals. The 5° deflection is normally used for making small steering corrections on the ground, typically during higher speeds, while taking off or landing. The system also has the ability to turn the nosewheel up to 76° in either direction using a steering handle and the rudder pedals for slow speed manoeuvring.

1.6.4 EMB-145 wing spoiler system

The EMB-145 is equipped with inboard and outboard spoilers. During a normal landing, once the weight is on the aircraft main wheels and both engine thrust lever angles are set below 30°or both engines' high-pressure rotor speeds (N_2) are below 56%, all 4 spoilers will automatically deploy if the main landing gear wheel speeds are above 25 knots. The main landing gear wheels are numbered from 1 to 4, starting with the left outboard wheel. Inboard spoiler operation is controlled by the no. 1 and no. 3 wheel speeds. When one of these 2 wheels reaches a speed of 25 knots, both inboard spoilers will deploy. The no. 2 and no. 4 wheel speeds control the

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6 Federal Aviation Administration, Code of Federal Regulations, Title 14, Part 25 (Proposed Special Condition, issued on 7 November 1996): EMBRAER Model EMB-145 Airplane, Thrust reverser systems

7 EUROCONTROL, *European Action Plan for the Prevention of Runway Excursions*, Edition 1.0 (January 2013), Appendix E: Aircraft Operators

8 H. Yao, J. Butterfield, S. Raghunathan, R. Cooper, and E. Benard, *The Aerodynamic Performance of a Thrust Reverser Cascade* (Queen's University: Belfast, UK 2004)

outboard spoilers. Once deployed, if any one of these criteria is no longer met, then the spoilers will retract.

During the occurrence aircraft's landing on Runway 32, the outboard spoilers extended almost immediately after touchdown, and remained extended for about 20 seconds. The inboard spoilers did not extend until 8 seconds after the outboard spoilers, and remained extended for only about 4 seconds.

1.6.5 EMB-145 anti-skid brake system

The EMB-145 is equipped with the Hydro-Aire Mark V main brake system, which is a fully digital, brake-by-wire system, with an anti-skid function. The brake system includes a brake control unit (BCU), inboard and outboard brake control valves (BCVs), pedal transducers, brake assemblies, pressure transducers, and wheel speed transducers. Application of the brake pedals by either pilot sends a signal to the BCU, which then sends a signal to the BCVs. The BCVs supply hydraulic fluid to the brake assemblies in proportion to the amount of brake pedal pressure applied. Hydraulic systems 1 and 2 supply the main brake system with a pressure of 3000 pounds per square inch (psi).

Brake control through the brake pedals is tiered. The first portion of pedal movement gives very little brake authority, the second portion gives moderate authority, and the third portion gives the most authority. Pressure feedback signals from the pressure transducers are used to ensure close correlation between commanded and resulting brake pressure. If both pilots activate the brakes at the same time, the brake pressure is proportional to the pedals with the most deflection.

For wheel speeds below 10 knots, the anti-skid function is deactivated, allowing the pilot to lock and pivot on a wheel. For wheel speeds above 10 knots, anti-skid protection is performed on an individual wheel basis. The brake system reads individual wheel speeds and compares these to a calculated reference value (the optimum velocity for the wheel). When the difference between these 2 values is extremely large, brake pressure is released to prevent a skid.

For wheel speeds above 30 knots, in addition to anti-skid protection, the braking system activates the locked wheel protection. Locked wheel protection compares the wheel speed of a wheel with its partner wheel. Inboard wheels are partnered together, and outboard wheels are partnered together. If the slower wheel speed is less than or equal to 30% of the faster wheel speed, the BCU sends a corrective signal (full brake pressure relief) to the associated BCV. The control valve removes all brake pressure to the associated wheel, allowing the wheel speed to recover. The 30% tolerance between the wheel speeds is provided to permit an amount of differential braking for steering purposes. When the speed of the fast wheel of a partnered pair is less than 30 knots, the locked wheel protection is deactivated for that pair of wheels.

The brake system includes touchdown protection that inhibits brake actuation before the main wheels have spun up during landing. This feature prevents brake application through the brake pedals before wheel spin-up when the aircraft is on the ground for less than or equal to 3 seconds, or when the wheel speed is less than or equal to 50 knots, whichever occurs first. The pressure at the brake will be the lowest pressure resulting from comparing pedal position, anti-skid protection, touchdown protection, and locked wheel protection. In this occurrence, about 1 second after touchdown, the pressure at the no. 1 and no. 3 brakes increased to about 400 psi (Appendix B). [9] Over the next 12 seconds, the no. 1 brake pressure fluctuated between 0 and about 300 psi, and then began fluctuating between 0 and 3000 psi until the aircraft departed the runway. During this same period of time, the no. 3 brake pressure fluctuated between 0 and about 200 psi, and then stayed at 100 psi for about 5 seconds. The pressure then increased rapidly to maximum system pressure, and stayed at or slightly below maximum pressure until the aircraft departed the runway.

1.6.6 EMB-145 emergency/parking brake

The EPB system is normally used to keep the main wheels from turning when the aircraft is parked. The EPB can also be used in an emergency situation when the normal brake system has failed. The system is mechanically controlled independently of the main brake system by the use of a control handle located on the left side of the centre control pedestal. When the handle is pulled up, pressure is applied to all 4 main landing gear brakes in proportion to the amount that the handle is displaced. The handle can also be locked in the actuated position for the purpose of parking. A shuttle valve mounted on the brake assembly isolates the normal brake lines from the EPB brake lines. The EPB system does not have anti-skid braking system protection, nor is its pressure recorded on the flight data recorder (FDR). Hydraulic system no. 2 supplies the EPB with 3000 psi.

When the brakes are applied through the pedals and the EPB is pulled on, the pressure applied at the brake will be the greater of the main brake system or the EPB system. Due to the design of the main brake system, the FDR-recorded brake pressure will be that of the main brake system, even if the pressure at the brake is EPB pressure.

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[9] The flight data recorder (FDR) recorded only the no. 1 and no. 3 brake pressures.

1.6.7 Main wheel tires

The aircraft is equipped with 4 main landing gear tires. Tread wear was not considered a factor in this occurrence. The manufacturer requires the main tires to be inflated to 160 ±4 psi. Twenty-four hours after the accident, the Transportation Safety Board (TSB) recorded the pressure for the no. 1 tire at 160 psi, the no. 2 tire at 150 psi, and the no. 3 and no. 4 tires at 145 psi. Inflation pressure in tire nos. 2, 3, and 4 did not meet the manufacturer's specification.

Photo 3. Damage seen on main landing gear tire no. 2 was evident on all 4 main landing gear tires.

Signs of reverted rubber hydroplaning (section 1.18.1) were observed on all 4 main tires (Photo 3). Skid marks running approximately 55° to the aircraft axis were visible atop the reverted rubber regions. Steam-cleaned marks from all 4 main wheel tires were observed in various locations along the runway (Photo 4).

Photo 4. White steam-cleaned marks

1.7 *Meteorological information*

1.7.1 *General*

An aerodrome forecast (TAF) for CYOW, valid from 1400 on 04 September 2011 until 1400 on 05 September 2011, was issued at 1338 on 04 September 2011. The TAF called for the following: wind 240° true (T) at 12 knots, visibility 6 statute miles (sm), scattered clouds based at 3000 feet agl, overcast ceiling at 10 000 feet agl, with a temporary condition between 1400 and 1800 of visibility 4 sm in light rain showers and mist, and overcast ceiling of 3000 feet agl. In addition, there was a 30% probability between 1400 and 1800 of wind variable at 20 knots gusting to 35 knots, with visibility 2 sm in thunderstorms and heavy rain, broken ceiling at 600 feet agl, and an overcast ceiling at 2000 feet agl with cumulonimbus cloud.

At the time of the approach and landing, the 1500 ATIS (information Zulu) recorded wind 250°M at 9 knots, visibility 15 sm, a broken cloud layer based at 4400 feet agl and an overcast cloud layer based at 12 000 feet agl, temperature 26°C, dewpoint 19°C, and altimeter 29.70 inches of mercury.

At 1527, a special meteorological report (SPECI) was issued at CYOW, reporting wind 300°T at 10 knots, visibility ½ sm in heavy rain showers, ceiling overcast at 3000 feet agl with extensive towering cumulus (TCU) covering 8 oktas of the sky, [10] and temperature 23°C. This SPECI was not passed to the flight crew due to the time normally required to make an observation and enter the data. The control tower did not receive the SPECI until after the aircraft had landed.

There were no pilot reports (PIREPs) in effect at the time of the accident.

1.7.2 Accident weather observation

At 1535, about 5 minutes after the accident, another SPECI was issued that reported wind 270°T at 13 knots gusting to 25 knots, visibility 1½ sm in heavy rain showers, ceiling overcast 3000 feet agl with TCU associated (8 oktas), and temperature 22° C.

The City of Ottawa Stormwater Unit maintains an automatic rainwater measuring system, part of which is located near the CYOW control tower adjacent to Runway 14/32. The system consists of a tipping-bucket rain gauge that sends electronic impulses to a computerized recording system. This information is not provided to the CYOW weather office. The total accumulated rainfall from 1520 until the aircraft landed at 1529 was approximately 10.2 mm. During this period, a review of the 5-minute cumulative data reveals rainfall intensity of 9.6 mm per hour over the first 5 minutes of rainfall, increasing to approximately 67.2 mm per hour over the next 5 minutes, and finally 45.6 mm per hour at the time LOF3363 landed. The TSB calculated the average depth of water that was on the runway from the time the aircraft touched down until it exited the side to be 4–6 mm (Photo 5 and Photo 6).

Based on section 3.9.5 of Environment Canada's *Manual of Surface Weather Observations* (EC MANOBS), [11] the rainfall rate at the time of the occurrence would equate to heavy rainfall (Appendix D).

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10 Cloud layer amounts are reported in eighths (oktas) of sky coverage.

11 Environment Canada, *Manual of Surface Weather Observations,* (EC MANOBS), section 3.9.5 – Intensity by rate of fall criteria (January 2011); current edition available at http://www.ec.gc.ca/Publications/default.asp?lang=En&xml=1F0AEEAB-EEF5-4382-BE97-E102F8615061 (last accessed on 14 February 2014)

Photo 5. View from the departure end of Runway 32, 10 minutes before landing

Photo 6. View from the departure end of Runway 32 as the aircraft exits the runway

1.8 Aids to navigation

The ILS for Runway 32 was operational, and there were no reported outages of navigation aids at the time of approach and landing.

1.9 Communications

Communications between LOF3363 and ATC during the flight period were normal. After the aircraft came to a stop, the flight crew carried out all items in the QRH, then shut down the electrical power. Approximately 4 minutes later, the crew turned the power back on to establish communications with ARFF personnel. After being advised of the fuel leak, the crew immediately shut down the electrical power.

1.10 Aerodrome information

1.10.1 General

CYOW has 3 runways: 07/25, 14/32 and 04/22. Runway 14/32 is 10 005 feet long by 200 feet wide, with a 150-foot long by 200-foot wide asphalt blast pad at each end. There is no runway end safety area (RESA) and the runway is not grooved. Currently, there are no grooved runways at any major civil airport in Canada except for Runway 07/25 at CYOW.

1.10.2 Runway maintenance

Runway friction testing is done at CYOW a minimum of 3 times per year during the non-winter months (April to November). The last runway friction test was performed 8 days before the accident. The average coefficient of friction for the entire length of Runway 14/32 was better than the published Transport Canada (TC) minimum friction values. The friction levels indicated that no maintenance action needed to be taken or needed to be programmed for Runway 14/32. The average coefficient of friction values also met the minimum values published by the Federal Aviation Administration (FAA) and the International Civil Aviation Organization (ICAO) (Table 4).

Table 4. Threshold criteria for corrective action to restore runway friction, by organization

Threshold criteria	Minimum friction values		
	TC [12]	FAA [13]	ICAO [14]
Runway average − corrective action programmed	0.60	0.60	0.60
Runway average − corrective action required	0.50	0.50	0.50
Runway segment [15]			
Lowest runway segment average − corrective action programmed	0.40	0.60	0.60
Lowest runway segment average − corrective action required	0.30	0.50	0.50

1.10.3 Grooving of runways

Cutting or forming grooves in existing or new runways is a proven and effective technique for improving drainage, minimizing skids and drift, improving braking, and reducing the risk of hydroplaning (Appendix C).

Annex 6 of ICAO defines a grooved or porous friction course (PFC) [16] runway as "a paved runway that has been prepared with lateral grooving or a porous friction course surface to improve braking characteristics when wet." [17] Transport Canada's *Aerodromes Standards and Recommended Practices* (TP312E) states that "the surface of a paved runway shall be so constructed as to provide good friction characteristics when the runway is wet." [18]

In 1997, the FAA published Advisory Circular (AC) 150/5320-12C: Measurement, Construction, and Maintenance of Skid-resistant Airport Pavement Surfaces, which stated the following in support of pavement grooving: [19]

> Pavement grooving was the first major step in achieving safer pavement surfaces for aircraft operations in wet weather conditions … a high level of friction could

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12 Transport Canada, *Aerodromes Standards and Recommended Practices* (TP312E) 4th edition (1993, revised 03/2005), sections 9.4.2.4 and 9.4.2.5; and Transport Canada Aerodrome Safety Circular (ASC) 2004-024, Appendix A, Table 1

13 Federal Aviation Administration, Advisory Circular (AC) 150/5320-12C: Measurement, Construction, and Maintenance of Skid-Resistant Airport Pavement Surfaces (1997), Table 3.2

14 International Civil Aviation Organization, *Airport Services Manual*, Part 2, Chapter 3, Table 3-1

15 Runway segment measurements by organization are as follows: TC = 100 m, FAA = 152 m, and ICAO = ~100 m. The FAA also takes into account the adjacent 152 m friction values to determine action.

16 The Eurocontrol SKYbrary article *Runway Surface Friction* describes PFC as "an alternative to grooving as a means of facilitating surface water dispersal…" which "…allows water to pass vertically through the surface layer and then move horizontally clear of the runway…"

17 International Civil Aviation Organization, Annex 6, Part 1, Attachment C-2

18 Transport Canada, *Aerodromes Standards and Recommended Practices* (TP312E) 4th edition (1993, revised 03/2005), section 3.1.4.2

19 Federal Aviation Administration, Advisory Circular (AC) 150/5320-12C: Measurement, Construction, and Maintenance of Skid-resistant Airport Pavement Surfaces (1997)

> be achieved on wet pavement by forming or cutting closely spaced transverse grooves on the runway surface, which would allow rain water to escape from beneath tires of landing aircraft.
>
> Grooving of all runways serving or expected to serve turbojet aircraft, is considered high priority safety work and should be accomplished during initial construction. Such existing runways without grooving should be programmed as soon as practicable.

On 20 November 2012, TC issued AC 300-008: Runway Grooving. The purpose of this AC is to provide information and guidance to airport operators regarding the grooving of runways. AC 300-008 states in part: [20]

> Runway grooving consists of providing parallel transverse channels (grooves) in the pavement surface. Grooving improves the macro-texture of the pavement surface, reduces water film thicknesses during rainfall and provides an escape channel for water that may become trapped between the pavement surface and an aircraft tire. These effects reduce the potential for aircraft hydroplaning under wet conditions. Grooving may also improve aircraft braking performance on a wet runway as compared to a wet non-grooved runway.

There is currently no regulation requiring grooved runways at Canadian airports. In Canada, runway grooving has been used to address site-specific issues (such as to promote drainage on runways with low or problematic transverse slopes) that could not be cost-effectively corrected by other means.

1.11 Flight recorders

The occurrence aircraft was equipped with a Honeywell solid-state cockpit voice recorder (CVR) (model no. 980-6022-001, serial no. [S/N] 1319) and a Honeywell solid-state FDR (model no. 980-4700-042, S/N SSFDR-10813). The CVR and FDR were removed from the aircraft and forwarded to the TSB Laboratory for download and analysis. The CVR provided 2 hours of recordings. Approximately 26.4 hours of flight data was recorded on the FDR, including the occurrence flight and 18 previous flights.

The FDR has the capability to record the speed of all 4 main wheels, the brake pressure at all 4 brakes, and the brake pedal deflection at both the pilot's and co-pilot's positions. The extent to which parameters are recorded is dependent on which BCU is installed on the aircraft. Based on the BCU installed on the occurrence aircraft, only the no. 1 and no. 3 brake pressures were recorded. With the absence of recorded wheel speed input, brake pedal positions, and brake pressure for the no. 2 and no. 4 brakes, the investigation could not determine when these wheels were in a skid.

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20 Transport Canada, Advisory Circular (AC) 300-008: Runway Grooving (Issue 01: 20 November 2012); Issue 02 (08 April 2013) available at http://www.tc.gc.ca/eng/civilaviation/opssvs/managementservices-referencecentre-acs-300-300-008-1724.htm (last accessed on 12 February 2014)

1.12 Wreckage and impact information

Due to the orientation of the aircraft when it slid off the left side of the runway, the left main landing gear collapsed outward against the bottom side of the left wing, and the right main landing gear collapsed inward into the landing gear bay. The aircraft came to rest with the flaps selected to 45°, the left wing on top of the displaced left main landing gear, and the right wing contacting the ground.

All 3 landing gear assemblies, as well as various hydraulic, electrical and flight control systems, sustained damage. The right main landing gear bay, right wing leading and trailing edges, right inboard and outboard flaps and flap actuators, and the wing-to-fuselage fairings sustained damage. The lower surface of the left wing was penetrated, allowing fuel to be released.

1.13 Medical and pathological information

There was no indication that incapacitation or physiological factors affected the crew's performance. The investigation determined that fatigue was not a factor in this occurrence.

1.14 Fire

There was no fire.

1.15 Survival aspects

TSA's standard operating procedures (SOPs) provide the following instructions: [21]

> An Emergency Evacuation could be required at any phase of ground operations; during Taxi, after a Rejected Takeoff or after Landing. All variables should be considered when determining the need for evacuation, i.e.; the presence or lack of fire and/or smoke, fuel spillage, structural damage, the door style (airstairs or jetway), known passenger disabilities, the outside environment, the immediate availability or lack of CFR, and any other factors you deem relevant. Then a sound decision should be made, with the bottom line: are the passengers and crew safer INSIDE or OUTSIDE the aircraft. […]
>
> **Precautionary Evacuation**
> Under some circumstances, such as a bomb threat, the captain may elect to deplane the passengers in a precautionary evacuation. In this case, he/she may want to move the passengers off as expeditiously as possible with the least amount of risk. The main cabin door shall be the primary exit to be used. Deplaning in this circumstance, passengers may also be asked to leave carry-ons on board so as not to slow down the precautionary evacuation.

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21 Trans States Airlines, *EMB-145 Standard Operating Procedures Manual (SOP)*, Section 1, part 7.6: Emergency Evacuation, page 74

For an evacuation to occur, the captain must make the decision to evacuate based on information from aircraft systems, from the flight crew members, and from external sources, such as air traffic controllers or ARFF personnel. A decision is made as to whether there is a greater risk of injury if everyone remains on board the aircraft or if they are evacuated. If the captain chooses an evacuation, the captain must then determine whether the passengers and flight crew should use all viable exits, or whether the flight crew should lead passengers away from the aircraft using conventional stairs or jetways. In this accident, it was decided in consultation with ARFF, after the captain was made aware of a fuel leak, that the aircraft would be evacuated using the main stairs. All passengers and crew evacuated into the heavy rain.

When all of the passengers were off the aircraft, a head count was performed by the flight crew. Ponchos were eventually handed out to the passengers by ARFF personnel, as there was no other alternate shelter available to protect passengers from the elements. A request was made by the CYOW Security Operations Centre (SOC) for bus transportation approximately 6 minutes after the aircraft was reported to be off the runway. The transit bus arrived on the scene approximately 19 minutes after the request. The passengers were then transported to the main terminal building where they cleared customs.

1.16 Tests and research

Not applicable.

1.17 Organizational and management information

1.17.1 Trans States Airlines LLC

TSA was founded as Resort Air in 1982, and its name changed to Trans States Airlines in 1989. The corporate headquarters is located in St. Louis, Missouri. Originally operating various types of turboprop aircraft, TSA started operating the Embraer EMB-145 in 1998. At the time of the accident, TSA operated a fleet of 26 aircraft. TSA is a *Federal Aviation Regulations* (FARs) Part 121 regional feeder airline, conducting flights for United Airlines and US Airways to 39 destinations.

1.17.2 Trans States Airlines safety program

TSA's Safety Program and Internal Evaluation Program are described in the company's *Safety and Regulatory Compliance Manual* (SAFE). This manual and the associated programs were established by the director of safety to assure the safety of operations and keep senior management fully informed of the safety status of the operations.

The director of safety was responsible for the implementation and ongoing maintenance of the programs and procedures contained within the safety program. TSA's Safety/Regulatory Compliance Department provided an independent surveillance of the daily airline operations, evaluated compliance with the FARs and with good safety practices, analyzed and summarized the resulting data, and reported on its findings. Individual departmental managers were responsible for any corrective action. This department also evaluated hazard reports initiated by company personnel, and forwarded these concerns to the appropriate departmental manager for corrective action.

Trans States Airlines did not have a safety management system (SMS), nor was it required to have one by regulation; its safety program did include some elements of a typical SMS.

1.17.3 Trans States Airlines training

Captains receive training and are tested every 6 months to ensure that they are current with regard to the operation of the aircraft. First officers receive training and are tested on an annual basis. As part of TSA's training curriculum, [22] aircraft performance on wet and contaminated runways is addressed in the general aircraft performance modules of both initial and recurrent training. Also discussed in the training curriculum is hydroplaning as it pertains to performance considerations when taking off and landing on contaminated runways. Night landings on contaminated runways are listed as an element of TSA's initial simulator training program. One PowerPoint slide is presented to students in class describing the differential braking technique [23] to be used while the anti-skid brake system is operating. No training is carried out in the simulator using the described differential braking technique.

Training and line checks in relation to operations on grooved and non-grooved runways, or the information that few Canadian airports have grooved runways, is not specifically addressed. The accident flight was one of the last flights to CYOW for the company, and TSA does not currently operate any scheduled flights into Canada.

1.18 Additional information

1.18.1 Hydroplaning

Hydroplaning occurs when a layer of water builds up between the aircraft tires and the runway surface, leading to a loss of traction and preventing the aircraft from responding to control inputs such as steering or braking. Landing at higher than recommended touchdown speeds will expose the aircraft to a greater potential for hydroplaning. Once hydroplaning starts, it can continue well below the minimum, initial hydroplaning speed. Non-rotating, unbraked wheels, such as when the aircraft is touching down, will not spin up on a flooded runway surface due to dynamic hydroplaning until the aircraft has decreased its ground speed to a value equal to or below the critical speed. [24] Dynamic hydroplaning [25] is described as follows:

> Dynamic hydroplaning is caused by the buildup of hydrodynamic pressure at the tire-pavement contact area. The pressure creates an upward force that

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22 Trans States Airlines, *Flight Operations Training Manual* (FOTM) Volume 1, Instructor's Handbook

23 See 1.18.4: Additional Guidance for Aircraft Skid Control on Wet Runways for a description of the differential braking technique.

24 National Aeronautics and Space Administration (NASA), Some Effects of Adverse Weather Conditions on Performance of Airplane Antiskid Braking Systems, Technical Note NASA TN D-8202 (1976)

25 Charles E. Dole, *Flight Theory for Pilots*, 4th edition (Jeppesen Sanderson: 1989), pages 201–203.

> effectively lifts the tire off the surface. When complete separation of the tire and pavement occurs, the condition is called total dynamic hydroplaning, and wheel rotation will stop. …Total dynamic hydroplaning usually does not occur unless a severe rain shower is in progress. There must be a minimum water depth present on the runway to support the tire. The exact depth cannot be predicted since other factors such as runway smoothness and tire tread, influence dynamic hydroplaning. Both smooth runway surface and smooth tread tires will induce hydroplaning with lower water depths. While the exact depth of water required for hydroplaning has not been accurately determined, a conservative estimate for an average runway is that water depths in excess of 0.1 inch [26] (2.54mm) may induce full hydroplaning.

The National Aeronautics and Space Administration (NASA) critical speed (i.e., hydroplaning speed formula) for a rotating tire is equal to 9 times the square root of the tire pressure. If a film of water of 2.54 mm or greater in depth is encountered at the moment of touchdown, when the wheels are not yet rotating, the formula is 7.7 times the square root of the tire pressure. An underinflated tire is more likely to hydroplane at a lower speed than one that is correctly inflated. The TSB calculated the minimum hydroplaning speeds based on the manufacturer's inflation pressure and for tire pressures recorded after the overrun (Table 5).

Table 5. Minimum hydroplaning speeds

Tire pressure (psi)	Minimum hydroplaning speed (knots)
	Rotating tire
160	113.8
150	110.3
145	108.4
	Non-rotating tire (rain at touchdown)
160	97.4
150	94.3
145	92.7

Reverted rubber hydroplaning, which normally follows dynamic hydroplaning, occurs when a locked tire skids along the runway surface, generating sufficient heat to revert (melt) the tire rubber to its original uncured state. Only this type of hydroplaning produces a clear mark on the tire tread in the form of a burn, a patch of reverted rubber.

Hydroplaning is also known to produce steam-cleaned marks on the runway when sufficient heat is generated between the tire and the runway to change the water into steam, producing a steam cleaned effect.

26 For a new tire with a full-tread groove depth on a textured runway surface

The following information describes the limitations of anti-skid brake systems: [27]

> Modern antiskid brake systems are very effective when available friction coefficients are high; however, on flooded runway surfaces, such systems may become ineffective. …An important aspect of the efficient operation of an anti-skid brake system is the availability of adequate friction levels at the tire runway contact. When available friction levels are high, the maximum braking torque applied to the wheel is successfully transmitted to the ground and the anti-skid braking system can modulate the braking pressures near the maximum. However, when the available friction coefficients at the tire runway contact are low, the braking performance of an aircraft is adversely affected in two ways. First, the low friction levels force the brake modulation at very low pressure. Since response characteristics of most braking systems are sluggish at low pressure levels, the braking performance is degraded. Second, low friction levels generate low wheel spinup accelerations which slow down the recovery from a skid and further degrade the braking performance. When brakes are applied during severe hydroplaning there is no reference speed available because the wheels are not spunup; the anti-skid is 'lost' and wheels remain in a locked condition until the pilot releases the brake pedals.

Aircraft landing speeds are typically greater than the hydroplaning speed. NASA has indicated that, when landing on a flooded runway: [28]

> [p]ilots must exercise caution with regard to brake application during the dangerous period when the aircraft ground speed is above the tire hydroplaning speed or anomalous antiskid behavior can be initiated.

TSA's *EMB-145 Standard Operating Procedures Manual* (SOP manual) states the following in its section Landing on Wet or Slippery Runways: [29]

> Always apply a maximum braking effort initially when landing on potentially slick runways in case hydroplaning or skidding becomes a factor. …[I]f you fail to maximize your braking energy early in the rollout, you can't get back the runway that was wasted if you later learn that braking action is poor or nil.

1.18.2 Approach and landing

In the cockpit, the flight crews have access to a landing V-speed [30] chart, as well as to the company's SOPs. Both documents contain the reference speed (V_{REF}) [31] for flaps 22° and for

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27 Satish K. Agrawal, "Braking Performance of Aircraft Tires," *Progress in Aerospace Sciences* (01/1986) Volume 23(2), pages 105–150

28 National Aeronautics and Space Administration (NASA), *Wet Runways*, NASA Technical Memorandum (TM) X-72650 (1975)

29 Trans States Airlines, *EMB-145 Standard Operating Procedures Manual (SOP)*, Section 2: Landing on Wet or Slippery Runways, page 69

30 V-speeds, or velocity-speeds, are standard terms used to define airspeeds or performance speeds that are important to the operation of aircraft.

flaps 45°, at various landing weights. The crew used the V-speed chart and, based on a landing weight of 41 522 pounds with flaps 45°, determined the V_{REF} to be 128 KIAS. On the V-speed chart, there is a note that states, "Wind Correction = ½ headwind + full gust". [32,33] Using this equation and the available wind information (wind 250°M at 9 knots), the crew calculated the V_{APP} (target approach speed) to be 133 KIAS. [34] The crew adjusted the V_{APP} to 140 KIAS at 2 nm final for landing, after being advised by the tower controller that the wind was now 320°M at 13 knots gusting to 20 knots. The TSB calculated the new V_{APP} to be 142 KIAS. [35]

TSA's SOPs provide the following guidance, in part, regarding aircraft configuration for a 2-engine visual approach: "On final, select flaps 45. Slow to V_{APP}… The aircraft will be stabilized and configured at not less than 1000 feet AGL." [36] The pilot monitoring (PM) is required to make callouts of any deviations while on approach below the minimum stabilized approach height. In addition, TSA's *General Operating Manual* (GOM) states: [37]

> Anytime one of the following conditions is exceeded when below the "stabilized approach height" a missed approach will be initiated.
>
> a. airspeed ± 5 knots
>
> b. localizer and/or glide slope deviation exceeds one dot deflection
>
> c. one dot deflection for VOR or RNAV approaches [38]
>
> […]
>
> e. Aircraft not properly configured
>
> f. "GO-AROUND" callout made by either the PF or PM.

The aircraft crossed the GREELY final approach fix slightly above glideslope at approximately 1470 feet agl with the landing gear extended and flaps set at 22°, and at a speed of 174 KIAS, which was 41 KIAS above the V_{APP} speed. At 1000 feet agl, the occurrence aircraft was 3 nm from the runway, the flaps were at 22°, and the speed was 155 KIAS. As the aircraft passed

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31 V_{REF} is the speed at which the aircraft should cross the threshold of the runway at 50 feet above ground level.

32 TSA standard operating procedures define full gust as the difference between the steady-state wind and the maximum gust velocity.

33 The *Trans States Airlines EMB-145 Airplane Operations Manual* (AOM) states that "Wind correction = ½ steady headwind component + gust increment above steady wind" (Embraer S.A., *Trans States Airlines EMB-145 Airplane Operations Manual* [AOM-145/114-04] section 1-02-49, Descent (Revision 38, 2011), page 1).

34 V_{REF} (128) + wind correction (5 knots) = 133 KIAS. The actual wind correction was 2 knots; however, the minimum wind correction as stated on the V-speed chart is 5 knots at all times.

35 V_{REF} (128) + wind correction (7 knots [1/2 headwind] + 7 knots [full gust]) = 142 KIAS

36 Trans States Airlines, *EMB-145 Standard Operating Procedures Manual (SOP)*, Section 1, part 4.5: Two-Engine Visual Approach and Landing, page 37

37 Trans States Airlines, *General Operations Manual* (GOM*) Flight Operations Edition*, Section 3-1, part 8.5: Stabilized Approach, page 120

38 VOR refers to VHF omnidirectional range. RNAV refers to area navigation.

through 800 feet agl, approximately 2.3 nm from the runway, flap 45 was selected, and the speed was reduced to about 140 KIAS. At no time did the PM make any of the standard deviation calls outlined above.

Regarding landings, TSA's SOP manual states the following, in part: [39]

> The key factor for a successful landing is a stabilized approach and proper thrust/flare coordination. At an average weight and V_{REF}, the aircraft is traveling down the runway at over 150 feet per second while in the flare, long flare times can lead to a touchdown outside the touchdown zone (TDZ) and/or subsequent hard braking. […]
>
> When the aircraft is approximately 200 feet above the touchdown zone, the PF should … reduce thrust slightly to cross the runway threshold at 50 feet and V_{REF}. […]
>
> The desired touchdown point is within the first 800 to 1500 feet beyond the landing threshold. Aircraft must touchdown in the first third of the available landing distance, but in no case more than 3 000 feet down the available landing distance. If this is not accomplished, a go-around must be executed.

In 2009, the Flight Safety Foundation (FSF) published a study on approach and landing accidents. In that study, the FSF found that a 5% increase in final approach speed increases the landing distance by 10% if a normal flare and touchdown are conducted, with deceleration of the aircraft on the ground. [40] The study also found that extending the flare and allowing the aircraft to float and bleed off excess airspeed can also increase the landing distance, because the excess speed must be bled off in the transition from the threshold crossing to the touchdown. This practice typically uses 3 times more runway than decelerating on the ground. [41]

1.18.3 Landing on wet runways

In August 2010, after a previous runway overrun on 16 June 2010, TSA started adding a note to every flight release. TSA issued a company-wide *Notice to Airmen* (NOTAM) that stated: "Effective immediately, departures and arrivals at YOW (Ottawa) on Runway 07/25 are prohibited if that surface is reported as damp or wet."

In addition to the above restriction, TSA's GOM provides the following direction to flight crews with regard to operating on a wet runway: "The Captain shall make all takeoffs and landings on non-grooved runways that are Wet or Contaminated regardless of runway length." [42]

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[39] Trans States Airlines, *EMB-145 Standard Operating Procedures Manual (SOP)*, Section 1, part 4.2: Landings, page 33

[40] Flight Safety Foundation, Landing Distances, *Approach and Landing Accident Reduction*, Briefing note 8.3 (2009)

[41] Flight Safety Foundation, Runway Excursions, *Approach and Landing Accident Reduction*, Briefing note 8.1 (2009)

[42] Trans States Airlines, *General Operations Manual* (GOM*) Flight Operations Edition*, Section 3-1, part 2.20: First Officer Restrictions, page 67

The wet runway landing technique recommended by TSA and Embraer is to make the landing firm and not to bounce. This technique will aid in breaking through the film of water on a runway to get positive wheel spin-up for the anti-skid brake system to function properly. TSA's SOPs include information regarding landing on wet or slippery runways. These SOPs state in part: [43]

> Wet runways can cause airplane hydroplaning. This is primarily a factor on runways that are not grooved, which is rare. When hydroplaning occurs, it causes a substantial loss of tire friction and wheel spin-up may not occur.
>
> Always apply a maximum braking effort initially when landing on potentially slick runways in case hydroplaning or skidding becomes a factor. […]
>
> - Anticipate the approach procedures and speeds: a well-planned and executed approach flare and touchdown minimise the landing distance. It is particularly important to slow to ref speed crossing the threshold when the runway conditions are less than optimal. Make it a habit on every approach to slow to the appropriate speed as per the SOP procedures.
> - Landings should be firm, on the runway centreline and in the touchdown zone. Do not prolong the flare in an attempt to get a smooth landing.
>
> […]
>
> - Lower nose wheel immediately to the runway. It will decrease lift and will increase main gear loading.
>
> […]
>
> - Apply brakes early in the rollout with moderate-to-firm pressure, smoothly and symmetrically, and let the anti-skid do its job. Attempting to modulate the brake use while the anti-skid is operating should generally be avoided, unless required to maintain directional control.
> - If no braking is felt, hydroplaning is probably occurring. Do not apply the Emergency/Parking Brake, as it will cause the spoilers to close and cut the anti-skid protection. Maintain runway centreline and keep braking until the airplane decelerates.

The investigation determined that the captain did not employ the wet runway landing technique outlined above. In addition, the investigation also determined that the captain's standard practice was to employ the typical dry runway landing technique when landing on dry or wet runways.

As stated in TSA's SOPs, in the section Touchdown and Rollout: [44]

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43 Trans States Airlines, *EMB-145 Standard Operating Procedures Manual (SOP)*, Section 2: Landing on Wet or Slippery Runways, page 69

44 Ibid., Section 1, part 4.3: Touchdown and Rollout, page 36

> Apply the brakes with no delay after the nose landing gear wheels have touched down. Use a single firm and steady brake application and hold pedal pressure until decelerated to taxi speed. Apply brake pressure as required to control the deceleration rate, up to a maximum comfortable deceleration. If the brakes are released, release them fully then reapply them early enough to allow constant pressure until taxi speed is achieved. Do not pump the brakes.

TSA's GOM contains definitions for different runway conditions. These definitions include: [45]

> **WET**……….a runway that has less than 1/8 inch (3mm) of water covering the area of the runway to be used for takeoff or landing
>
> **CONTAMINATED** …….a runway that has more than 1/8 inch (3mm) of water or slush, compacted snow or ice covering the area of the runway to be used for takeoff or landing

ICAO Annex 6, Part 1, uses the following definitions: [46]

> a) Contaminated runway - A runway is contaminated when more than 25 per cent of the runway surface area (whether in isolated areas or not) within the required length and width being used is covered by:
>
> — water, or slush more than 3 mm (0.125 in) deep.
>
> b) Dry runway - A dry runway is one which is clear of contaminants and visible moisture within the required length and the width being used.
>
> c) Wet runway - A runway that is neither dry nor contaminated.

There does not appear to be a common definition in Canada for the term "wet runway". NAV CANADA's *Air Traffic Control Manual of Operations* (ATC MANOPS) defines wet runway thus: "A wet runway is covered with sufficient moisture to cause it to be reflective, but is not contaminated." [47] The word "contaminated" is not defined. As well, TC does not provide a definition for contaminated.

1.18.4 Additional guidance for aircraft skid control on wet runways

The *Trans States Airlines EMB-145 Airplane Operations Manual* (AOM) states, "If no braking action is felt, hydroplaning is probably occurring. …Maintain runway centerline and keep braking until airplane is decelerated." [48] These instructions are applicable to all landing situations, including a skid or loss of directional control.

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45 Trans States Airlines, *General Operations Manual* (GOM*) Flight Operations Edition*, Section 3-1, part 7.3: Runway Conditions, page 95

46 International Civil Aviation Organization, Annex 6, Part 1

47 NAV CANADA, Air Traffic Control Manual of Operations (ATC MANOPS), ATC DEF-18

48 Embraer S.A., *Trans States Airlines EMB-145 Airplane Operations Manual* (AOM-145/114-04) section 1-02-79, Landing on Wet or Slippery Runways (Revision 38, 2011), page 17

Numerous other aircraft manufacturers' [49] operations manuals specifically address the actions to be taken by pilots when the aircraft has encountered a situation involving a skid and loss of directional control. These instructions include an immediate, momentary release of brake pressure (both brakes) to allow wheel spin-up, so that control can be regained before re-applying the brakes.

Throughout the AOM, there are references to using differential braking to control the aircraft. The TC *Aeroplane Flight Training Manual* provides the following information about differential braking: [50]

> In an aircraft with differential braking systems (a separate brake system for each main wheel), a turn may be assisted by applying a sufficient amount of brake pressure on the same side as the rudder pedal being used to initiate the turn.

The information contained in the AOM section Anti-Skid Protection describes the differential braking technique: [51]

> The anti-skid does not apply pressure on the brakes, but only relieves it. So, to perform a differential braking technique, the pilot should reduce pressure on the side opposite to the turn, instead of applying pressure to the desired side.

The AOM section Locked Wheel Protection states: [52]

> The anti-skid function modulates the brake pressure to a level which prevents the wheels from skidding. If one of the wheels locks, the anti-skid function reduces the brake pressure of the associated pair, thus eliminating the skiding [*sic*].
>
> If the pilot applies differential pedal force to steer the airplane through differential braking, the anti-skid function maintains the skid pressure level, [53] thus precludind [*sic*] the airplane from turning.
>
> The correct action consists in a reduction of the opposite pedal force to a point below the skid level, which permits the reduction of the corresponding brake pressure.

What is learned first creates a strong impression (a phenomenon known as the primacy effect). [54] The typical and frequently used technique for turning using differential braking is to

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[49] Boeing 727, McDonnell Douglas MD80, and Bombardier CRJ700/705/900

[50] Transport Canada, Technical Publication (TP) 1102, *Aeroplane Flight Training Manual*, 4th Edition

[51] Embraer S.A., *Trans States Airlines EMB-145 Airplane Operations Manual* (AOM-145/114-04) section 2-12-10: Anti-Skid Protection (30 March, 2001), page 4

[52] Ibid., Locked Wheel Protection, page 5

[53] Skid pressure level is the brake pressure at which wheel skid activity occurs (source: Crane Aerospace, *Operators Handbook).*

increase pedal deflection (pressure) on the side of the turn. This elementary technique is learned in basic pilot training. Development of a primacy effect would be the case for using differential braking to turn/steer an aircraft. Over time, the action of applying pedal deflection on the side of the turn reinforces the assumption that this action would be the correct response for directional control of the aircraft. This action is known as movement compatibility. [55]

1.18.5 Reapplying aircraft electrical power

The TSB has determined [56] that an ignition source in close proximity to combustible material is one of the unsafe conditions that have contributed to post-impact fires and resulting fire-related injuries and fatalities in the past. Damaged electrical components and wiring can cause electrical arcing and provide a source of ignition for nearby combustible materials, such as leaking fuel.

1.18.6 Trans States Airlines' previous accident

On 16 June 2010, an Embraer EMB-145LR operated by and landing at the Ottawa/Macdonald-Cartier International Airport overran Runway 07, coming to rest 550 feet beyond the departure end (A10H0004). The findings as to causes and contributing factors for this event were the following:

- Inaccurate target approach speed calculation;
- Incorrect flap setting;
- Faster than recommended threshold crossing speed;
- Non-initiation of a go-around when speeds were exceeded;
- Extended touchdown point;
- Smooth landing onto a wet runway;
- Accumulation of water on the runway; and
- Hydroplaning of the aircraft.

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54 Federal Aviation Administration, *Aviation Instructor's Handbook* (FAA-H-8083-9A) (2009)

55 M.S. Sanders and E.J. McCormick, *Human Factors in Engineering and Design* (1992), pages 58–60

56 Transportation Safety Board (TSB), Aviation Safety Issues Investigation Report SII A05-01: *Post-Impact Fires Resulting From Small-Aircraft Accidents* (29 August 2006), available at http://www.bst-tsb.gc.ca/eng/rapports-reports/aviation/etudes-studies/siia0501/siia0501.asp (last accessed on 12 February 2014)

2.0 Analysis

2.1 General

There was no indication that an aircraft system malfunction contributed to this occurrence. In addition, there is no indication that the flight crew's performance was in some way degraded as a result of physiological factors, such as fatigue. As a result, this analysis will focus on the operational factors, environmental conditions, and aircraft-related systems that played a role in the occurrence.

2.2 Approach and landing

The flight crew had calculated the reference speed (V_{REF}) to be 128 knots indicated airspeed (KIAS) and the target approach speed (V_{APP}) to be 133 KIAS. The aircraft crossed the GREELY final approach fix slightly above glideslope at approximately 1470 feet above ground level (agl), with the landing gear extended and flaps set at 22°, and at a speed of 174 KIAS, which was 41 KIAS above the V_{APP} speed. The approach was flown at speeds in excess of the TSA-recommended approach speeds. Both the Trans States Airlines (TSA) *General Operating Manual* (GOM) and standard operating procedures (SOPs) specify that the aircraft will be stabilized and configured at not less than 1000 feet agl.

As per TSA's SOPs, the pilot monitoring is required to call out any deviations from the standards while on the approach. The SOP states, in part, that a missed approach must be conducted if the airspeed is in excess of ±5 knots or if the aircraft is not properly configured below the stabilized approach height of 1000 feet agl. No callouts with regard to speed deviations below the minimum stabilized approach height were verbalized by the pilot monitoring during the approach.

When an aircraft is on approach to Runway 32, the height of 1000 feet agl would be reached by an aircraft on the glideslope at approximately 2.9 nautical miles (nm) final. At this point, the landing gear of the occurrence aircraft, LOF3363, was down. However, the aircraft configuration was flaps 22° and an airspeed of 155 KIAS, instead of the required flap 45° and V_{APP} airspeed of 133 KIAS. Flap 45° was selected at 2.3 nm final, at 800 feet agl. When the flight crew was advised of the updated wind condition, they were 2 nm final, and they recalculated and increased the V_{APP} to 140 KIAS. The aircraft crossed the threshold at 139 KIAS, 11 knots above V_{REF}. Immediately before touchdown, at about 5 feet agl, the captain selected maximum thrust on the engines. This action resulted in increase in the airspeed and extension of the flare to a touchdown point at 3037 feet, which was 1537 feet beyond the TSA-recommended maximum touchdown zone of 800 to 1500 feet beyond the runway threshold. Although the aircraft in this occurrence went off the side of the runway, the combination of excessive airspeed crossing the runway threshold and a delayed touchdown point significantly decreases the distance available to safely stop an aircraft.

The proper landing technique as described in TSA's SOPs for landing on a wet runway is a firm landing, at the recommended speed and within the specified touchdown zone. This technique ensures that the tires break through the film of water on the runway, so that there will be a positive spin-up of the wheels to ensure that the anti-skid brake system and spoiler system operate properly. For this occurrence, the approach and landing technique used to land the aircraft was unchanged from the technique normally used for all of the landings performed by the captain, which increased the likelihood that the wheels would not break through the film of water on the runway.

After touchdown, the captain used a steady and firm application of the brakes, which is the recommended technique for best braking effectiveness. The captain assessed that the aircraft was not decelerating as expected, and elected to engage the emergency/parking brake (EPB), which is contrary to the TSA SOPs. As a result of the activation of the EPB with the wet runway condition, the main tire rotation slowed, which disabled the anti-skid braking system and prolonged the skid.

The TSA SOPs state that attempting to modulate the brakes while the anti-skid is operating should generally be avoided unless required to maintain directional control. These instructions would suggest that, during a situation involving loss of directional control during hydroplaning, modulating the brakes (release and reapply) is an acceptable method.

2.3 Wet runways

It had been raining for 10 minutes before the occurrence. During the aircraft's approach, the rain became heavy at Ottawa/Macdonald-Cartier International Airport (CYOW). The International Civil Aviation Organization's (ICAO's) definition of a contaminated runway refers to a water depth of more than 3 mm. The estimated depth of water on Runway 32 at the time of landing was 4–6 mm, which equates to a contaminated runway according to the ICAO definition.

2.4 Hydroplaning

Dynamic hydroplaning is usually associated with heavy rain showers, and can be induced with as little as 2.54 mm of water on the runway surface. In this occurrence, there was a heavy rain shower just before the occurrence landing, resulting in a water depth on Runway 32 that would have made it conducive to hydroplaning.

After the captain applied the brakes, the aircraft began to skid. Brake application was maintained throughout the landing roll and up until the aircraft stopped. Steam-cleaned marks were noted at various locations along the runway, and all 4 of the aircraft's main landing gear tires exhibited patches of reverted rubber. The tires had angular cuts across these patches, which are consistent with all 4 wheels being locked when the aircraft departed the runway surface. This sign indicates that the aircraft experienced hydroplaning almost immediately after landing and periodically throughout the landing roll. The presence of water on the runway caused the aircraft to hydroplane, which led to a loss of directional control and braking ability. This condition would have been exacerbated at some time during the landing roll because the EPB was applied.

Three of the 4 main tires were underinflated, which lowered their hydroplaning speed. When landing on a wet runway with underinflated tires, there is an increased risk of hydroplaning and possible runway excursion.

2.5 Wing spoiler system

Almost immediately after landing, the outboard spoilers deployed, indicating that the speed of either the no. 2 or the no.4 wheel (or both) was greater than 25 knots. About 20 seconds later, the outboard spoilers retracted, indicating that the speed of both wheels had dropped below 25 knots.

The inboard spoilers deployed about 8 seconds after the outboard spoilers. The aircraft experienced hydroplaning almost immediately, and hydroplaning would prevent or delay the wheels from spinning up. Since no discrepancies were noted with the spoiler system components, it is likely that the no. 1 and the no. 3 wheel speeds were below 25 knots for about 9 seconds after touchdown. The inboard spoilers retracted within about 4 seconds, indicating that the speed of both of these wheels had dropped below 25 knots. Therefore, it is likely that the inboard spoilers deployed later than the outboard spoilers and remained extended for a shorter duration, because the associated wheel speeds were below 25 knots as a result of the aircraft hydroplaning.

2.6 Braking

For wheel speed below 10 knots, anti-skid protection is deactivated, and pressure at the brakes is proportional to the brake pedal deflection. Maximum braking, which involves full deflection of the brake pedals, was applied at touchdown. The recorded brake pressures during the 14 seconds after touchdown were fluctuating between 130 and 340 psi, indicating that the anti-skid function was activated and that wheel speed was greater than 10 knots.

Brake pressure was noted within 1 second of touchdown, indicating that touchdown protection was deactivated almost immediately. For this to happen before the 3-second delay, the speed of at least 1 wheel would have to be greater than 50 knots. Because only the outboard spoilers had deployed at this time, either the no. 2 or the no. 4 (or both) wheel speeds would have been greater than 50 knots.

Locked wheel protection is activated when the speed of the fast wheel of a partnered pair is greater than 30 knots. Since the speed of at least 1 wheel was greater than 30 knots, it and the partner wheel would have locked wheel protection. Because of the limited data recorded on the flight data recorder (FDR), it is not possible to confirm which partnered pair (or whether both) had locked wheel protection.

The pressure at the brake will be the lowest pressure resulting from comparing pedal position, anti-skid protection, touchdown protection, and locked wheel protection. For about 14 seconds after touchdown, the no. 1 and no. 3 brake pressures fluctuated; however, no significant brake pressure was recorded during this time. This observation is consistent with the design of the braking system when anti-skid is operating, during which time the pedals are at full deflection and the tires are hydroplaning because they have not had positive wheel spin-up.

2.7 Thrust reversers

In this particular occurrence, the aircraft was landing on a very wet runway. Had the aircraft been equipped with thrust reversers, the application of reverse thrust as soon as possible after touchdown may have permitted the aircraft to slow down below hydroplaning speed much sooner, and possibly prevented the runway excursion. The use of thrust reversers reduces the risk of runway excursions when landing on wet runways.

2.8 Aircraft skid control on wet runways

When the runway is wet, the pilot may be confronted with dynamic hydroplaning. When an aircraft is skidding due to hydroplaning, there is no contact between the tires and the runway surface, and tire rotation may have completely stopped. Because hydroplaning wheels are not touching the runway, braking and directional control are almost nil. If the tires have not spun up, or have spun down to a speed above the anti-skid cut-out but below the aircraft's ground speed, the anti-skid system may no longer be functioning as intended. Numerous aircraft manufacturers require the pilot to momentarily release the brakes so that control of the aircraft can be regained. Releasing the brakes gives the wheels the opportunity to spin up, thereby allowing the anti-skid system to function normally. However, the *Trans States Airlines EMB-145 Airplane Operations Manual* (AOM) instructs pilots to maintain braking throughout the landing roll. This is done in the expectation that the tires will eventually make contact with the runway surface, allowing for control to be regained. When an aircraft is skidding or there is a loss of directional control, anomalous anti-skid behavior can be initiated, because the wheel speeds are not the same as the aircraft ground speed.

Embraer's guidance regarding the differential braking technique appears to imply, but does not state clearly, that this technique is specific to a situation in which braking is already being applied, anti-skid is actively modulating the brakes pressures (which indicates that the tires are near a skid situation), and the pilot wants to use differential braking to turn/steer the aircraft. What the guidance does not state is that, under these conditions, the aircraft is on the verge of skidding.

The typical and frequently used technique for turning the aircraft using differential braking, learned in basic pilot training, is to increase pedal deflection (pressure) on the side of the turn. If no specific training is carried out to apply a revised differential braking technique, it would be difficult for pilots to overcome this fundamental, learned control-response connection and not apply more pedal deflection on the same side as the intended turn/steer. To help ensure consistent application of the proposed action of reducing deflection on the opposite pedal of the turn/steer, frequent training would be required so that a pilot recalls it when a given set of parameters are present.

2.9 Communications

After the initial power-down while carrying out the items in the *Quick Reference Handbook* (QRH), the crew determined that they needed to communicate with ARFF regarding the safety of the aircraft exterior. The batteries were then powered up to operate the radios. Unbeknownst to the flight crew, there was an active fuel leak. When this information was relayed to the flight crew, the aircraft power was immediately shut down. With the power-up of the aircraft electrical system with an active fuel leak, there was a risk that an electrical spark could ignite the fuel and start a fire.

2.10 Flight recorders

Although the Transportation Safety Board (TSB) was able to download high-quality data from the FDR, the parameters that were not recorded due to the model type of and input to the FDR made it more difficult to determine the sequence of events (Appendix E).

2.11 Grooved runways

Aircraft landing performance on wet runways is a widely recognized safety concern. Grooved runways improve drainage, thereby minimizing skids and drift; they improve braking and reduce the risk of hydroplaning. Studies have shown that wet grooved runways often provide almost the same level of braking as dry runways. The use of non-grooved runways increases the risk of hydroplaning, which may result in runway excursions. The caution stated in the SOPs about the fact that non-grooved runways are rare is misleading. Grooved runways are common in the United States, but virtually nonexistent in Canada. In the absence of information and training about non-grooved runways, there is a risk that crews will not carry out the appropriate landing techniques when these runways are wet.

Runway grooving is not mandatory in Canada or the US; however, Transport Canada (TC) and the Federal Aviation Administration (FAA) specifically promote the benefits of grooving. The FAA states the following about grooving in Advisory Circular (AC) 150/5320-12C, "[runway grooving is]…considered high priority safety work and should be accomplished during initial construction." [57]

2.12 Safety action taken following previous accident

The events of this accident have some similarities to the previous TSA accident that occurred on 16 June 2010. [58] Of particular note from the 2010 accident are the following:

- The crew flew the approach faster than recommended.
- The aircraft crossed the threshold 8 knots above V_{REF}, resulting in an extended flare to a touchdown of 2270 feet, which was 770 feet beyond the TSA-recommended touchdown point of 800 to 1500 feet, but within the first third of the available landing distance as per TSA SOPs.

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57 Federal Aviation Administration, Advisory Circular (AC) 150/5320-12C: Measurement, Construction, and Maintenance of Skid-resistant Airport Pavement Surfaces (1997)

58 TSB Aviation Investigation Report A10H0004

- The smooth landing on a wet runway led to viscous hydroplaning, which resulted in poor braking action and reduced aircraft deceleration, contributing to the runway overrun.
- The crew did not initiate a go-around when V_{REF} was exceeded by more than 5 KIAS.

A few of the items that TSA did correct following the 16 June 2010 accident were:

- All take-offs and landings on non-grooved runways that are wet or contaminated are to be accomplished by the captain.
- All departures and arrivals at YOW (Ottawa) on Runway 07/25 are prohibited if that surface is reported as damp or wet.
- The normal landing flap setting was changed from 22° to 45°.

This 2011 occurrence had the following SOP-related issues in common with the 2010 accident:

- An approach performed at a speed higher than recommended;
- A go-around not performed as per SOPs when the speed was more than 5 knots above V_{APP} during the stabilized portion of the approach;
- A faster than recommended threshold crossing speed;
- An extended touchdown point; and
- A smooth touchdown onto a wet runway.

If pilots do not comply with SOPS, and companies do not assure compliance, then there is a risk that occurrences resulting from such deviations will persist.

3.0 Findings

3.1 Findings as to causes and contributing factors

1. Heavy rainfall before and during the landing resulted in a 4–6 mm layer of water contaminating the runway.

2. The occurrence aircraft's airspeed during final approach exceeded the company-prescribed limits for stabilized approach criteria. As a result, the aircraft crossed the runway threshold at a higher than recommended V_{REF} airspeed.

3. A go-around was not performed, as per standard operating procedures, when the aircraft's speed was greater than 5 knots above the appropriate approach speed during the stabilized portion of the approach.

4. The application of engine thrust just before touchdown caused the aircraft to touch down 3037 feet from the threshold at a higher than recommended airspeed.

5. The combination of a less than firm landing and underinflated tires contributed to the aircraft hydroplaning.

6. The emergency/parking brake was applied during the landing roll, which disabled the anti-skid braking system and prolonged the skid.

7. The aircraft lost directional control as a result of hydroplaning and veered off the runway.

3.2 Findings as to risk

1. The typical and frequently used technique for differential braking that pilots are trained to use may not be effective when anti-skid systems require different techniques.

2. If aircraft electrical power is applied with an active fuel leak, there is a risk that an electrical spark could ignite the fuel and start a fire.

3. The use of non-grooved runways increases the risk of hydroplaning, which may result in runway excursions.

4. If there is an absence of information and training about non-grooved runways, there is a risk that crews will not carry out the appropriate landing techniques when these runways are wet.

5. The use of thrust reversers reduces the risk of runway excursions when landing on wet runways.

6. If pilots do not comply with standard operating procedures, and companies do not assure compliance, then there is a risk that occurrences resulting from such deviations will persist.

3.3 Other findings

1. The central maintenance computer was downloaded successfully; however, there were no data present in the memory unit.

2. Although the Transportation Safety Board was able to download high-quality data from the flight data recorder, the parameters that were not recorded due to the model type and input to the flight data recorder made it more difficult to determine the sequence of events.

4.0 Safety action

4.1 Safety action taken

4.1.1 Ottawa/Macdonald-Cartier International Airport

The Ottawa International Airport Authority acquired 2 rapid-deployment emergency shelters in February 2012. These shelters will be used to provide a temporary shelter from the elements on site following an emergency.

The Ottawa International Airport Authority is currently undergoing a multi-year runway rehabilitation program, which started with the resurfacing of Runway 04/22 in 2011. In 2012, the complete reconstruction of Runway 07/25 was completed. This reconstruction included a change to the profile of the runway from a crossfall to a centre crown, the addition of Federal Aviation Administration (FAA) / International Civil Aviation Organization (ICAO) standard runway end safety areas (RESAs), and the chamfering of all sub-terrain obstacles within the runway strip. After allowing the pavement to cure for a year, Runway 07/25 was grooved in 2013 as per FAA and Transport Canada advisory circulars.

Currently, the re-design of Runway 14/32 has commenced, beginning the process of a complete reconstruction for this runway. The reconstruction plans are similar to those for the rehabilitation of Runway 07/25: a change to the profile of the runway from a crossfall to a centre crown, the addition of FAA/ICAO standard RESAs, the chamfering of all sub-terrain obstacles within the runway strip, and grooving of the runway. This reconstruction will take place in 2014.

4.1.2 Embraer S.A.

Embraer published revision 33 of the *Embraer 145 Aircraft Maintenance Manual* (AMM) Part 1 (SDS – System Description Section) in June 2013. To ensure that the literature contained within the AMM is consistent and accurate, the AMM revision includes, among other items, a clarification of the descriptions related to the brake system.

This report concludes the Transportation Safety Board's investigation into this occurrence. The Board authorized the release of this report on 18 December 2013. It was officially released on 27 March 2014.

Visit the Transportation Safety Board's website (www.bst-tsb.gc.ca) for information about the Transportation Safety Board 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

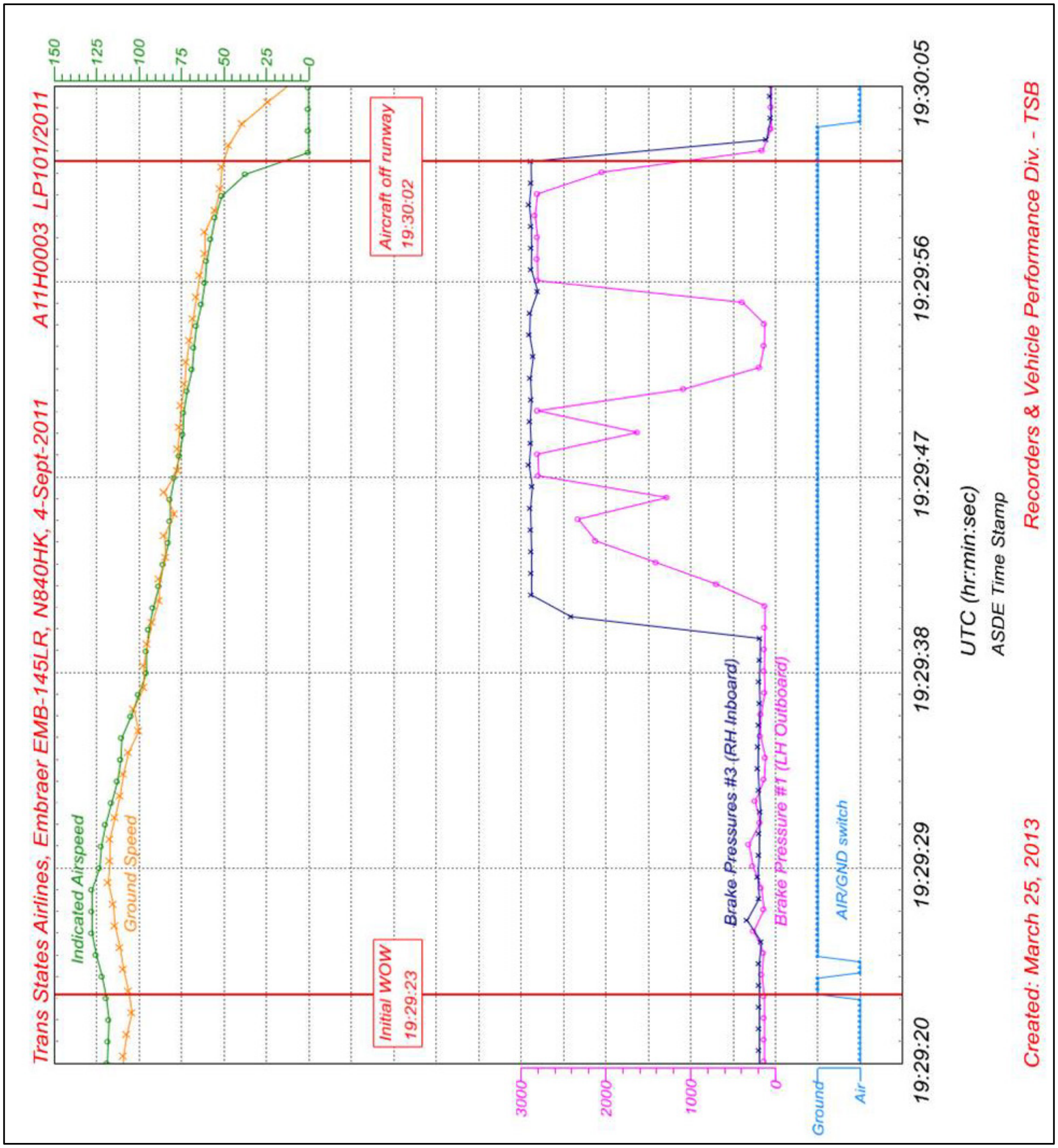
Appendix A – List of TSB Laboratory reports

The following TSB Laboratory reports were completed:

- LP101/2011 – FDR/CVR/Radar Analysis
- LP112/2011 – Main Landing Gear Tire Examination
- LP127/2011 – Maintenance Records Review
- LP128/2011 - Brake and Spoiler System Analysis
- LP129/2011 – Runway Survey
- LP167/2011 – Braking Performance Analysis

These reports are available from the Transportation Safety Board of Canada upon request.

Appendix B – Brake pressures during landing rollout



Appendix C – Grooved runway

Photo 7. A grooved runway (the section where the trucks are parked) versus a non-grooved runway, shown after being flushed with water during the grooving process (photo used with permission from the St. Louis Downtown Airport [KCPS])

Appendix D – Rain intensity

As described in section 3.9.5 of the *Environment Canada Manual of Observations* (EC MANOBS), when the intensity of rain, rain showers, or freezing rain must be determined without the aid of instrument measurements, the following table may be used as a guide:

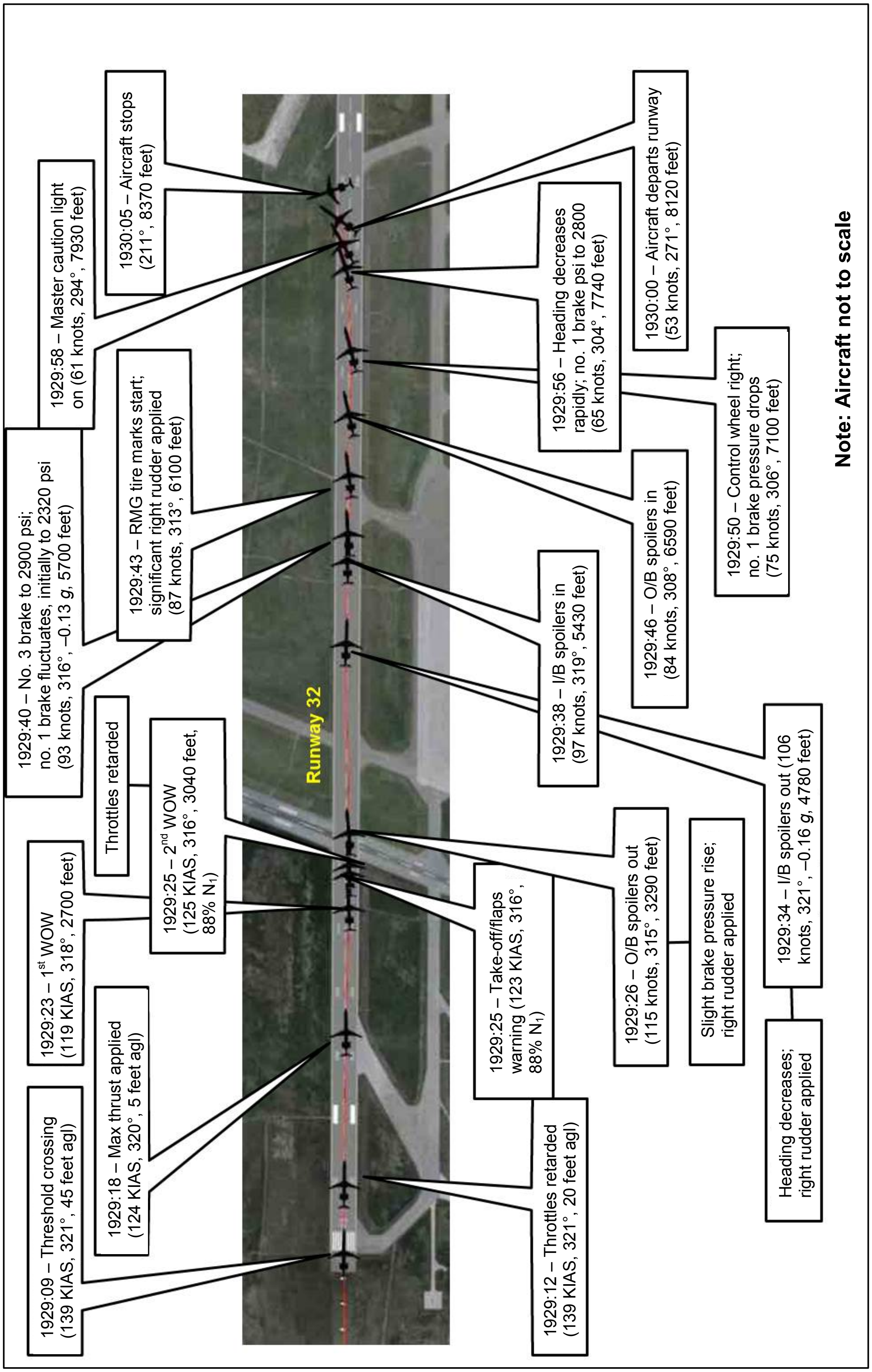
	Light Rain	**Moderate Rain**	**Heavy Rain**
Individual drops	Easily seen	Not easily seen	Not identifiable (rain in sheets)
Spray over hard surface	Hardly any	Noticeable	Heavy to a height of several centimetres
Puddles	Form slowly	Form rapidly	Form very rapidly

Source: Environment Canada, *Manual of Surface Weather Observations* (EC MANOBS), section 3.9.5 – Intensity by rate of fall criteria (January 2011); current edition available at http://www.ec.gc.ca/Publications/default.asp?lang=En&xml=1F0AEEAB-EEF5-4382-BE97-E102F8615061 (last accessed on 14 February 2014)

If a rain gauge is available, the intensity of rainfall can be accurately measured (given in mm per hour):

Rain	LIGHT if rate of fall is 2.5 mm/h or less
Rain Showers	MODERATE if rate of fall is 2.6 mm to 7.5 mm/h
Freezing Rain	HEAVY if rate of fall is 7.6 mm/h or more

Appendix E – Sequence of events



(**Legend:** agl = above ground level; *g* = local acceleration due to gravity; I/B = inboard; KIAS = knots indicated airspeed; N_1 = speed of the low-pressure rotor in the engine; O/B = outboard; psi = pounds per square inch; RMG = right main gear; WOW = weight on wheels)