Transportation Safety Board
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Bureau de la sécurité des transports
du Canada

AVIATION INVESTIGATION REPORT

A10Q0213

RUNWAY EXCURSION

AMERICAN AIRLINES INCORPORATED
BOEING 737-823, N901AN
MONTREAL/PIERRE ELLIOTT TRUDEAU
INTERNATIONAL AIRPORT, QUEBEC
30 NOVEMBER 2010

Canada

Aviation Investigation Report

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American Airlines Incorporated
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Summary

The American Airlines Incorporated Boeing 737-823 (registration N901AN, serial number 29503) departed Dallas / Fort Worth International Airport, United States, as flight AAL802 on a scheduled flight to Montreal / Pierre Elliott Trudeau International Airport, Quebec. At 1953 Eastern Standard Time, after touching down on Runway 24R in light rain during the hours of darkness, the aircraft gradually veered left of centerline. It departed the runway surface and stopped in the grass and mud, approximately 90 feet from the runway edge and 6600 feet from the threshold. None of the 106 passengers, 6 crew members, or 1 off-duty crew member were injured. Evacuation was not deemed necessary; all passengers and cabin crew deplaned via an air stair and were transported by bus to the terminal. Damage to the aircraft was minor.

Ce rapport est également disponible en français.

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1.0 Factual Information

1.1 History of the Flight

Flight AAL802 departed from Dallas/Fort Worth International Airport (KDFW), United States (US) at 1705. [1] The captain was occupying the left seat and was the pilot flying (PF). The first officer was occupying the right seat and was the pilot monitoring (PM). The flight to Montreal/Pierre Elliott Trudeau International Airport (CYUL), Quebec, was uneventful and on schedule.

The crew received weather updates for CYUL from the recorded automatic terminal information service (ATIS) while en route and again before landing. Runway 24R was the runway in use for landing, and its condition was reported to be 100% bare and wet. There was light rain, and the winds reported to the crew while on final approach were from 150° magnetic (M) at 16 knots, giving an expected 90° left crosswind for landing. The crew flew the instrument landing system (ILS) Runway 24R approach. The approach and landing checklists, as well as all calls, were completed as per company standard operating procedures.

The windshield wipers were not used during the approach and landing, as the light rain flowed off the windshield effectively. The autobrake system has settings of 1, 2, 3, or MAX for landing. [2] The autobrake setting is not recorded on the flight data recorder (FDR), but the deceleration performance during the landing was consistent with a selected autobrake system setting of 2. The flaps were selected to the 30° position. Based on the aircraft landing weight, both the autobrake setting and the flaps selection were appropriate for the runway conditions and length. The calculated V_{REF} [3] speed of 145 knots [4] was appropriate for the aircraft landing weight and environmental conditions.

The aircraft was configured for landing before crossing the Jarry final approach fix (FAF), which is located 4.9 nautical miles (nm) from the threshold of Runway 24R. The winds at the FAF were from 180°M at 44 knots [5], decreasing gradually to 157°M at 14 knots over the threshold, resulting in a 2.2-knot headwind component and a 13.8-knot crosswind component from the left at touchdown. Although there was a crosswind for landing, it was considered well within the manufacturer's crosswind guidelines for this aircraft. [6] The approach was stable, with only minor deviations from the localizer and glideslope. The autopilot was disengaged at

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[1] All times are Eastern Standard Time (Coordinated Universal Time minus 5 hours).

[2] Selection of 1 of these 4 settings gives the desired deceleration rate for landing.

[3] "V_{REF}" refers to the reference landing approach speed (not less than 1.23 V_{S1g} times the 1g stall speed in normal landing configuration).

[4] All aircraft speeds are indicated airspeed unless stated otherwise.

[5] Wind direction and speed are taken from the flight data recorder (FDR) data.

[6] For a runway with standing water, the crosswind component of 20 knots should not be exceeded. Crosswind guidelines are not considered limitations. American Airlines policy for maximum crosswind component for landing is 33 knots.

approximately 1830 feet above sea level (asl), while the autothrottles remained engaged until touchdown.

The aircraft crossed the threshold at a radio altimeter height of 32 feet above ground level (agl), [7] and at an airspeed of 156 knots (V_{REF} + 11). The initial touchdown was firm at an airspeed of 150 knots (V_{REF} + 5), and at a distance of 825 feet past the threshold. [8] The automatic speed brake and autobrake systems activated simultaneously within 1 second after touchdown. This activation was immediately followed by manual selection of maximum reverse thrust. Aircraft deceleration was considered normal.

After touchdown, the aircraft tracked the runway centerline, with only minor heading changes required during the initial 16 seconds of the landing roll. Starting at 1953:10, at a distance of 4370 feet down the runway and at a speed of approximately 89 knots, the aircraft began to veer left immediately after reverse thrust reduction to detent 2 [9] (Appendix B). The PF's initial reaction, 3 seconds after the start of the veer, was to apply right control-wheel input, which occurred at 19:53:13. Right rudder pedal was later applied at 19:53:17 [10] to correct for the heading change and deviation; however, the aircraft did not immediately respond to the rudder pedal input. Right control-wheel deflection reached 90° at 19:53:19. More right rudder pedal was then applied up to the equivalent of 83% rudder availability; the input lasted about 3 seconds. Although the aircraft heading started to return toward the runway heading starting at 1953:20, the aircraft continued to travel toward the left side of the runway. According to FDR data, the aircraft had a slight sideways motion. However, there was no evidence to suggest that the tires locked up to this point or at any other time during the landing roll-out. At that time, the aircraft was abeam Echo taxiway and 60 feet left of runway centerline. The PF then increased reverse thrust to MAX detent and released right rudder application. The aircraft exited the runway surface at 19:53:23, [11] 61 feet past the Echo taxiway, on a heading of 230°M, at a ground speed of 59 knots.

The autobrake system was in operation for the entire landing roll; no manual braking was attempted at any time during the deviation from the runway centerline. The aircraft came to a full stop, with all landing gear in the grass and mud, at 1953:32. At no time during the approach, landing, or deceleration of the aircraft did either crew member notice any aircraft abnormalities or warning lights, or receive any aural warnings of a faulty system.

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[7] Radio altimeter height as recorded is calibrated to show the height on the bottom of the main gear above terrain.

[8] *American Airlines Flight Manual*, Part 1, Bulletin FM-017 − Landing Touchdown Point (8-03-10) states that the desired touchdown point for narrow-body aircraft is within the first 800 to 1500 feet beyond the landing threshold.

[9] This position provides adequate reverse thrust for normal operations. When necessary, the reverse thrust lever can be pulled beyond detent 2, providing maximum reverse thrust. The thrust reverser is for ground operations only, and is used after touchdown to slow the airplane, reducing stopping distance and brake wear. The FDR indicated that the thrust change was symmetrical.

[10] Ground speed was approximately 75 knots.

[11] The time of the runway excursion was based primarily on accelerometer noise and changes in aircraft attitude.

The crew notified the tower controller that the aircraft had departed the runway, and emergency rescue vehicles were sent to the site. The crew initiated the evacuation checklist; however, passengers were advised to remain seated as there was no fire, smoke, or immediate need to evacuate. The engines were shut down, and the auxiliary power unit was started in order to provide lighting and heating to the aircraft. As indicated by company procedures, [12] the crew pulled the cockpit voice recorder (CVR) circuit breaker to preserve recorded flight information. An air stair was provided to disembark the aircraft occupants by the right aft exit. They were then transported to the terminal by bus.

1.2 Injuries to Persons

Table 1. Injuries to persons

	Crew	Passengers	Off-duty crew	Total
Fatal	–	–	–	–
Serious	–	–	–	–
Minor / none	6	106	1	113
Total	6	106	1	113

1.2.1 Damage to Aircraft

Damage to the aircraft was considered minor. There was no structural damage. There was no damage to the interior cabin or cockpit areas.

The nosewheel steering system was checked for range of travel and response with both pedals and tiller. The system was functioning according to specifications. The brakes showed no discrepancies and operated normally. The antiskid and autobrakes control unit showed no fault. Tire pressure was measured on the day following retrieval of the aircraft, which had been left overnight in a heated hangar; pressure in all tires was within normal specifications. The tires were intact and showed no signs of reverted-rubber hydroplaning. [13] With the exception of a few chevron marks, [14] the tires were in acceptable operational condition and did not show any adverse conditions resulting from the event. All tires and brakes were removed and replaced as a precautionary measure.

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[12] *American Airlines Flight Manual*, Part I – Abnormal and Emergency, Section 19 – Deactivation of the Recorder, and Part I – Bulletin FM-013, 4.1 B

[13] Reverted-rubber (steam) hydroplaning occurs during heavy braking that results in a prolonged locked-wheel skid. Only a thin film of water on the runway is required to facilitate this type of hydroplaning. The tire skidding generates enough heat to cause the rubber in contact with the runway to revert to its original, uncured state.

[14] Chevron marks are tread damage that may be caused by running and / or braking on cross-grooved runways.

A boroscope inspection of the engines showed some light foreign-object damage, [15] but the damage was considered within the maintenance-manual tolerances. Nicks found on the fan blades were polished before departing CYUL on a special ferry permit. The left main landing-gear lower torque-link bracket was found bent and was replaced in the US.

1.3 Other Damage

Damage to the airport environment was limited to 1 runway light when the aircraft departed the runway surface. Twelve-inch-deep ruts were left in the grass by the aircraft wheels and by heavy equipment used to retrieve the aircraft.

1.4 Personnel Information

The flight crew was certified and qualified for the flight in accordance with existing regulations. In the days preceding the incident, the captain and the first officer had 2 and 7 days of rest, respectively. The crew had been on duty for approximately 9 hours at the time of the occurrence. Fatigue was not considered a contributing factor in the occurrence.

The captain had approximately 15 000 hours of total flying time, and had previously been a pilot with the US Navy. During 23 years of employment with American Airlines, the captain flew as a flight engineer on Boeing 727 and DC10 aircraft, and as a first officer on MD11, A300, B757, and B767 aircraft. The captain had a total of 3300 hours as captain on A300, B757, and B767 aircraft and, at the time of the occurrence, had 200 hours experience as captain on the B737.

The first officer had over 10 000 hours of total flying time, and was previously a pilot with the US Navy. During 12 years of employment with American Airlines, the first officer first flew as a flight engineer on B727 aircraft, and then as first officer on B737 aircraft. At the time of the occurrence, a total of 6800 hours had been accumulated as first officer on B737.

1.5 Aircraft Information

1.5.1 General

The occurrence aircraft [16] was certified, equipped, and maintained in accordance with existing regulations and approved procedures. The weight and centre of gravity were within the prescribed limits. All inspection-schedule requirements were complied with before the flight. There were no deferred items on the minimum equipment list at the time of the occurrence. The last required scheduled maintenance [17] pertinent to the nosewheel steering system had been accomplished on 21 July 2010. There were no reported repairs or anomalies to the nosewheel steering system in the 3 months preceding the occurrence, nor were there any technical difficulties or system failures reported by this occurrence crew.

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[15] Foreign object damage is damage caused by any material that can be ingested by the engines.

[16] This Boeing 737 was equipped with blended winglets.

[17] According to the maintenance planning document

Table 2. Aircraft information

Manufacturer	The Boeing Company
Type and model	Boeing 737-823
Year of manufacture	1999
Serial number	29503
Certificate of airworthiness	09 February 1999
Total airframe time	34 841 hours
Engine type (no.)	CFM56-7B24 (2)
Maximum allowable take-off weight	174 200 lb

1.5.2 Aircraft Nosewheel Steering System

The nosewheel steering system (Figure 1) provides directional control of the aircraft on the ground. Its components are located in the flight compartment and the nose landing-gear wheel well. Rudder pedal steering is available during taxiing, landing, and take-off, and is used when small directional-control changes are required. Full deflection of the rudder pedals produces about 7° of nosewheel deflection left or right.

Movement of the steering wheel (tiller) will turn the nosewheel up to 78° left or right. The inputs are transmitted to a steering metering valve through a steel cable loop. The tiller, only available on the left side of the cockpit on the occurrence aircraft, will always override the rudder pedal inputs to the nosewheel steering system.

The nosewheel steering system is mechanical/hydraulic, with the angle of the nosewheel altered through 2 hydraulic cylinders, termed steering actuators, mounted on the nose gear. The travel of these actuators is controlled with a hydraulic control unit, the steering metering-valve module, mounted together with the actuators. The control unit is actuated by the rudder pedals and the tiller via control cables.

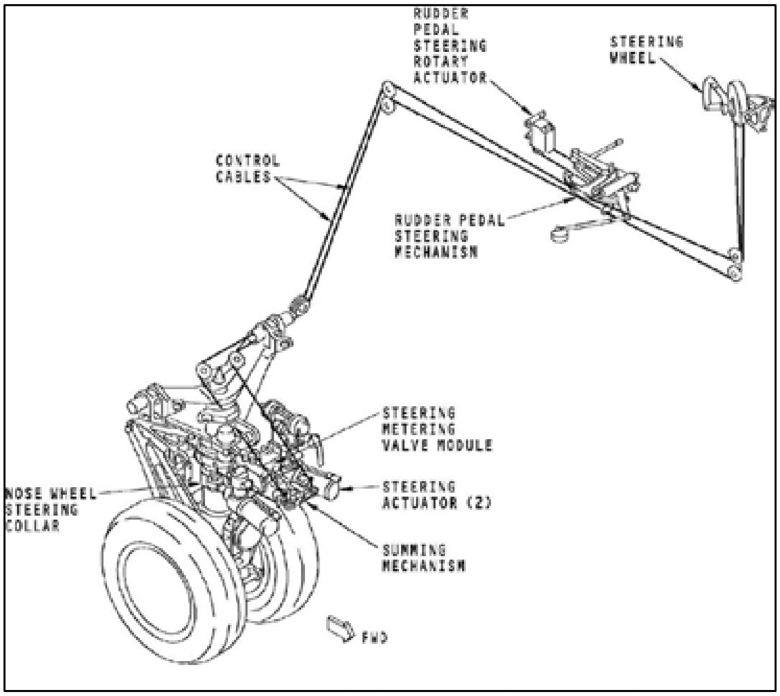

Figure 1. Boeing 737NG nosewheel steering system and summing mechanism (Copyright © 1997 The Boeing Company, unpublished Work. All Rights Reserved.)

A steering summing mechanism, located at the front of the nose oleo, combines steering inputs and nose-gear deflection feedback. It acts upon the metering-valve input lever, thereby initiating a turn, or neutralizing it once the desired amount of deflection has been reached. [18]

1.5.3 Aircraft Hydraulic System

The aircraft has 2 main hydraulic systems, referred to as A and B systems, which are powered by the engine-driven pumps and the electric motor-driven pumps. Normal operating pressure is 3000 pounds per square inch (psi). Various filters assure a level of hydraulic fluid cleanliness throughout the system. The hydraulic fluid [19] powering the steering system is tapped off the landing-gear extension system, which is normally supplied by the hydraulic system A. The fluid goes through a 100-micron [20] mesh-sized inlet filter as it enters the steering metering valve, which in turn supplies the right and left steering actuators according to the inputs from the tiller or rudder pedal.

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[18] *Boeing 737 Aircraft Maintenance Manual*, Chapter 29: Hydraulic Power

[19] The hydraulic fluid used by the operator since the early 1990s is Skydrol LD-4.

[20] 100 microns = 0.0039 inches

1.6 Meteorological Information

The hourly aviation routine weather report (METAR) at 1900 on 30 November, indicated winds from 140° True (T) at 16 knots, 7 statute miles (sm) visibility in light rain [21], few clouds at 700 feet agl, overcast ceiling at 5000 feet agl, temperature 6.4°C, dew point 5.6°C, altimeter 3013 inches of mercury (in. Hg), remarks ⅛ stratus fractus, 8/8 stratocumulus, and mean sea level pressure 1020.4 millibar.

The METAR at 2000 indicated winds from 140°T at 16 knots, 6 sm visibility in light rain and mist, scattered cloud at 1000 feet agl, ceiling broken cloud at 2200 feet agl, overcast cloud at 5000 feet agl, temperature 6.7°C, dew point 5.8°C, altimeter 3010 in. Hg, remarks 4/8 stratus fractus, 2/8 stratocumulus, 2/8 stratocumulus, and mean sea level pressure 1019.5 millibar.

Precipitation data obtained from Environment Canada show that a total of 6.8 millimetres of rain fell during the period between 1300 and 1900, on 30 November. External factors that may have contributed to the loss of directional control, such as strong gusts of wind, were also considered. No rapid changes in direction or gusts of wind were recorded during the time of the occurrence. [22]

1.7 Aids to Navigation

All aids to navigation were serviceable in the Montreal area at the time of the occurrence. The approach and touchdown were normal.

1.8 Communications

Communications and the air traffic control services provided by NAV CANADA were clear, timely and unambiguous during the approach and landing. There were no technical difficulties.

1.9 Aerodrome Information

1.9.1 Airport Operator

CYUL is a major airport operated by les Aéroports de Montréal (ADM). Three runways surfaces are available at CYUL. On the evening of the occurrence, aircraft were landing on Runway 24R and Runway 24L, and departures were from Runway 24L.

Runway 24R is 11 000 feet long and 200 feet wide, is an ungrooved asphalt/concrete surface runway, and is aligned along 238°M. Runway 24R is equipped with high-intensity approach

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[21] Manual of Surface Weather Observations (MANOBs), section 3.9.5, defines light rain as a rate of fall of 2.5 millimetres per hour or less.

[22] The Operational Information Display System (OIDS) wind display is a 2-minute average that is updated approximately every 5 seconds, with direction rounded to the nearest 10°.

and runway lighting, as well as runway centerline lights; all were in use and selected at level 2 [23] intensity at the time of the occurrence.

1.9.2 Runway Friction Testing and Maintenance

Winter operations, which run from mid-November to mid-April, were in effect at the airport on the day of the occurrence. Runway surface inspections [24] are done at minimum every 8 hours, or as frequently as needed depending on changing weather conditions and pilot reports. The last runway surface condition inspection had taken place at 1523, and indicated that Runway 24R was 100% bare and wet. Aircraft Movement Surface Condition Reports (AMSCR) are distributed to ADM's operations centre and to NAV CANADA's CYUL airport air traffic control (ATC) tower, flight service stations, and NOTAM [25] office. AMSCRs are made available to flight crew arriving at CYUL via the ATIS and the CYUL ATC tower.

During winter operations, when runways may be contaminated with snow or ice, ADM uses decelerometer readings to obtain runway friction reports, more commonly known as the Canadian runway friction index (CRFI). AMSCRs will be accompanied by a CRFI report if runways are contaminated in any way. Decelerometers are not to be used with wet snow, water on pavement, slush on pavement, or loose snow greater than 1 inch in depth. They are to be used on water on ice, slush on ice, and loose snow less than 1 inch in depth.

The longitudinal and lateral slopes of Runway 24R at CYUL meet the International Civil Aviation Organization (ICAO) and Transport Canada (TC) standards for runway sloping in order to promote rapid drainage capacity of the runway surface. Inspection of the runway following the occurrence did not reveal water accumulation anywhere along its length or width. Rapid water drainage is recommended so as to avoid hydroplaning upon landing. Quick access recorder (QAR) information, together with braking reports received during the investigation from other crews that had landed before the occurrence aircraft, revealed that braking action on Runway 24R was good. [26] The occurrence aircraft FDR data showed that hydroplaning did not occur. Although the runway was wet on landing, it was not a contributing factor in this occurrence.

1.9.3 Airport Surface Detection Equipment

Ground radar information from airport surface detection equipment (ASDE) was reviewed to verify whether the jet blast from any other aircraft manoeuvring near Runway 24R could have

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[23] Runway centerline lighting intensity varies from 1 to 5, with 5 being the highest intensity. The intensity selection will vary depending on ground visibility.

[24] Runway inspections are done visually, by vehicle, at a maximum speed of 60 kilometres per hour. A runway is considered wet when the inspecting person's hand is wet when touching the surface of the runway and/or if water can be heard while vehicle tires are rolling on the runway.

[25] Notice to Airmen

[26] "Good" indicates that braking deceleration is normal for the wheel-braking effort applied. Directional control is normal.

affected AAL802’s landing. No other aircraft were in proximity of Runway 24R at the time of AAL802’s landing roll.

1.10 Flight Recorders

1.10.1 Flight Recorder Information

Flight recorders were recovered on the evening of the occurrence and transported the following day to the Transportation Safety Board (TSB) Laboratory for analysis.

The CVR was a solid-state L3 Communications FA2100, on which 31 minutes of data were recorded. On the occurrence aircraft, the 30-minute CVR records as long as the aircraft power remains on, and it will overwrite itself as long as the CVR is powered. The recording started approximately 20 minutes before landing, as the PF was completing the approach briefing, and ended approximately 10 minutes after landing. [27]

The FDR was a solid-state L3 Communications FA2100, on which 52 hours of flight data were recorded, including data from the occurrence flight. The FDR download file was forwarded to the operator, American Airlines, to the US National Transportation Safety Board (NTSB), and to the aircraft manufacturer, Boeing.

The FDR on the occurrence B737 did not record any data related to the nose-gear steering system, such as nose-gear deflection angle, or the tiller. There is no regulatory requirement to record this information. However, these parameters are now being recorded on some recently certified aircraft types, since the latest nose-gear designs include the sensors required for nose-gear steering control; these sensors can also supply data to the FDR.

For comparison purposes, the aircraft FDR data for the landing in KDFW and take-off from KDFW earlier in the day were also reviewed for aircraft behaviour and handling; no relevant noteworthy information was observed.

Examination of recorded parameters relevant to a loss of directional control focused on the directional control inputs: rudder position, rudder pedal inputs, use of brakes, and engine thrust. Decelerating devices for the landing roll-out were also reviewed, and included the wheel brakes, thrust reversers, and speed brakes; it was determined that these systems were operating normally.

A ground track was calculated using the ground-speed and drift-angle data recorded on the FDR. The recorded drift was negligible during the initial landing roll-out, and the calculations showed that the aircraft tracked straight ahead and on runway centerline. This finding was consistent with the ASDE radar, which also showed the aircraft tracking runway heading.

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[27] International Civil Aviation Organization (ICAO), Annex 13 to the Convention on International Civil Aviation, *Aircraft Accident and Incident Investigation*, 9th Edition (2001), Amendment 12B (5.12) requires states conducting accident investigations to protect cockpit voice recordings. Canada complies with this requirement by making all on-board recordings—including CVRs—privileged in the *Canadian Transportation Accident Investigation and Safety Board Act*.

The heading deviation left of runway centerline was not associated with left rudder pedal inputs by either pilot. FDR data indicate operation of the control wheel and operation of the reverse thrust at the start of the uncommanded veer; therefore, the tiller, only available on the captain's side of the aircraft, was likely not used to commence the veer. The data also show no asymmetrical braking or asymmetrical thrust (Appendix C).

1.10.2 Previous Aircraft Landing

Another aircraft, a B737-700, landed on Runway 24R at 1931, approximately 22 minutes before the occurrence aircraft. Precipitation and winds recorded for the 1900 METAR remained similar for the time of landing of AAL802. The QAR download file was obtained from the B737-700 operator, and the parameters relevant to the landing were plotted for comparison purposes. The data showed good deceleration, consistent with this flight crew's account of braking conditions after the occurrence; the maximum recorded longitudinal deceleration was 0.24 *g* (recorded as a negative acceleration), which was the same as on the occurrence aircraft landing. Although there was a direct crosswind of approximately 16 knots, there were no directional control issues experienced during the B737-700 landing roll-out, suggesting adequate tire cornering [28] capability.

1.11 Wreckage and Impact Information

Once the aircraft veered off the runway, it travelled approximately 485 feet along the side of the runway, coming to a stop on a heading of 212°M in the grass and mud. The nose gear and right main gear were 90 feet and 50 feet, respectively, from the runway pavement edge (Photo 1).

There were no visible white steamed-clean markings on the runway pavement, which would have been indicative of hydroplaning. There were no ground scars, tire-skid marks, or damage to the runway surface. One runway edge light was damaged when the aircraft departed the runway surface.

Photo 1. AAL802 Boeing 737 off runway

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[28] Tire cornering refers to the forces that are generated in the direction perpendicular to the direction of motion of the tires; the cornering forces provide runway tracking capability. Good tire-to-ground friction and high vertical loads help both braking and cornering.

1.12 Medical and Pathological Information

Not applicable.

1.13 Fire

Not applicable.

1.14 Survival Aspects

Not applicable.

1.15 Tests and Research

1.15.1 Boeing Simulations

The FDR parameters indicated that all systems were operating normally, and that the heading deviation off the runway centerline was uncommanded by the crew. The TSB requested that Boeing, the aircraft manufacturer, assist in facilitating an understanding of the directional control difficulty event.

Boeing performed various simulations using recorded FDR data to drive required parameters. A math pilot [29] was used to drive the rudder pedal parameter. The desktop simulation offers flexibility in being able to drive the simulation controls with FDR data or use math pilot models. A math pilot applies control inputs to track specified parameters in an attempt to zero the error between the recorded FDR data and simulation. [30] In this case, the math pilot was set up to match the calculated ground track and the recorded heading using the rudder pedal parameter, which was then compared to the pedal position as recorded on the FDR.

The simulation was set up on the ground, with similar initial conditions (e.g., weight, speed, etc.), control inputs, and throttle inputs to the recorded FDR inputs. The simulation was driven with the FDR stabilizer position, column position, wheel position, and throttle positions. The simulation brake pressures were driven symmetrically with the biased [31] FDR right brake pressure. In addition, a math pilot was used to drive the rudder pedal position necessary to match the recorded heading and the calculated ground track. A mid centre of gravity of 20% was assumed. The simulation winds were driven with a constant wind and direction of 16 knots

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[29] “Math Pilot” refers to a simplified mathematical model, developed by Boeing and used to simulate the pilot.

[30] Boeing AAL802 report 2013

[31] As the left brake pressure transmitter was faulty, only right brake pressure data were used for simulation.

and 150°, as was reported at the time of landing. The runway surface contamination was modeled using a Federal Aviation Administration (FAA) wet runway. [32]

The scope of the simulation study was determined through discussion among TSB, Boeing, NTSB, and American Airlines personnel, and the following factors were considered as possible causes for the deviation from runway centerline:

- Whether the runway was wet or flooded
- Variations in the crosswind, such as wind gusts
- Difference in the braking action between the left and right main gear
- Differences in the amount of reverse thrust
- Nose-gear steering anomalies

These possible causes were simulated by Boeing. Based on the engineering simulations performed, the best match between the simulation and FDR data from all of the possible cases analyzed was determined to be a nose-gear steering anomaly. A nose-gear steering rate jam was the best match, as opposed to a nose-gear steering position jam. Several nose-gear steering rates were studied (½° per second, 1° per second, 2° per second and 5° per second); [33] the ½°-per-second rate jam provided the best match. Boeing believes that the most likely cause of the uncommanded steering input was a temporary, low slew-rate, nose-gear steering rate jam.

1.15.2 Nose-gear Steering Rate Jam

A nose-gear steering rate jam occurs when the feedback to the steering system is interrupted, causing the nose gear to continue turning (slewing) at a fixed rate until full travel is reached or until the rate jam is eliminated.

One explanation for a rate jam is trapped debris within the metering valve (slide/sleeve), which prevents it from completely closing. This prevention causes the nosewheel to change angle at a given rate, thereby causing an uncommanded steering input. A metering-valve rate jam is difficult to confirm, since it may not necessarily cause damage to the valve assembly, and the debris causing the jam may be flushed away through the hydraulic system fluid once the jam is cleared, leaving no evidence of a jam. The calculated, theoretical size of the debris capable of producing a ½°-per-second rate jam is estimated to be .0035 inches in size. [34] When a valve is being assembled or when a valve is being installed on an aircraft, there are 2 instances when hydraulic ports are open and debris has the potential to enter the valve. Also, Boeing presumes that debris can be generated from hydraulic fitting threads when the valve is being installed, or can be generated from within the valve during in-service use, such as if an internal component starts to deteriorate, or elsewhere within the hydraulic system. In all past cases in which the likely cause of an uncommanded steering input was also associated with a nosewheel steering

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[32] Boeing AAL802 report 2013

[33] In other rate jam occurrences, Boeing has seen only low slew rates of 5° per second or less. The theoretical size of possible debris within the valve, capable of jamming the valve to give a rate higher than ½° per second, would be greater than .0035 inches, and therefore bigger than the 100-micron inlet screen.

[34] .0039 inch = 100 microns

rate jam, there was no sign of deteriorating parts within the valves examined. Hydraulic fluid cleanliness standards are discussed further in 1.17.4.

Parker Hannifin Corporation (PHC), the nosewheel steering valve manufacturer, explains that by design, the control valve is able to shear any particles or debris by being manufactured with a very close tolerance fit, which would prevent larger particles (greater than approximately 0.000100 inch) from getting stuck between the spool and the sleeve. If a particle smaller than the clearance were to get stuck between the spool and the sleeve, the valve has more than adequate chip shear capability to overcome any resistance of these extremely small, insignificant particles. In the ½°-per-second rate-jam scenario, the theoretical particle is estimated to be 0.0035 inches in size, and would not become lodged in the clearance of the valve. The 0.0035-inch particle most likely would become lodged in the metering orifice between the spool and the sleeve (as shown in Appendix D) as the spool opens at the metering orifice. Per calculation, the force required to shear a theoretical 200-ksi tensile-strength steel particle of this size is only 5 pounds at the nosewheel steering metering-valve input. PHC states that in similar valves where shear capability has been tested, hard metallic debris that is sheared off tends to leave visible evidence of markings and scratching on the spool and sleeve edges. Due to this designed shear capability of the valve, and since this event and none of the previous events exhibited visual evidence of shearing due to debris, PHC has not conducted further testing of the nosewheel steering metering valve.

The second cause of a rate jam is debris, such as ice or stones, becoming lodged in the external linkage that operates the steering valve. A jam of the external summing linkage that operates the input lever to the steering valve will have the same effect (rate jam) as a jam of the valve's internal slide/sleeve. The steering assembly is shielded by a plastic cover, [35] but is not sealed and is exposed to environmental conditions while the aircraft is on the ground, when the gear is extended on approach for landing, and until the gear is retracted after take-off. No testing or research has been conducted by Boeing to attempt to replicate a rate jam scenario due to an external linkage jam.

In this occurrence, Boeing came to the conclusion that the heading deviation on landing roll was likely due to a nose-gear steering rate jam at a low slew rate (approximately ½° per second), and was temporary in nature, lasting a period of 8 seconds, from 0053:10 to 0053:18.

1.15.2.1 *Nose-gear Steering Metering-valve Operation*

When a steering command is made, cables operate the steering metering valve, and hydraulic pressure causes the steering cylinders to rotate the shock-strut inner cylinder to turn the nosewheel. Cables also transmit the movement of the steering collar to the steering metering valve to null it and stop the nosewheels at the commanded position. Since both cables are connected to a fixed reference (steering collar), any differential movement of the cables causes an increase in tension on 1 and a decrease in tension on the other. The tension differential will cause the input crank to rotate and actuate the steering metering valve.

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[35] The plastic cover serves to preclude jamming from tools, loose fasteners, mud, stones, slush, and ice.

The nosewheel steering metering-valve module is located on the nose-gear shock strut, and provides hydraulic power to operate the nosewheel steering in response to mechanical inputs. Movement of either the tiller or rudder pedals is transmitted by cables to a summing mechanism. The summing mechanism then moves the steering metering valve, which directs 3000-psi hydraulic fluid to the nosewheel steering actuators to turn the steerable portion of the nose gear. The actuators get pressure on the extend side, the retract side, or both sides, to move the nose-gear wheels from 0° to 78°. When the nosewheels get to the commanded position, the summing mechanism moves the metering valve back to neutral. This movement stops hydraulic pressure to the actuators. The actuators hold the wheel at the current position.

The steering metering valve essentially tracks the pedal movement, so that any time the pedals are moved toward the left, the nose gear will also steer left. If the nose gear is steered to the right with a right pedal input, and then the right pedal is released, the system commands the steering metering valve to perform a left turn to steer the nose gear back to the center (the neutral position). If the valve, or the linkage that operates the valve, becomes jammed in a position for a commanded turn, the gear will continue to slew until the jam is unjammed or the steering reaches full travel. This situation is referred to as a nose-gear steering rate jam. Thus the steering metering valve has the potential to become jammed in a left turn not only when a left pedal input is applied, but also when a right pedal input is released.

The FDR data shows that during the 8 seconds of the heading change to the left, the right rudder pedal was released 4 times, which would command a movement toward the neutral position, thus creating 4 possible instances for a left rate jam to have occurred.

1.15.2.2 *Nose-gear Steering Metering-valve Teardown, Examination and Functional Testing*

Following the conclusion that a nose-gear steering rate jam was most likely the initiating factor for the uncommanded steering event, the nose-gear steering metering valve [36] on the occurrence aircraft was removed on 17 February 2011 and shipped to the valve manufacturer, PHC, at the Parker Aerospace facilities in California, for testing and teardown. As the nosewheel steering assembly was tested and found to be fully functional following the occurrence in CYUL, the valve had not been removed at that time. The valve had remained on the occurrence aircraft since the 30 November 2010 event, and no other directional control difficulties were noted; this finding would concur with a temporary jam situation, since the nosewheel steering system continued to operate normally after the occurrence.

The nosewheel steering metering-valve module is an on-condition replacement item; therefore, the total time in service is not necessarily tracked by the operator. An external inspection of the valve showed no damage. The PHC safety seals on the occurrence nosewheel steering valve safety wire indicated that the valve was assembled at the PHC facility. There were no PHC records to indicate that the valve had been returned to the facility since manufacture. [37] American Airlines records show that the valve was installed on the occurrence aircraft in 2002.

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[36] PHC valve part number 383900-1007, serial number 1621

[37] The valve was manufactured in the 3rd quarter of the year 2002; the PHC manufacture date reference number is 3Q02.

1.15.2.3 *Steering Metering-valve Fluid Examination*

One ounce of translucent purple fluid, consistent in colour and odour to Skydrol, was recovered and submitted to the PHC Materials and Processes Lab for analysis. This sample was taken collectively from the return, inlet, and swivel ports before removal of the inlet screen. Metal particles found in the hydraulic fluid sample were bigger than the inlet filter mesh. Since this valve module does not have an inlet-filter bypass valve, it is unlikely that the large metal particles came from upstream of the inlet filter. The small fluid-sample size did not permit classification of the fluid on a cleanliness scale. Removal of the inlet filter screen [38] revealed that its mesh was intact, and approximately 1% of the screen area was obstructed by brown-coloured, teflon film debris.

1.15.2.4 *Steering Metering-valve Functional Testing*

The valve was functionally tested. Tests performed indicated that the unit was capable of normal operation. Disassembly of the nosewheel steering metering-valve module did not reveal any mechanical anomalies other than slight burnishing and scuffing associated with normal wear.

1.15.2.5 *Additional Boeing Simulations*

The TSB asked Boeing if, when using the engineering simulation, it would have been possible for the PF to keep the aircraft on the runway using only the rudder pedals.

Additional simulations completed by Boeing consisted of modifying the rudder pedal inputs to attempt to keep the aircraft on the runway. Boeing ran 2 scenarios with the engineering simulations.

The first scenario consisted of an increase of right rudder pedal input (up to full rudder deflection) starting from a neutral position at 1953:13 (i.e., 3 seconds after the start of the uncommanded left veer). This time was chosen as it was the time at which right control-wheel input was applied instead of right rudder pedal. During the simulation, from 1953:13, an increase of right rudder pedal input was applied, reaching full rudder deflection at 1953:17; therefore a gradual application of rudder pedal was involved, with maximum pedal reached after 4 seconds. Rudder pedal was not released until the simulation was terminated. The jam is assumed to have released at 1953:18 [39] (Appendix E).

The second scenario consisted of applying and holding full rudder pedal from 1953:19, [40] exceeding the amount of rudder pedal input that was recorded on the FDR at that time, when the aircraft heading started to return to the runway heading. This rudder pedal input was held for approximately 3 seconds, until the aircraft was recovering back toward the runway centerline (Appendix E).

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[38] The inlet filter, part number BASX0500300B, has a 100-micron mesh size.

[39] Ground speed was 68 knots.

[40] Ground speed was 64 knots. The simulation ended at 1953:22; the speed was 56 knots.

These simulations showed, in both scenarios, that there would have been sufficient control available to prevent significant deviation from centerline. Rudder pedal only was used during the simulations. Additional directional control would have been available from differential braking or differential reverse thrust. Boeing simulations suggest that there was enough control power from the rudder pedals to keep the aircraft on the runway, assuming that the rate jam cleared at 1953:18, as explained above.

1.16 Organizational and Management Information

1.16.1 American Airlines Training

American Airlines flight crews undergo regular classroom and simulator training to provide them with the expertise to conduct safe flight operations, while also providing operational efficiency and passenger comfort. During this training and during line operations, flight crew refer to different manuals. Some of the manuals provide technical information and systems description, while others provide information relevant to the limitations and operation of the aircraft. Training is structured so as to expose crews to the different failure scenarios that they might be faced with during operations in flight and on the ground.

Checklists are developed to assist flight crew in addressing particular systems failures or faults. Checklists cover normal procedures and emergencies, and most often will correspond to a light, an alert, or another indication. These lights, alerts, and other indications are cues for the crew to select and execute the associated checklist. Non-normal checklists are used by the flight crew to manage non-normal situations. Boeing also includes guidance for situations that go beyond the scope of the non-normal checklists. The guidance is general in nature and, in reference to directional control problems on landing or take-off, instructs a crew on how to make accommodations for demanding situations that may require the use of various controls to prevent drift and runway excursions.

A search of the various reference manuals [41] available to this flight crew identified multiple sections that describe how to deal with jammed or restricted flight controls, such as ailerons, spoilers, rudder, and elevators. No reference was found on how to deal with a nose-gear steering problem or rate jam. There are also sections that deal with crosswind procedures, crosswind procedures with slippery runway, asymmetrical thrust, and landing with flat tires. Aircraft behaviour for these types of occurrences may, depending on conditions, be similar to the aircraft behaviour encountered with a nose-gear steering problem or rate jam.

A nose-gear steering rate jam during landing roll would not be annunciated by any light, alert, or other indication. Given that it can occur on landing roll or take-off, a checklist specific to this type of event would not be consulted. The reaction to this type of event would have to be immediate and intuitive, as various situations may adversely affect airplane characteristics during landing roll or take-off roll. Aggressive differential braking and / or use of asymmetrical

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[41] *Boeing 737 NG Flight Crew Training Manual*, *Boeing 737-800 Flight Crew Operations Manual*, *American Airlines Boeing 737 Operating Manual*, and *American Airlines Aircraft Flight Manual*

reverse thrust, in addition to other control inputs, may be required to maintain directional control. [42]

1.17 Additional Information

1.17.1 Pilot Reaction

A simple model of human information processing consists of a series of stages of mental operations between a stimulus and a response. Basically a stimulus is perceived, the information is processed, a decision is made, and an action is taken; or it might be decided that none is required. Once this process is completed, the person waits to sense the results before taking further action. Pattern recognition is part of the processing stage. It consists of mapping the physical cues obtained from the senses into meaningful cues from memory. The entire process can be completed well within a single second. [43] It will take longer when the stimulus perceived does not match what is expected or no pattern is immediately recognized. Dekker [44] explains:

> People update their understanding of an unfolding situation on the basis of cues that come in. This understanding in turn directs them to act (or not) in one way or another, which changes the situation which in turn updates people’s understanding of what is going on.

In some instances, pilot reaction can be influenced by strong habit intrusion, which occurs when features of the present environment contain elements similar or identical to those in highly familiar circumstances. These are activities judged as being recently and frequently engaged in, and as sharing similar locations, movements, and objects with the intended actions. In essence, these actions become largely automatic in their execution. [45]

Training significantly affects how an emergency or abnormal situation is handled. Studies completed on pilot reaction time in simulators have shown that during simulated emergencies, when pilots are expecting some kind of emergency to be introduced, reaction time will be shorter than in real-life situations, when the emergency situation is not expected and may not have been recently practised. Certain training manoeuvres are made mandatory through the provisions of present regulations. [46] Certain crucial checklists are considered memory items, are

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[42] *Boeing 737 NG Flight Crew Training Manual*, Situations Beyond the Scope of Non-Normal Checklist, p. 8.35

[43] Pilot reaction time can be defined as the time between the onset of a stimulus and the beginning of an overt action, and could involve the simultaneous use of the hands and feet. The FAA defines reaction time as the human response time plus response initiation time.

[44] S. Dekker, *The Field Guide to Human Error Investigations* (Ashgate Publishing Limited: 2002), page 94

[45] J.T. Reason, *The Human Contribution: Unsafe Acts, Accidents and Heroic Recoveries* (2008)

[46] *Federal Aviation Regulations* (FARs) Part 121, Appendix H, Section H121.1 through H121.4 (United States); *Canadian Aviation Regulations* (CARs) Standard 725, Airline Operations − Aeroplanes, Division VIII − Training, Sections 725.124 and 725.125 (Canada)

practised often, and readily come to the mind when encountered. Crews are rarely faced with a situation for which there is no checklist or procedure, even though this can be the case in actual emergencies. [47]

In this event, when the aircraft started to gradually veer to the left of runway centerline, the PF did not immediately apply right rudder pedal to counter the heading deviation. Three seconds after the start of the veer, the PF's initial reaction was to gradually turn the control wheel to the right, until it reached its maximum (90°), 6 seconds later. The PF felt as if the aircraft were on ice, as if it were skidding. A slight sideways motion was recorded in the FDR data. The crew members were not anticipating a slippery runway, although it was wet; the outside air temperature was 7°C.

Seven seconds after the start of the uncommanded veer to the left, the PF started to increase right rudder pedal input, reaching approximately 83% of full travel 2 seconds after that. At this point, the aircraft heading started to increase, bringing the aircraft back to the right. The PF reduced right rudder pedal input and, 1 second later, the aircraft left the paved runway surface (Figure 2).

Differential braking can be applied to help steer or stop the aircraft; however, the PF did not use manual differential braking to attempt to either steer or stop the aircraft during the event.

There was no request by ATC before landing to expedite exiting the runway. There were no other aircraft close behind on approach following AAL802. The crew did not feel pressed to exit the runway quickly, nor was it the PF's intention to exit on Echo taxiway, as the aircraft speed was too high at that exit intersection. Exiting at the end of Runway 24R, or at taxiway B2, also favoured the assigned arrival gate.

The PM did not take over the controls from the PF during the deviation from runway centerline as the PF was active on the controls, nor would the PM's intervention on the controls have been expected under the circumstances encountered.

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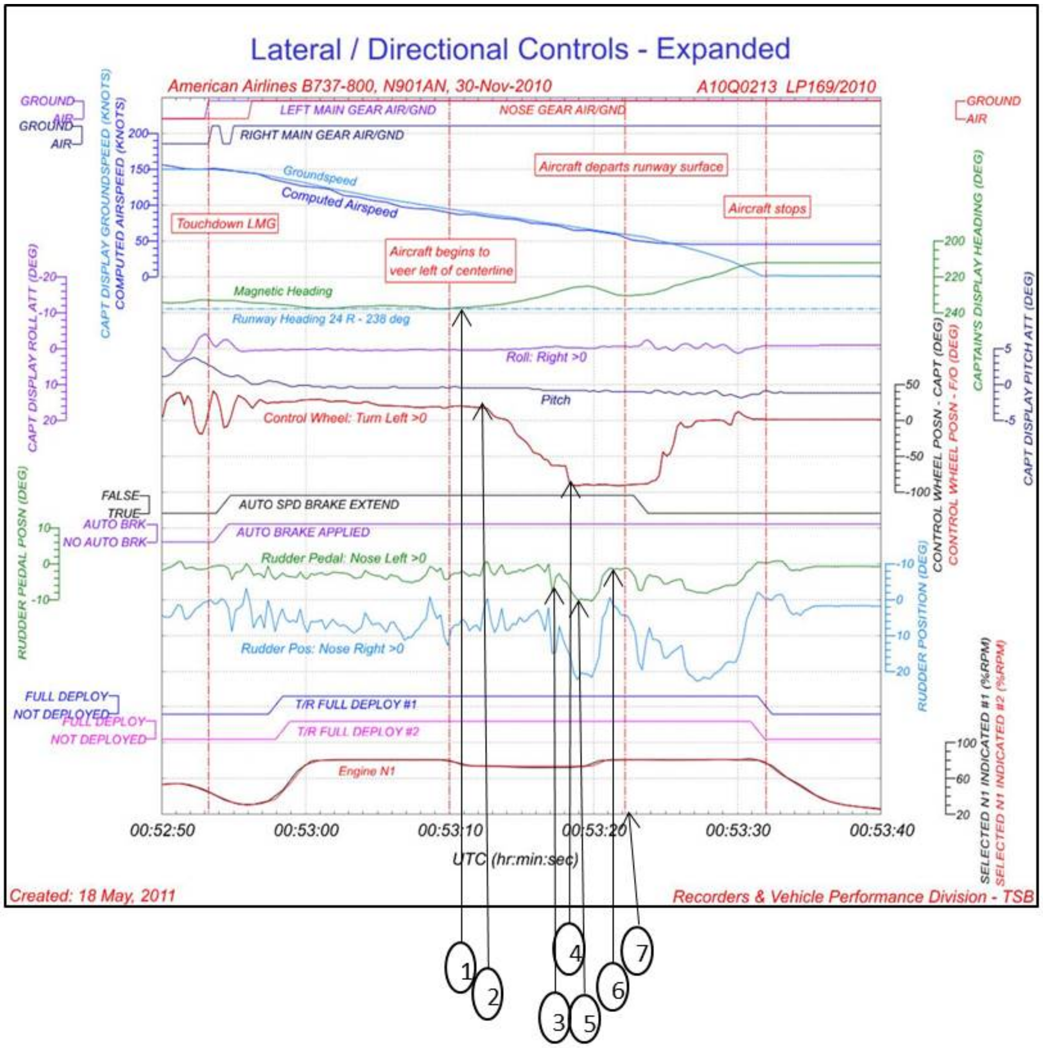
[47] B.K. Burian, I. Barshi, and R.K. Dismukes, *The challenges of aviation emergency and abnormal situations*, NASA Technical Memorandum 2005-213462 (Moffett Field, CA: NASA Ames Research Center, 2005)

Figure 2. Pilot reaction to uncommanded left veer



1. Heading starts decreasing to the left
2. PF initiates to turn control wheel to the right
3. PF increases input to right rudder pedal
4. Control wheel reaches maximum deflection
5. PF increases right rudder pedal input to approximately 83% of travel
6. PF reduces right rudder pedal input
7. Aircraft crosses edge of runway

1.17.2 Previous Occurrences

Over a 21-year period, there have been a total of 11 occurrences (including this one) involving Boeing aircraft, [48] for which the aircraft manufacturer has either analyzed FDR data or done some evaluation, and has attributed the events to a likely nose-gear steering rate jam. The first event was in 1991. All events have occurred on landing, and have resulted in just over half of these aircraft departing the intended runway surface to some degree. The B737 was involved in 7 of the 11 events. Boeing estimates that the rate at which a nose-gear steering rate jam occurs is in the order of 1 occurrence in 10 000 000 cycles (1×10^{-7} occurrences per cycle). This is based on the known number of events of which Boeing was aware and for which there was some analysis or examination completed. Teardown examination of the valves involved in several of these occurrences did not show any valve malfunction or anomaly; consequently, no conclusions as to the exact cause of the nose-gear steering rate jams has been identified. However, aircraft behaviour, simulations conducted by Boeing, and diagnosis by exclusion completed while analyzing available FDR data lead to the most likely cause being a nose-gear steering rate jam. The specific cause of the rate jam remains unknown. Boeing also assumes that there may be approximately 1 occurrence per year over the entire Boeing worldwide fleet, based on the current fleet size. The number of occurrences could be higher if events have occurred but have not been reported.

Due to the lack of conclusive evidence as to the exact cause of the uncommanded steering-input events, and even though information collected suggests nose-gear steering rate jams, Boeing has not informed the industry of the possibility of nose-gear steering rate jams occurring, nor is it mandatory to do so given the rate at which they seem to occur; the lack of evidence of a part failure, malfunction, or defect of a given part; [49] and the lack of aircraft damage and injury to occupants. There is no information or guidance provided to operators or crews regarding the controllability of a B737 aircraft in the event of a nose-gear steering problem similar to the one encountered in this occurrence. This flight crew was unaware of the possibility of a nose-gear steering rate jam.

Although advised by Boeing that these rate-jam events are reported to the FAA, nothing indicates that the FAA has conducted a risk-assessment, or that these events are systematically tracked in the FAA hazard tracking system (HTS). Depending on the consequences of such an event, this type of event would not necessarily fall into the *Federal Aviation Regulations* (FARs) 21.3 reporting criteria—as a part has not been considered faulty and has not failed—or into the NTSB accident/incident reporting criteria. Also, if there is no damage to the aircraft or injury to occupants, it is not reportable. [50]

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[48] The 21-year period covers from the first occurrence in 1991 to November 2012. Boeing models affected include 707/720, 727, 737, 747 (some models), 757, 767, and 777.

[49] FAA Code of Federal Regulations (CFR) Title 14: Aeronautics and Space, Part 21 – Certification Procedures for Products and Parts, Subpart A

[50] 49 CFR, Part 830

1.17.3 Swedish Occurrence

The Swedish Accident Investigation Board completed an investigation of a runway excursion incident in April 2004 involving a B737-600. [51] This occurrence is considered to be one of the likely nose-gear steering rate-jam occurrences analyzed by Boeing. [52]

The aircraft landed at Ängelholm-Helsingborg Airport (ESTA). When the speed had decreased to approximately 60 knots, and as the pilot in command had taken over the steering on the runway using the nosewheel control (tiller), the aircraft suddenly started a yaw to the right. With the nosewheel steering, rudder, and differential wheel-braking, the pilot attempted to steer the aircraft back on course, but without success. After rolling a further 100 meters (328 feet), the aircraft left the runway, finally coming to a stop with the nosewheel just outside the right runway edge. No technical fault was found. The Swedish report states:

> The incident was caused because the design of the nose wheel steering on this aircraft type permits a spontaneous turn without operation by the pilots. A contributory factor is that the aircraft manufacturer considers the malfunction to be acceptable if the failure rate is lower than 1x10^{-}5.

1.17.4 Hydraulic Fluid Cleanliness

In the hydraulic system, the liquid serves as both a power-transmitting medium and a lubricant. The presence of solid contaminant particles in the liquid interferes with the ability of the fluid to lubricate and causes wear to the components. [53] Maintaining hydraulic fluid cleanliness is important to proper hydraulic system operation and prolongs the life of certain components. Hydraulic fluid contaminants include solid particles, air, water, or any other object that impairs the functioning of the pressurized hydraulic system.

In 1998, the FAA identified National Aerospace Standard (NAS) 1638 as an industry standard that defines hydraulic fluid cleanliness levels; class 9 is considered the in-service limit. [54] While this standardization has led the way to the development of other systems, such as International Organization for Standardization (ISO) 4406, the NAS 1638 class system is still being cited in industry. The cleanliness level of a hydraulic fluid is determined by counting the number and size of particles in a given sample of fluid. This class 9 requirement has been added to the *B737 Aircraft Maintenance Manual*. Boeing does not impose a requirement for regular sampling of hydraulic system fluid. It is suggested to the operator to take samples after the first year of service and then adjust the intervals as their operations' experience indicates to maintain class 9 or below. Boeing also recommends fluid sampling after certain hydraulic system events, which are listed in the aircraft maintenance manual.

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[51] Swedish Accident Investigation Board, Report RL 2005: 14e, Case L-06/04. This occurrence is among the 11 known occurrences.

[52] Since the Swedish occurrence in 2004, the Boeing fleet has expanded by 3197 aircraft (27%) worldwide. Globally, Boeing deliveries to July 2012 totalled 14 725 aircraft.

[53] *International Journal of Aerospace Engineering*, Article ID 156281 (Hindawi Publishing Corporation: 2010)

[54] Class numbers indicate cleanliness levels; class 1 is the cleanest fluid.

American Airlines had hydraulic-fluid sample testing done on the occurrence aircraft in July 2009; the fluid cleanliness level was determined to be a class 12 fluid. Following this sampling analysis, it was recommended that the operator drain and refill the system reservoir with new fluid. It was also suggested that system filters be replaced. American Airlines samples the hydraulic system every 3400 flight hours (normally accomplished every 24 months). For the occurrence aircraft, the A and B hydraulic reservoirs were drained and replenished with new fluid during a maintenance base visit between 18 June and 21 July, 2010. No hydraulic fluid samples were taken and / or tested specifically to confirm hydraulic fluid cleanliness after the 2010 maintenance base visit. No hydraulic fluid samples had been taken following the occurrence on 30 November 2010; the hydraulic fluid cleanliness level at the time of the occurrence was not determined.

1.17.5 Certification

The Boeing 737, manufactured in the US, was certificated under FARs Part 25 −Airworthiness Standards, Transport Category Airplanes. Most of the FARs, including Part 25, started on 01 February, 1965. Once an airplane design is certified using some parts of the FARs, it is certified regardless of whether the regulations change in the future. The B737-800 was certified as a derivative of the original B737-100. However, various amended regulations were also complied with at the time of the 800 series development.

Boeing’s Internet site states that the company has delivered 7010 B737 aircraft worldwide. [55] There are 246 Boeing aircraft registered in Canada; 158 of these are B737s. There are 1289 Boeing aircraft registered in the US.

The original nosewheel steering valve installed on earlier B737 models was manufactured by Sargent Aerospace & Defense. The main control valve (nosewheel steering valve) on the occurrence aircraft was a valve manufactured by PHC; its initial design has remained unchanged since 1997. This valve is very similar in design and operation to the earlier certified valve, and both are built to Boeing specifications. PHC has published 3 service bulletins (SBs) for the B737 nosewheel steering valve. Two of the SBs address the incorporation of new swivels with improved surface finish and new seals that provide longer life and reduced external leakage. The third SB addresses the replacement of a bushing on the towing lever to prevent sticking due to external corrosion in the towing lever mechanism. The B737 NG valve also made by PHC is very similar to what is used on Boeing’s 777, 767, 757, and some models of the 747; however, it has a different manifold design. Overall, Boeing and PHC state that this occurrence valve and the similarly designed units on the other Boeing models have been considered very reliable, with very few service problems.

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[55] Boeing 2010 statistics show 5 000 000 landings per year for the B737 NG fleet. The Boeing 737 is used on short-haul flights, for which more landings take place per year than landings by aircraft used on long-haul flights.

1.17.6 Risk Assessment Methodology

1.17.6.1 *Safety Programs*

Many safety programs exist throughout the aviation industry and are used by operators to ensure that flight operations remain efficient and safe. These safety programs are usually interfaced and coordinated with the flight operational quality assurance (FOQA) program, which is a safety program designed to improve aviation safety through the proactive use of recorded flight data. Digital flight data generated during aircraft operations are collected routinely and analyzed for the purpose of identifying and correcting deficiencies in all areas of flight operations. FOQA data can help reduce or eliminate safety risks, as well as minimize deviations from regulations. Through access to the combined and de-identified FOQA data, the FAA can identify and analyze national trends and target resources to reduce operational risks within aviation operations that are of interest.

Many airlines have a FOQA program in place (including American Airlines, among their other safety programs), [56] but they do not currently capture steering events. In order to possibly capture events such as nose-gear steering problems, it would be necessary to add specific filters (gatekeepers) to the software parameters so that these events can be flagged. The flagging of steering events would be clumsy, as there are no sensors on the nose-gear steering system, and numerous steering events caused by a multitude of other variables would be captured instead. Further analysis would be necessary following any flagging to ascertain whether the event were a rate jam or not, as the determination calls for diagnosis by exclusion.

Data concerning an event with a Boeing aircraft are provided to the FAA by Boeing via their continued operation safety program (COSP). Once a COSP report is filed by Boeing, its internal safety review process is launched and involves many safety review steps by various departments. The FAA may decide to take part or not in this review process at any point along the various steps completed by Boeing. See Appendix F to view the table used by the FAA to ensure that the safety issue of concern meets certification requirements. If the issue does not meet requirements, then appropriate corrective action is considered necessary. Boeing has reviewed all of the 11 known nose-gear steering rate-jam events. The review process revealed a known rate of occurrence of less than $1 \text{ X } 10^{-7}$, with the severity level as Major, and therefore, as per the table in Appendix F, no further action was deemed necessary.

1.17.6.2 *Risk Assessment*

The FARs Part 25 airworthiness standards are based on, and incorporate, the objectives and the principles or techniques of the fail-safe design concept, which considers the effects of failures [57] and combinations of failures in defining a safe design. According to FAA Advisory Circular AC 25.1309.1A, the following is one of the basic design objectives pertaining to failures:

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[56] American Airlines uses the Aviation Safety Action Program (ASAP), Advanced Qualification Program (AQP), Air Carrier Internal Evaluation Program (IEP), Line operations safety audits (LOSA) and FOQA.

[57] A failure is the loss of function, or a malfunction, of a system or a part thereof.

> In any system or subsystem, the failure of any single element, component, or connection during any one flight (brake release through ground deceleration to stop) should be assumed, regardless of its probability. Such single failures should not prevent continued safe flight and landing, or significantly reduce the capability of the airplane or the ability of the crew to cope with the resulting failure conditions.

To assess whether an event is a safety issue or not, the FAA uses the FAA Monitor Safety / Analyze Data (MSDA) process, which is designed to filter, review, analyze, and trend aviation safety data. MSDA is meant to help identify safety issues in the in-service fleets, and identify corrective actions to mitigate safety risks across the fleet. The process also identifies other causes of safety issues that cannot be addressed by fleet (product / part) corrective actions.[58] The MSDA process may be triggered by data received because an event was reportable by definition or from data provided by a manufacturer, a maintenance provider, or an operator.

The MSDA process document explains that the process covers everything from receiving data to determining fleet corrective action. Issuing the corrective action is outside MSDA; it is part of the airworthiness directive (AD), special airworthiness information bulletin (SAIB), and / or other FAA actions or recommendations processes. Certain certificate holders (e.g., the manufacturer) have their own processes to filter, review, analyze, and trend aviation safety data on their products (e.g., a COSP program).

A risk assessment exercise [59] uses a classification of failure conditions [60] by their severity: minor, major, hazardous, and catastrophic. Probable, remote, extremely remote, and extremely improbable are terms to define the probability of a failure condition. Each failure condition should have a probability that is inversely related to its severity. Minor failure conditions may be probable. Major failure conditions must be improbable. Catastrophic failure conditions must be extremely improbable. [61]

There are 2 fundamental types of risk analyses: quantitative and qualitative. Each method of analysis has pros and cons. The results of a qualitative analysis are meant to support experienced engineering and operational judgement (e.g., to determine compliance with the requirements of system design and analysis). [62] The TSB uses qualitative analysis when conducting a risk-assessment.

The FAA, the regulatory body following certification and in-service fleet airworthiness, and Boeing, for example, use quantitative and qualitative analysis to assess the risk level of a safety

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[58] FAA Order 8110.107A, Monitor Safety / Analyze Data

[59] Risk assessment is the term used to describe the complete process of assessing a risk.

[60] “Failure condition” refers to the effects on the airplane and its occupants, both direct and consequential, caused or contributed to by 1 or more failures, considering relevant adverse operational or environmental conditions.

[61] Definitions of the terms used to define severity and probability are in the FAA Advisory Circular AC 25.1309.1A.

[62] *FAA System Safety Handbook* risk assessment matrix, Chapter 3

issue or event. Quantitative analysis usually expresses numerical probability ranges for each flight-hour, based on a flight of mean duration for the airplane type. However, for a system function that is used only during specific flight operations (e.g., take-off, landing, etc.), the acceptable probability would be based on, and expressed in terms of, the duration of that specific phase of flight. [63]

When using the FAA or Boeing definitions in assessing rate-jam events, and given the rate of occurrence of these events, the severity level is assessed as major [64] and extremely remote on the probability scale for a rate of 1 X 10^{-7} (Table 3 and Table 4).

Table 3. Severity Definitions for FAA AMS Process [65]

Catastrophic	Results in multiple fatalities and / or loss of the system
Hazardous	Reduces the capability of the system or the operator ability to cope with adverse conditions to the extent that there would be: Large reduction in safety margin or functional capability Crew physical distress / excessive workload such that operators cannot be relied upon to perform required tasks accurately or completely (1) Serious or fatal injury to small number of occupants of aircraft (except operators) Fatal injury to ground personnel and / or general public
Major	Reduces the capability of the system or the operators to cope with adverse operating condition to the extent that there would be – Significant reduction in safety margin or functional capability Significant increase in operator workload Conditions impairing operator efficiency or creating significant discomfort Physical distress to occupants of aircraft (except operator) including injuries Major occupational illness and / or major environmental damage, and / or major property damage

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[63] FAA Advisory Circular AC 25.1309-1A, System Design and Analysis, page 15

[64] Although no significant damage to aircraft or injuries to occupants has occurred in past likely events, Boeing considers this event of major severity, not hazardous.

[65] *FAA System Safety Handbook*, Chapter 3: Principles of System Safety (December 30, 2000), available at http: / / www.faa.gov / regulations_policies / handbooks_manuals / aviation / risk_management / ss_ handbook / media / Chap3_1200.pdf (last accessed on 25 September 2013). AMS refers to Acquisition Management System.

Minor	Does not significantly reduce system safety. Actions required by operators are well within their capabilities. Include Slight reduction in safety margin or functional capabilities Slight increase in workload such as routine flight plan changes Some physical discomfort to occupants or aircraft (except operators) Minor occupational illness and/or minor environmental damage, and/or minor property damage
No Safety Effect	Has no effect on safety

Table 4. FAA Likelihood of Occurrence Definitions [66]

Probable	Qualitative: Anticipated to occur 1 or more times during the entire system/operational life of an item. Quantitative: Probability of occurrence per operational hour is greater than 1 X 10^{-5}
Remote	Qualitative: Unlikely to occur to each item during its total life. May occur several times in the life of an entire system or fleet. Quantitative: Probability of occurrence per operational hour is less than 1 X 10^{-5}, but greater than 1 X 10^{-7}
Extremely Remote	Qualitative: Not anticipated to occur to each item during its total life. May occur a few times in the life of an entire system or fleet. Quantitative: Probability of occurrence per operational hour is less than 1 X 10^{-7}, but greater than 1 X 10^{-9}
Extremely Improbable	Qualitative: So unlikely that it is not anticipated to occur during the entire operational life of an entire system or fleet. Quantitative: Probability of occurrence per operational hour is less than 1 X 10^{-9}

If using a probability assessment of extremely remote and a severity level of major, the quantitative risk level remains within the certification and in-service fleet following requirements established by the FARs (Appendix F). [67] This level would correspond to an "Acceptable" level of risk as per the FAA definitions of risk levels. [68] Nothing indicates that the

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[66] FAA System Safety Handbook, Chapter 3: Principles of System Safety (December 30, 2000), available at http://www.faa.gov/regulations_policies/handbooks_manuals/aviation/risk_management/ss_handbook/media/Chap3_1200.pdf (last accessed on 25 September 2013). AMS refers to Acquisition Management System.

[67] Ibid

[67] Boeing has certified its aircraft to meet requirements for both the FARs (Federal Aviation Regulations) and the JARs (Joint Aviation Requirements of certain European countries).

[68] FAA Order 8040.4A, Appendix C. Acceptable = A safety risk without restriction or limitation; hazards are not required to be actively managed, but must be documented.

FAA has conducted a risk assessment on nose-gear steering rate jams, nor does it seem that these events are being tracked in the FAA HTS.

1.17.7 Defence Analysis

A major component of any transportation system is the set of defences [69] put in place to protect people, property, and/or the environment. These defences can be used to reduce the probability of unwanted events, and to reduce the negative consequence associated with unwanted events.

Analysis of defences leads to a better understanding of the safety issues and safety problems associated with an occurrence. In particular, this analysis is used, in conjunction with the risk assessment process, to validate safety deficiencies. The objective of a defence analysis is to examine the situation to determine the absence or status of defences.

Less-than-adequate defences are those that are:

- provided for, but not advertised or made known to users;
- absent or not provided;
- in place, but not practical; or
- not functioning as intended.

Since the cause of the nose-gear steering rate-jam events cannot be conclusively determined, and consequently no defences can be applied to the source, it would be appropriate to look at defences applicable beyond the source. Boeing states that its defence for these events is the rigour of the in-service fleet safety review process that is completed each time a COSP and review process is initiated for a known rate-jam event. Other than this monitoring process provided by Boeing, this investigation was unable to identify any other defences or mitigation strategies put in place to reduce the adverse consequence of a possible runway excursion following a nose-gear steering rate-jam event.

1.17.8 Search of Other Databases

The TSB searched for similar occurrences in various aviation databases, such as that of the TSB of Canada (whole database, over a period of 20 years), the Air Accident Investigation Branch of the United Kingdom and the Australian Transportation Safety Board (over a period of 10 years), the National Transportation Safety Board (whole database) of the US, the European Coordination Centre for Accident and Incident Reporting Systems (going back to 1970), and the National Aeronautics and Space Administration (NASA) confidential Aviation Safety Reporting System database (going back a period of 20 years). After reading through the queried events' summaries and eliminating those that were not relevant in nature to uncommanded nose-gear steering events, no significant numbers of events were found. Insufficient details were available for the events retained and about the aircraft systems troubleshooted. Not enough information was available to confirm whether the events may have likely been due to a nose-gear steering rate jam. Their only resemblance to this occurrence event was that there seemed to be an

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[69] Defences can be divided into 2 categories, physical and administrative and can be aimed at limiting the likelihood of an accident and the harm that will be inflicted should an accident occur.

uncommanded steering initiating event that could not be readily explained by the crew or by the maintenance inspection that followed (Appendix G).

Insufficient information was gathered or recorded at the time to allow any conclusions on these steering-difficulty events, as they were not subject to full investigations; and post-occurrence troubleshooting, if any, in most cases was not recorded. When considering those entered in the NASA confidential reporting database, it is apparent that the events were disturbing enough that the individuals involved made the effort to report their concerns.

Due to the nature of these nose-gear steering rate-jam events, it is likely difficult for flight crew to distinguish, if the jam is of a relatively short duration, whether a change in heading is due to wind gusts, crosswind and / or runway conditions, and / or pilot skill and technique. If the event is gradual, is temporary in nature, and does not terminate with a runway or taxiway excursion, then it is likely not reported. Because the rudder remains effective for speeds over 60 knots and the heading deviations can be controlled in most cases if responded to in an immediate and pointed manner, the events may remain undetected and consequently not reported, documented, or analyzed. None of the likely known events analyzed by the manufacturer to date have ended in major damage to the aircraft or injury to occupants; however, not all runway environments are hospitable, and the potential for more serious damage, and for injury, remains a possibility, due to the possibility of a runway excursion and collision with another aircraft, vehicle, or object during the excursion.

Most recently, in 2011 and 2012, 2 other likely nose-gear steering rate-jam events have occurred involving the B737; in both events, the aircraft departed the paved runway surface to some extent. In 1 case, Boeing was involved with the analysis of the QAR data and in the other, the FDR data. It found that both occurrences were similar in nature to this occurrence. In the 2011 event, the aircraft was turned off the runway onto a high-speed taxiway. It continued to turn and exited the side of the taxiway at approximately 50 knots; there was minor damage to the nose gear and tires. The nosewheel steering metering valve was not subject to a teardown. In the 2012 case, the aircraft departed the runway surface on landing; the nosewheel steering valve, manufactured by Sargent Aerospace & Defense, was sent for teardown, and no faults were found. There was no damage to the aircraft or the environment. Neither of these events caused injuries to the occupants.

1.17.9 Efforts to Reduce Runway Excursions and the Need for Data Collection

In 2005, NAV CANADA proposed to other Canadian aviation stakeholders that a national interdisciplinary forum be formed to exchange information on runway safety. On 01 January 2006, the Runway Safety and Incursion Prevention Panel (RSIPP) came into effect. The mandate of the panel is to provide a national forum for the exchange of safety-related information, with the aim of promoting runway safety and reducing safety risks. Although the initial focus was mainly on runway incursions, efforts are now being made to collect statistics on runway excursions. In 2010, NAV CANADA launched an area on its corporate website, on behalf of RSIPP, that addresses runway safety in Canada and includes promotional material for use by the aviation community. In the period of 2010 to 2011, RSIPP launched a runway-excursion awareness campaign, which will include the creation of a runway-excursion database and an awareness program for aviation stakeholders, and will share industry best practices to help reduce the risk of runway excursions. Identification of the associated risk factors and risk-control options was necessary to categorize events, recognize trends, and pinpoint hazards. At time of writing of this report, the RSIPP runway-excursion database had not yet been created.

NAV CANADA statistics show that for the period covering April 2010 to March 2012, there were 147 runway excursions on landing and 21 excursions on take-off in Canada. [70] Of the 147 landing excursions, 111 were attributed to pilot directional control difficulties. All 21 take-off excursions were attributed to pilot directional control difficulties. [71]

In the US, as a result of accidents and related NTSB findings, the FAA announced a Call to Action Plan in June 2009 to increase air-carrier participation in voluntary safety programs and advance the use of safety management systems (SMS), which are data-driven and risk-based. Later, in April 2012, the US Government Accountability Office (GAO) recommended that the FAA develop and implement better means for collecting data on runway excursions and use this data proactively to prevent accidents and manage risk.

The TSB collects data on accidents and incidents. Through safety recommendations and safety advisories, it strives to increase safety for the public and decrease the risk of recurrence. The TSB's Watchlist includes landing accidents and runway overruns. However, information collected on the contributing risk factors associated with runway-excursion veer-offs is not necessarily collected in a manner that allows systematic analysis; consequently, the TSB database is lacking risk-factors information relative to veer-offs. The TSB is presently researching which would be the most appropriate runway-excursion risk factors to collect in its database.

In the same vein, in order to decrease the number of runway excursions, TC has developed regulations relating to winter maintenance and planning, regular monitoring and dissemination of accurate airfield information to aircrew, and training and testing of airside vehicle operators, and it has made efforts in ensuring that air crews are provided with accurate and up-to-date information on runway surface conditions, so that they may better understand and plan for landing or deviate to another airport. Data relevant to excursions is being collected within the TC database; however, there is no TC runway-excursion safety study presently underway that would help in identifying the associated risk factors.

In November 2012, the FAA, airlines and aviation labor unions announced a partnership with the NTSB to share summarized safety information that could help prevent accidents. The information, shared through an initiative called the Aviation Safety Information Analysis and Sharing (ASIAS) Executive Board, will help the NTSB determine whether an accident is a unique event or an indication of systemic risks. Under ASIAS, airlines and unions already voluntarily share safety information with the FAA to identify trends. Also, as of November 2012, ICAO and the Flight Safety Foundation (FSF) signed a new agreement formalizing their collaborative air safety data-sharing and risk-mitigation efforts. In January 2013, Eurocontrol issued its European Aviation Safety Plan (EASP) for the Prevention of Runway Excursions. [72]

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[70] These statistics include all types of aircraft. The nature of the pilot directional control difficulties was not stated.

[71] NAV CANADA, *Quarterly Runway Safety Report* (March 2012). Data include all types of aircraft. It was not stated how many of these excursions were veer-offs or overruns.

[72] One of the many items underlined in the efforts to prevent runway excursions by all practicable means was training (for operational staff) on unfamiliar situations that may lead to runway excursions.

Runway-excursion risk-factors data collection and data sharing in general is necessary to help identify the safety deficiencies that contribute to these events, whether they be veer-offs or overruns.

1.18 Useful or Effective Investigation Techniques

Not applicable.

2.0 Analysis

2.1 General

The crew performed a stable approach and normal landing at night, in light rain conditions. Runway conditions were reported to be bare and wet. Braking conditions were considered to be good. All aircraft systems were operating normally on approach and landing during the initial deceleration and landing roll. A detailed examination of the flight data recorder (FDR) data indicated that the left veer from runway centerline, 16 seconds after landing, was uncommanded by the crew. This analysis will focus on pilot reaction, the need for industry awareness on nose-gear steering rate-jam events, and the need for better data collection.

2.2 Recorder Information, Data, and Engineering Simulations

By pulling the cockpit voice recorder (CVR) circuit breaker, the crew preserved the CVR recording. It is often the case that this item is forgotten. It is important that operators include this item in the checklist to be used after an event, as the recorded information is an important part of an investigation. The likelihood of overwriting the 30-minute CVR recorded information was high, compared to that for the new 2-hour CVR, had the circuit breaker not been pulled in a timely way. For this occurrence aircraft, the CVR records as long as the aircraft power remains on. The FDR is much less likely to be overwritten, as its stop logic is such that once certain systems are shutdown, it stops recording.

Boeing’s simulations, conducted with the occurrence FDR data available, helped eliminate several possible scenarios that could have led to the uncommanded steering event. The scenario that best matched the available FDR data for this event was a nose-gear steering metering, low-slew rate jam. FDR information and aircraft behaviour indicate that these rate jams seem to be temporary in nature, with steering returning to normal after the rate jam unjams.

These occurrences highlight the need for FDR-recorded nose-gear steering system data or other means of recording nose-gear and steering-system information, in order to help increase opportunities for identifying safety deficiencies. Nose-gear steering angle, if recorded, would have determined whether the nose-gear system was at fault. Conclusive evidence of a rate jam would likely have led to more testing of the system to uncover the cause.

Boeing desktop simulations showed that the occurrence crew would have been able to keep the aircraft on the runway had sufficient rudder pedal input been utilized (within 3 seconds) after the start of the heading deviation. It also showed that, had right rudder pedal input been applied as the rate jam unjammed, the aircraft could have also remained on the paved runway surface. The simulations conducted did not include the use of differential braking and differential reverse thrust, which were also available to help maintain directional control of the aircraft. Boeing states that, in most rate-jam events, depending on the aircraft’s ground speed at which the rate jam occurs, the rudder is efficient enough to maintain directional control of the aircraft. Manual braking and reverse thrust would also be available to help maintain control of the aircraft.

2.3 Pilot Reaction

After a stable approach, normal touchdown, and initial landing roll, the pilot flying (PF) tracked the runway centerline using small control-wheel and rudder pedal inputs to compensate for the left crosswind; the aircraft responded normally to these inputs. As the aircraft drifted left of runway centerline, the PF turned the control wheel out of wind, or downwind (i.e., to the right), and used small right rudder pedal inputs to counter the weathervaning effects of the crosswind. The PF's reaction of turning the control wheel to the right had elements of automaticity associated with a learned stimulus-response sequence. The human cognitive system is extremely good at remembering response patterns, and then reapplying them whenever their calling conditions are encountered. [73] Strong habit intrusion is defined as the unintended activation of a strong pattern. [74] The PF's initial reaction of rotating the control wheel to the right was likely due to a strong habit intrusion, such as would be seen as a directional control response in a car; this type of reaction would be an unconscious one. The initial response of turning the control wheel delayed the more appropriate response of correcting the heading deviation by using the rudder pedals. It may also be that the PF unconsciously turned the control wheel out of wind, as the aircraft was veering into wind off centerline. Although the crew was qualified, trained, and highly experienced, it is likely that the assessment and lack of understanding of the situation, due to the absence of recognizable cues and at times conflicting cues, delayed decision-making and reaction time to the uncommanded steering event.

It is likely that the PF did not use full right rudder pedal to counter the initial gradual heading deviation, as full rudder pedal inputs during landing roll at high speed are rarely needed, and situations encountered in past have not required such a degree of movement of the rudder pedals to control the aircraft heading on landing. Under normal circumstances, slight rudder pedal input would have been sufficient to counter a slight heading deviation, as it was gradual and occurred at a rate of about ½° per second. However, because of the uncommanded left nose-gear steering rate jam, the initial amount of right rudder pedal input applied by the PF was insufficient to counteract the left veer and bring the aircraft back to runway centerline. Later, [75] more right rudder pedal was applied. The aircraft heading started to go back to the right; however, the aircraft continued to travel toward the runway edge. Right rudder pedal input was then decreased to neutral in an attempt to reduce any side loads to the aircraft as it departed the runway.

This steering malfunction occurrence has no warning light or aural indication of a nose-gear steering jam. No warning of a system failure will delay reaction time, as the crew may not readily identify the symptoms or the problem at hand as an immediate danger; slight deviations in heading on landing or take-off can be quite common and are usually easily rectified by slight rudder pedal inputs. Manual braking or differential braking were not used, as the PF felt like the aircraft was on ice and skidding. The aircraft remained on the autobrake setting selected before landing; deceleration was normal until it departed the runway surface. Neither crew member was aware that a nose-gear steering rate jam may have occurred or could occur.

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[73] J. Reason, *Human Error*, (Cambridge University Press: 1990), pages 51-52

[74] Ibid, pages 68-70.

[75] At 1953:17 and at a computed airspeed of 72 knots

Besides the fact that the crew members were unaware that an uncommanded steering event could occur from a nose-gear steering rate jam, there were no warning horns, lights, alerts, noise, or vibration to indicate to the crew that a steering problem existed. The only indication was that the aircraft was slowly veering left. Several factors may have led to confusion and delayed the PF's response, such as the following:

- The landing was executed with a 16-knot left-hand crosswind, but was within limits.
- The aircraft was drifting toward the left side of the runway into wind.
- The runway was wet but not flooded.
- The aircraft felt like it was sliding sideways on ice.
- Outside air temperature was above freezing, which normally would prevent the possibility of ice on the runway; there had been no need to prepare for landing on a slippery runway.
- Once normal right rudder pedal input was applied, the aircraft did not respond immediately; more than the usual amount of rudder pedal was necessary.
- Visual cues would have been less evident, due to the darkness and light rain on the windscreen.
- There were no vibrations, noises, or other indications of a steering abnormality.

The speed at which these uncommanded steering events may occur, the rate of the jam encountered (e.g., ½° per second, 1° per second, 2° per second, 5° per second), the amount of runway available on either side of the runway centerline (in this case, 100 feet on each side) and the duration of the jam, leave little time for the crew to assess, recognize, and act before the aircraft is in danger of exiting the runway. In this case, a steering malfunction did not come to mind; rather, the PF felt like the aircraft was on ice and skidding when it did not respond to a normal application of right rudder pedal input. This physical sensation of skidding on ice would not lead the PF to react in the same way as would another type of steering malfunction, flat tire, or asymmetrical thrust situation. Also there was no noise or vibration that may have typically accompanied other trained directional-control difficulty scenarios, such as a flat tire or nosewheel position jam. Up until the time that the uncommanded steering event began, the aircraft was tracking normally, decelerating normally, and responding to small control inputs normally. There was no indication that a system was faulty.

The pilot monitoring (PM) did not take over the controls from the PF during the deviation from runway centerline, as the PF was active on the controls; nor would the PM's intervention on the controls have been expected under the circumstances encountered.

2.4 Nose-gear Steering Rate-jam Events and Valve Examination

As in previous valve teardowns following uncommanded steering events, the teardown of this nose-gear steering metering valve from the occurrence aircraft did not reveal any anomalies or operational difficulties that could explain its role in the uncommanded steering events. Nosewheel steering was tested and found to be functional after this occurrence, and no further directional control difficulties were reported between the time of the occurrence in November 2010 and the time the nose-gear steering metering valve was removed for examination in March 2011. Since the valves examined in these events were tested and found to be operational, and no defects have been found, the valve itself cannot be confirmed as the initiating cause in the uncommanded steering events; the cause of these rate jams remains elusive. The risk of a jam happening within the valve is estimated by the valve manufacturer to be extremely unlikely.

Boeing has not conducted any further testing or research to confirm the second possible cause of a rate jam, which is the interruption of feedback somewhere in the external linkage input to the metering valve. Aircraft behaviour would show the same low-slew rate jam as with a jam within the valve. The nose-gear wheel well, which includes the nose-gear steering assembly, is exposed to the outside elements, such as dirt, sand, stones, ice, snow, and water. Despite the presence of a plastic cover positioned on the nose-gear assembly, debris could possibly become jammed and affect the assembly's normal operation.

2.5 Awareness

Boeing estimates the rate of occurrence based on known likely events, for which it has analyzed FDR data and conducted simulations in order to make comparisons with other possible scenarios. However, the number of likely rate-jam occurrences analyzed may not reflect the actual number of these events, which may be erroneously associated with other external factors, such as sudden wind gusts, effects of crosswinds, slippery runways, pilot skill, or technique. Additionally, if the crew manages to keep the aircraft on the runway as intended, an occurrence becomes a non-event, and the deviations are most likely not reported or discussed within the companies' flight safety programs. In most cases, sufficient rudder pedal input would allow the crew to maintain the aircraft on the intended runway surface. Depending on the definition of an accident or reportable incident, these events may not be reported to the appropriate authorities and/or the manufacturer for analysis and collection of risk-factors data. Boeing has not informed fleet operators of the possibility of nose-gear steering rate jams, nor is it mandatory to do so.

Boeing has assessed this type of event severity as major, with an occurrence likelihood of extremely remote and therefore not a safety issue. The rate of occurrence of 1×10^{-7} occurrences per cycle falls within the certification and in-service fleet following requirements laid out by the Federal Aviation Administration (FAA), and therefore no further action is deemed necessary. The present risk level assessment is based on the known rate of occurrence. It is possible that rate-jam occurrences may not be reported, as the manufacturer has not informed industry of the possibility of these uncommanded steering events. Risk-mitigation strategies are most often data driven, and therefore, implementation of safety action cannot take place without the historic data to drive change. Nothing indicates that the FAA has completed a risk assessment on this type of occurrence, nor does it seem that these events are being tracked in the FAA hazard tracking system (HTS). If a risk-level assessment is deemed acceptable, then no tracking or corrective action is necessary. The risk-assessment evaluation done by Boeing shows that the rate at which these events may occur meets the *Federal Aviation Regulations* (FARs) in-service fleet requirements and do not require dissemination of information or action. Aside from monitoring rate-jam occurrences through the continued operation safety program (COSP), no other defences have been put in place.

Flight crews receive training that provides them with aircraft system knowledge, as well as information on the operation of those systems and their associated limitations. The occurrence crew, the operator, and maintenance personnel were not aware of the possibility of uncommanded steering events, or that these events could be initiated by a nose-gear steering rate jam. Consequently, the operator has not developed procedures, provided guidance, or informed company flight crew about the possibility of such events. Dissemination of information on this type of occurrence may allow flight crews to report such an event in a timely manner so as not lose crucial recorded data.

Debris is believed to be causal to nose-gear steering rate jams, whether it be internal to the valve or external to the nose-gear steering system. This debris is lost when the jam unjams. Given this explanation, all evidence is lost before any troubleshooting or investigation can start. Flight crews' and maintenance crews' lack of awareness does not allow reporting or troubleshooting a rate-jam problem. FDR information to confirm a rate jam will be lost if a steering-difficulty event is not snagged by the flight crew. No guidance has been given to maintenance crews as to how best to capture evidence in order to identify such an event with the objective of finding a cause and fix. In the absence of information on uncommanded steering events due to nose-gear steering rate jams, there is a risk that the cause of these events will continue to be unresolved and unmitigated, leading to a risk of runway excursions.

2.6 Need for Data Collection

The latest Flight Safety Foundation (FSF) statistics show that approximately 29% of the total number of accidents involving commercial transport aircraft from 1995 through 2008 were runway-excursion accidents (veer-offs and overruns), and 83% of runway-related fatalities occurred during runway-excursion accidents. [76] Efforts are being made worldwide to collect and share important risk-factors data present in runway excursions; however, more effort within individual organizations is needed. Although nose-gear steering rate-jam occurrences would likely make up a very small portion of these runway excursions (veer-offs at slow speeds), information on rate jams and the identification of the risk factors present during these events may help identify the source of the uncommanded veer or the factors that may elevate the risks associated with such events.

A search of several databases has shown that there are cases where uncommanded steering events may have occurred, but for which there is a lack of data and analysis to confirm the initiating cause of the events. Contributing to the lack of data collection is lack of awareness, as the manufacturer has not made fleet operators aware of the possibility of such events occurring. Consequently, reporting of any events by operators, flight crews, and maintenance services is nonexistent. Since risk-assessment exercises and risk-mitigation options are data driven, it would be important to attempt to capture as many of these occurrences as possible.

Many airlines use a flight operational quality assurance (FOQA) program, or similar program, which helps capture certain flight parameters in order to flag events that are of some concern. It would be possible, with the proper filters in place, to capture steering events; however, this may lead to capturing the many steering events that are not necessarily due to a rate jam. As no sensors are on the nose steering system, accurate system behaviour cannot be obtained to flag the behaviour relevant to rate jams. Analysis of available data, to determine whether a rate jam is a possibility, relies on a process of elimination or diagnosis by exclusion.

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[76] Flight Safety Foundation (FSF), *Reducing the Risk of Runway Excursions: Report of the Runway Safety Initiative* (May 2009), page 5, available at http://www.icao.int/safety/RunwaySafety/Documents%20and%20Toolkits/fsf-runway-excursions-report.pdf (last accessed on 04 October 2013)

3.0 Findings

3.1 Findings as to Causes and Contributing Factors

1. Following a stabilized approach and normal landing, the aircraft deviated left of the runway centerline, likely as the result of a nose-gear steering metering low-slew rate jam.

2. The delayed response to the uncommanded steering event by the pilot flying was not sufficient to counteract the movement toward the left, and the aircraft departed the runway surface.

3.2 Findings as to Risk

1. In the absence of information on uncommanded steering events due to nose-gear steering rate jams, there is a risk that the cause of these events will continue to be unresolved and unmitigated, leading to a risk of runway excursions.

2. The lack of flight data recorder information or other types of recording devices on the nose-gear steering system may hinder the identification of safety deficiencies.

3.3 Other Findings

1. The flight operational quality assurance programs in place at many airlines already target certain events with a view to underlining safety concerns. With additional filters, it would be possible to flag steering events in order to help in verifying for rate-jam events.

4.0 Safety Action

4.1 Safety Action Taken

4.1.1 American Airlines

In April 2011, as part of its pilots' recurrent training, human-factors class, American Airlines introduced a simulation and discussion of this Boeing 737 runway excursion. This training is given to company pilots to educate them on the possibility of a runway excursion due to a nosewheel steering problem on landing roll-out after a normal approach and landing.

4.2 Safety Concern

Despite efforts in analyzing past nose-gear steering, low-slew rate-jam events and carrying out post-event valve examinations, the cause of these uncommanded steering events remains uncertain. The safety review process completed by the manufacturer and based on a quantitative, cycle-based occurrence rate of 1×10^{-7}, classified this event as an extremely remote probability, and gave it an acceptable risk level, combined with a major severity level. An occurrence rate of 1×10^{-7} meets the *Federal Aviation Regulations* (FARs) certification requirements. Additionally, an acceptable level of risk does not require further tracking of the hazard in the Federal Aviation Administration (FAA) Hazard Tracking System. Consequently, other than flight data analysis and valve examination, the manufacturer has not taken further action following the 11 known nose-gear steering rate-jam events that have occurred over the past 21 years.

Rate of occurrence determines whether a manufacturer needs to take safety action. In order to determine the rate of occurrence, there is a need to capture as many events as possible. This capture allows identification of possible safety deficiencies, and aids in the application of risk-mitigation strategies. Since no defences have been put in place to mitigate the risk of a runway excursion following a rate jam, damage to aircraft and injury to aircraft occupants remains a possibility.

The present known low rate of nose-gear steering rate jams may be explained by the fact that, directional control difficulties on take-off or landing would not often result in an excursion and/or damage or injury, and therefore would not be reported. The lack of reporting may also be due, in part, to the fact that operators, flight crew and maintenance personnel have not been made aware of the possibility of rate-jam events, nor have they been provided information on how to recognize, react or troubleshoot. The rate of occurrence would have to show a significant increase to validate corrective action, as safety action is based on FARs certification and in-service fleet following requirements.

Despite technological advancements in recording devices, many Boeing aircraft do not record nosewheel steering system parameters. Boeing models affected include 707/720, 727, 737, 747 (some models), 757, 767, and 777.

The cause of these low-slew, nose-gear steering rate jams over the past 21 years remains uncertain. A lack of recognition and reporting prevents adequate data collection, analysis, and implementation of risk-mitigation strategies if necessary.

The Board is concerned that, in the absence of information as to the cause of uncommanded steering events due to nose-gear steering rate jams, there remains a risk for runway excursions to occur.

This report concludes the Transportation Safety Board's investigation into this occurrence. Consequently, the Board authorized the release of this report on 19 September 2013. It was officially released on 5 November 2013.

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 Engineering Branch Laboratory Reports were completed:

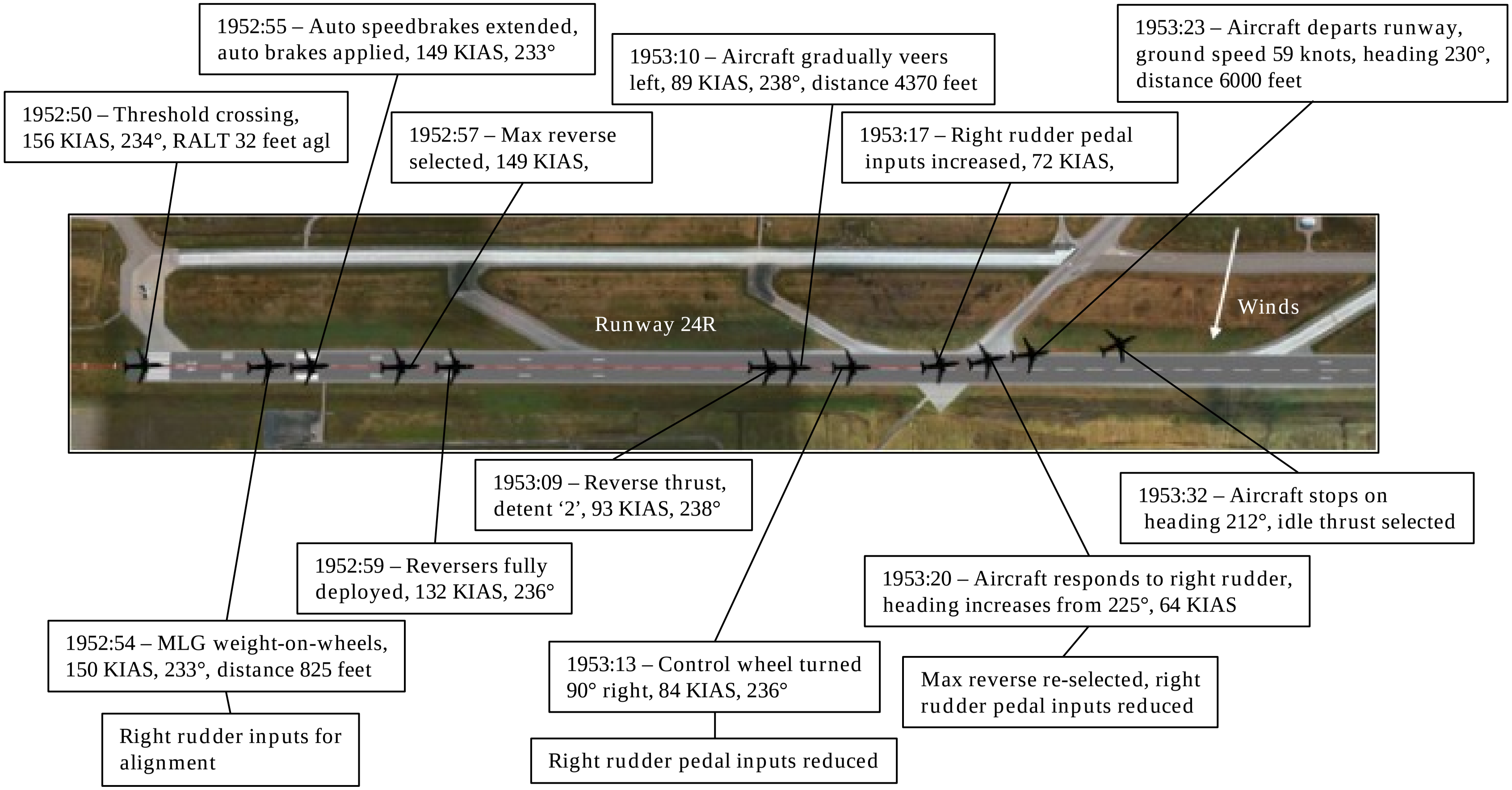
LP169/2010 – FDR and CVR Analysis

LP187/2010 – Aircraft Performance Analysis

LP035/2011 – Nosewheel Steering Valve Evaluation

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

Appendix B – Sequence of Events: Flight AAL802



1952:50 – Threshold crossing, 156 KIAS, 234°, RALT 32 feet agl

1952:54 – MLG weight-on-wheels, 150 KIAS, 233°, distance 825 feet

Right rudder inputs for alignment

1952:55 – Auto speedbrakes extended, auto brakes applied, 149 KIAS, 233°

1952:57 – Max reverse selected, 149 KIAS,

1952:59 – Reversers fully deployed, 132 KIAS, 236°

1953:09 – Reverse thrust, detent '2', 93 KIAS, 238°

1953:10 – Aircraft gradually veers left, 89 KIAS, 238°, distance 4370 feet

1953:13 – Control wheel turned 90° right, 84 KIAS, 236°

Right rudder pedal inputs reduced

1953:17 – Right rudder pedal inputs increased, 72 KIAS,

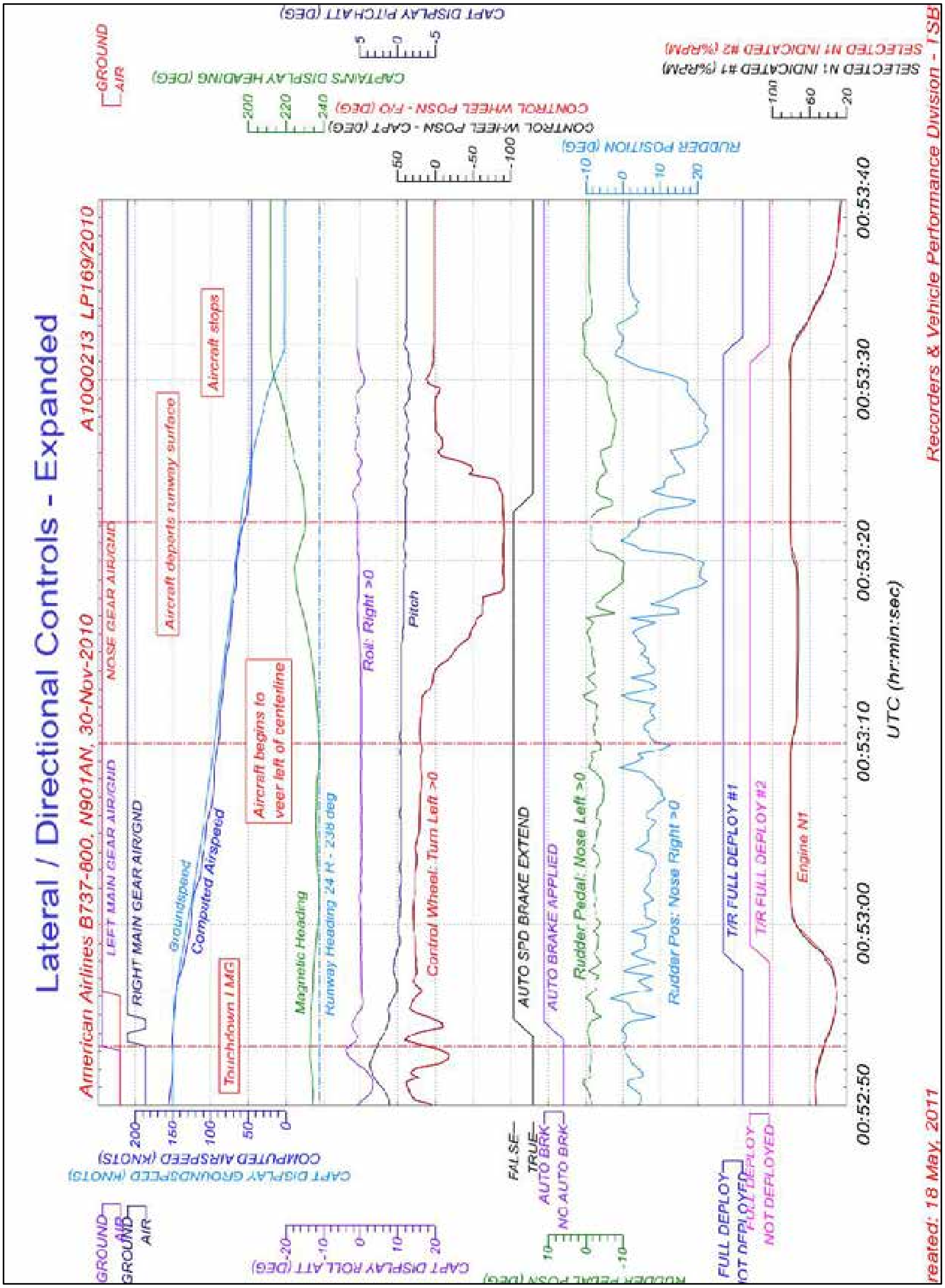
1953:20 – Aircraft responds to right rudder, heading increases from 225°, 64 KIAS

Max reverse re-selected, right rudder pedal inputs reduced

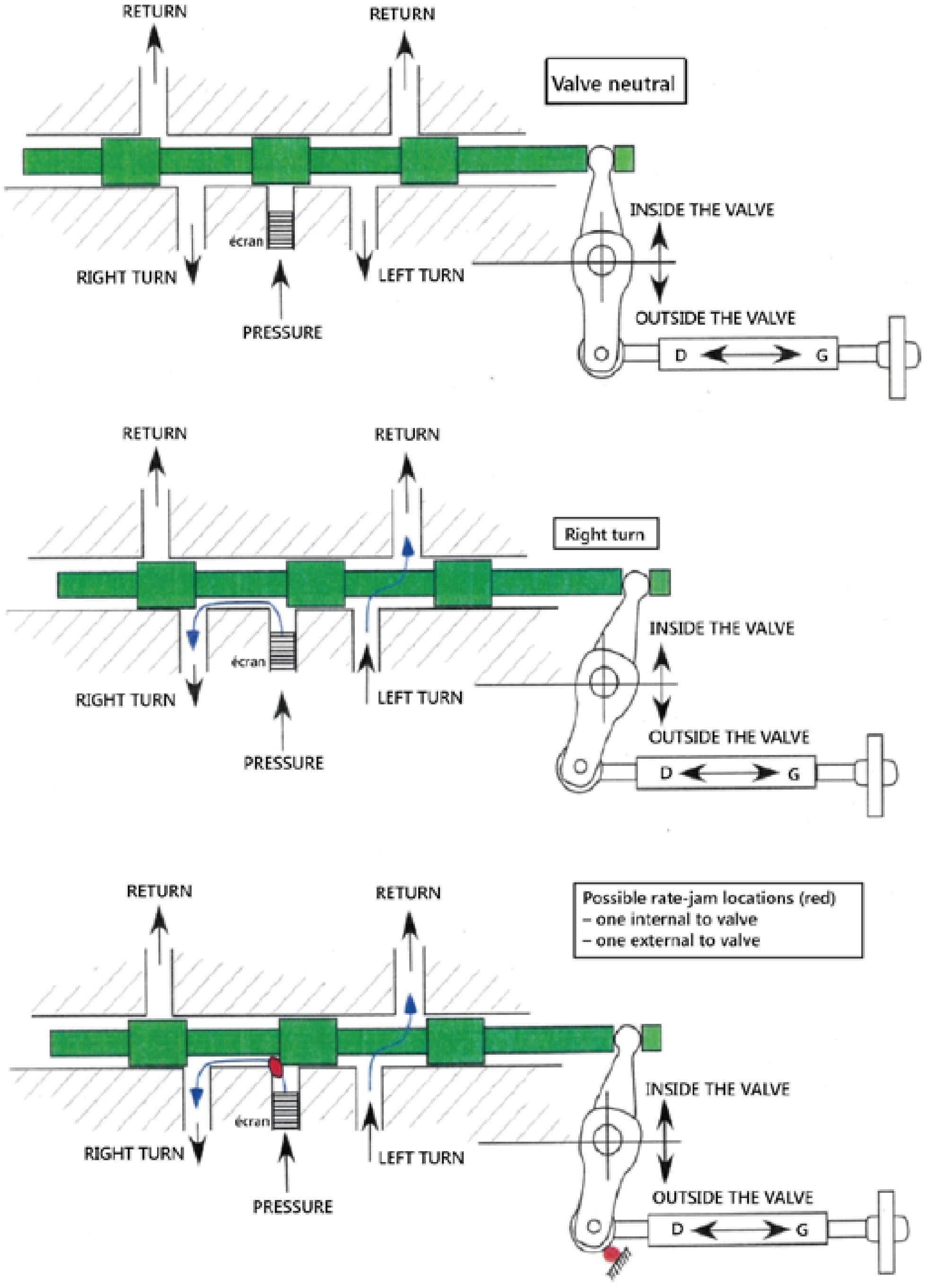
1953:23 – Aircraft departs runway, ground speed 59 knots, heading 230°, distance 6000 feet

1953:32 – Aircraft stops on heading 212°, idle thrust selected

Appendix C – Flight Data Recorder Lateral/Directional Controls

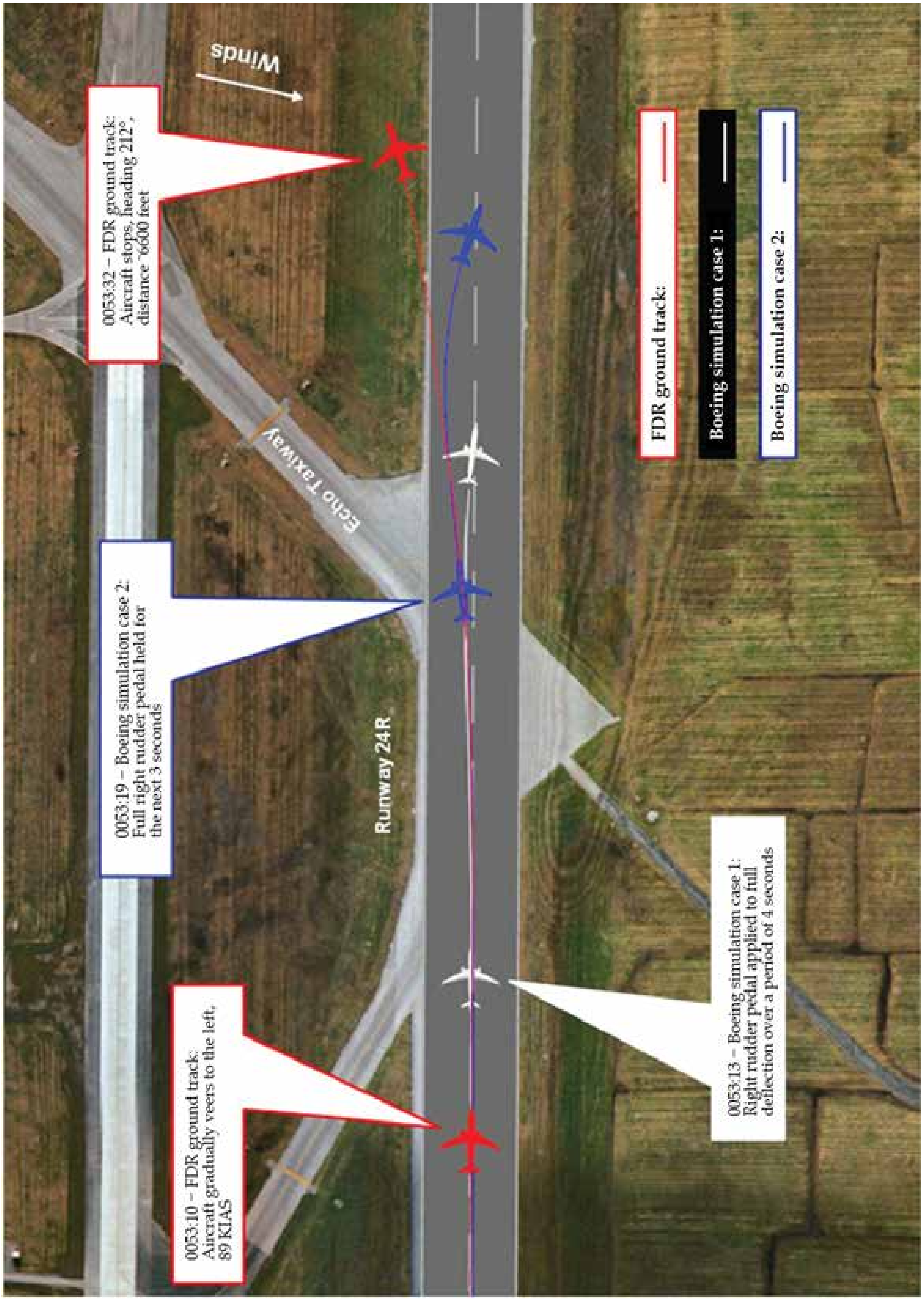


Appendix D – Possible Debris Location for Nose-gear Steering Rate Jam

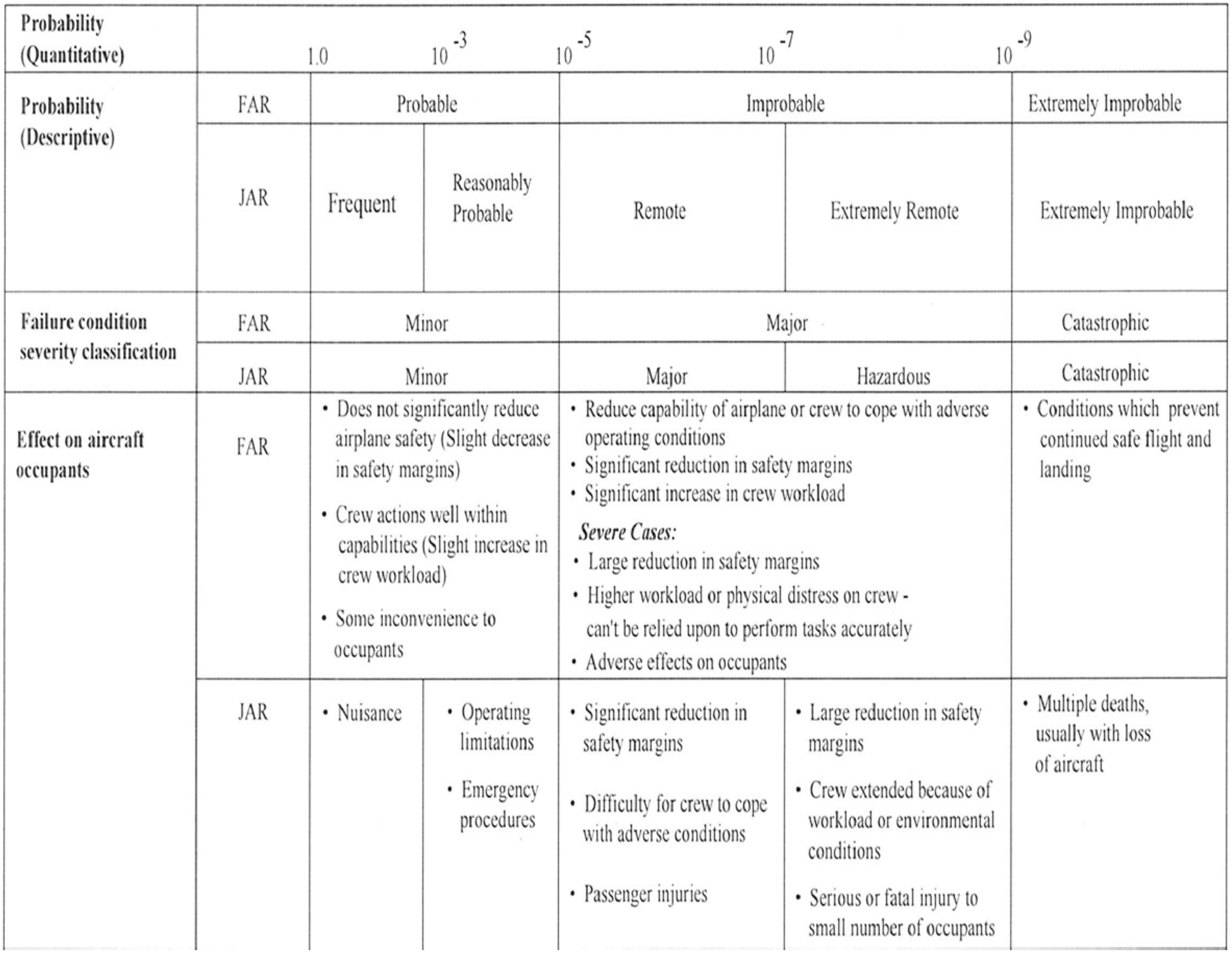


Boeing©

Appendix E – Boeing Simulations of Nose-gear Steering Rate Jam at ½° per second



Appendix F – Most Severe Consequence Used for Classification [77]



Probability (Quantitative)		1.0	10^{-3}	10^{-5}	10^{-7}	10^{-9}
Probability (Descriptive)	FAR	Probable		Improbable		Extremely Improbable
	JAR	Frequent	Reasonably Probable	Remote	Extremely Remote	Extremely Improbable
Failure condition severity classification	FAR	Minor		Major		Catastrophic
	JAR	Minor		Major	Hazardous	Catastrophic
Effect on aircraft occupants	FAR	• Does not significantly reduce airplane safety (Slight decrease in safety margins) • Crew actions well within capabilities (Slight increase in crew workload) • Some inconvenience to occupants		• Reduce capability of airplane or crew to cope with adverse operating conditions • Significant reduction in safety margins • Significant increase in crew workload ***Severe Cases:*** • Large reduction in safety margins • Higher workload or physical distress on crew - can't be relied upon to perform tasks accurately • Adverse effects on occupants		• Conditions which prevent continued safe flight and landing
	JAR	• Nuisance	• Operating limitations • Emergency procedures	• Significant reduction in safety margins • Difficulty for crew to cope with adverse conditions • Passenger injuries	• Large reduction in safety margins • Crew extended because of workload or environmental conditions • Serious or fatal injury to small number of occupants	• Multiple deaths, usually with loss of aircraft

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[77] *FAA System Safety Handbook*, Chapter 3: Principles of System Safety (December 30, 2000)

Appendix G – Search of Other Databases

Source: Australian Transportation Safety Board (ATSB)

200300561

27 February 2003

Boeing 737

The flight crew reported that during the landing roll, at approximately 80 knots, the aircraft swerved to the left toward the runway edge. The runway centerline was regained through use of full right rudder, right braking, and nosewheel steering. The aircraft did not depart the sealed runway surface.

200402661

19 July 2004

Boeing 737

During the take-off run, the crew noticed a sharp lateral movement of the aircraft. They continued, but kept the take-off configuration until approximately 3000 feet. After consulting the operator's engineering and operations departments, the decision was made to continue the flight. Subsequent analysis of the FDR agreed with the crew's observations, but was inconclusive as to the cause.

200600103

08 January 2006

Boeing 737

During the initial take-off run at low speed, the aircraft commenced an uncommanded divergence from the runway centerline. The crew rejected the take-off.

Source: Transportation Safety Board of Canada

A03F0141

23 July 2003

Boeing 767

The aircraft veered momentarily to the right at approximately 100 knots during the take-off. The deviation was corrected using rudder. The aircraft tracked normally during the remainder of the take-off run. Once landed at destination, the crew requested that the aircraft be inspected before taxi to the gate. No abnormalities were found. Maintenance inspected the landing gear, tires, brakes, engines, flight controls, and other aircraft structures, and found no damage or faults. The engine data computer systems (EDCS) and the right programming and indication module unit (PIMU) recorded no faults or engine exceedances. The cause of the veer was not determined.

Source: National Aeronautics and Space Administration Aviation Safety Reporting System

550790

Boeing 737

Take-off roll. Power advanced toward take-off thrust. Autothrottles commanded to engage. Throttles moving toward take-off power simultaneously. Aircraft veered hard left on take-off roll from original centerline alignment. Nosewheel steering commanded toward right to counteract aggressive pull toward left. No response from nosewheel steering tiller. Applied differential braking to correct aircraft back to centerline. Hopping / scraping of nosewheel or dragging of left main brake created burnt rubber smell from skidding tires. Take-off roll discontinued at 15 knots. Aircraft within 30 feet from departing prepared surface. Cleared active runway onto first available taxiway. Towed back to gate.

576165

Boeing 747

FO made normal approach and landing. Prebriefed to make turnoff of active on taxiway M then onto taxiway E. As aircraft was northeast bound on taxiway E, as Captain was assuming control of the tiller, aircraft was drifting right of taxiway centerline. Captain assumed control and inputted a left-hand steering command. Aircraft was unusually sluggish to respond, so Captain inputted further left-hand command, at which time the aircraft suddenly swerved to the left and drifted across the centerline of taxiway E, and began heading to the left edge of the taxiway. Captain immediately added additional 4-hand steering input from what the Captain had input to correct back to centerline, but again, aircraft was slow to respond and drifted off the edge of the taxiway with the left-hand wing gear and nose gear coming to rest on soft earth. All braking and steering inputs to keep aircraft on taxiway seemed to have little or no effect.

727681

Boeing 737

Captain aborted initial take-off due to aircraft drifting uncontrollably to the left. The following events were observed leading up to the abort: 1) Flight control check during taxi out was normal. 2) Winds were reported from the south at 20 knots. 3) The take-off thrust was set and stable before 60 KIAS. 4) Forward pressure was being applied to the control column, and approximately 50% right rudder was required to maintain centerline before the event. 5) At approximately 60 KIAS, the aircraft drifted left of centerline, and full right rudder was applied in an attempt to return to centerline. The rudder had no effect in steering the airplane to the right. 6) At approximately 70 KIAS, the aircraft was halfway between the centerline and left runway edge and still drifting to the left despite full right rudder. 7) The captain elected to abort the take-off. 8) The weather was clear, but there was snow blowing across the runway. 9) The rejected take-off and subsequent taxi to the gate were uneventful. 10) After coordinating with maintenance and dispatch, an aircraft swap was initiated and the flight completed.