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

AIR TRANSPORTATION SAFETY INVESTIGATION REPORT A21F0210

RUNWAY EXCURSION ON TAKEOFF AND IN-FLIGHT FUEL IMBALANCE RESULTING IN DIVERSION

Jazz Aviation LP
Mitsubishi Heavy Industries, Ltd. CL-600-2D24 (Regional Jet Series 900), C-GJZV
San Diego International Airport, California, United States
29 November 2021

Canada

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Executive summary

On 29 November 2021, the Mitsubishi Heavy Industries, Ltd. CL-600-2D24 aircraft (Regional Jet Series 900) (registration C-GJZV, serial number 15424) operated by Jazz Aviation LP was conducting flight JZA767 from San Diego International Airport, California, United States, to Vancouver International Airport, British Columbia, with 2 flight crew members, 2 cabin crew members, and 69 passengers on board. At about 1842 Pacific Standard Time, during the hours of darkness, the aircraft took off to the left of the centreline on Runway 27, and the left main landing gear wheels contacted 3 runway edge lights before the aircraft's trajectory was corrected towards the runway centreline.

While the aircraft climbed, the flight crew detected a fuel imbalance that they were unable to correct, so they shut down the right engine and declared an emergency. The aircraft diverted to Los Angeles International Airport, California, United States, where it landed and stopped on the runway at approximately 1946. Passengers disembarked and were transported to the terminal. None of the passengers or crew members were injured. Emergency personnel reported that 1 of the left main landing gear tires was deflated and that smoke was coming from the wheel. The aircraft's No. 1 tire sidewall was later found to have been damaged, and the aircraft's left flap had sustained 2 punctures.

In this occurrence, the misaligned takeoff and the fuel imbalance were 2 separate and unrelated events, and the investigation treated them as such.

To determine the factors that contributed to the aircraft's misalignment on the runway, the investigation examined the visibility conditions in which the aircraft took off from San Diego International Airport. From pushback to takeoff, the aircraft was operating at night and in fog, in an area where visibility was between ¼ statute mile and ½ statute mile and deteriorating. As a result, there were few visual cues available to the flight crew to identify

and verify the aircraft's position on Runway 27. One of these cues was the portion of the lead-on taxiway centreline marking that was visible in front of the aircraft; however, when taxiing to position on the runway, the captain taxied the aircraft off the taxiway centreline marking in order to increase the runway distance available for takeoff. In doing so, he had even fewer visual cues on which to rely to determine the aircraft's position on the runway. When the aircraft subsequently turned left to establish the runway heading in preparation for takeoff, the captain perceived the left runway edge marking as the runway centreline. The limited and ambiguous visual cues that were available likely met the captain's expectations and, as a result, the aircraft was aligned laterally with the left edge, rather than with the centre of the runway.

Runway 27 had a displaced threshold, and the investigation compared the visual environment of a displaced threshold area with that of a runway threshold. It was found that if flight crews line up on runways in the area before the displaced threshold or conduct intersection departures, both under degraded or nighttime visual conditions and without confirming the aircraft's lateral position on the runway, there is an increased risk of runway misalignments or runway side excursions. This is because displaced threshold areas and runway-taxiway intersections do not have runway threshold markings or runway numbers, 2 distinctive features that allow flight crews to define the width—and therefore, the centreline—of the runway.

The nature of operations at the occurrence airport was also considered. San Diego International Airport, one of the busiest single-runway commercial service airports in the world, has a high volume of arrivals and departures that occur in very quick succession, producing a cadence that flight crews must follow. It was found that the complexity of instrument flight rules operations on a single runway surface, with arrivals on one end and departures from the other end, created an environment in which the flight crew perceived a time pressure for the takeoff. As a result, the first officer was completing the line-up checks while the captain taxied to position, and the first officer therefore did not monitor the progress of the taxi. Due to the reduced number and quality of visual cues and the perceived time pressure felt by the first officer, he did not recognize that the aircraft's nose was aligned with the left edge of the runway when he assumed the role of pilot flying shortly before the take-off roll commenced.

The investigation determined that shortly afterwards, during the take-off roll, the aircraft's left main landing gear wheels contacted and severed 3 runway edge lights, causing damage to the aircraft's tires and flaps. However, this contact was not recognized by the flight crew because they perceived the sounds and vibrations as normal contact with the embedded runway centreline lights, and consequently, they continued with the departure. This aspect of the occurrence revealed a particular safety risk to other aircraft. Owing to the fact that the airport is not equipped with a foreign object debris detection system, the debris was not discovered by the airport operator or controllers until several hours after the misaligned takeoff. If foreign object debris on runways is not detected and identified in a timely manner, there is a risk that it will result in aircraft damage during critical phases of flight.

The investigation also examined the causes of the fuel imbalance during the occurrence. It is likely that, during the completion of either the before-takeoff or after-takeoff checklists, the flight crew inadvertently pressed the gravity crossflow push-button switch instead of the co-located crossflow auto override push-button switch. As a result, during the flight, fuel periodically transferred between the aircraft's wing tanks by gravity when the aircraft was banked left or right, leading to a worsening fuel imbalance condition.

The guidance provided to flight crews by the air operator, Jazz Aviation LP, and the manufacturer, the Mitsubishi Heavy Industries Regional Jet Aviation Group, to address fuel imbalances was found to be unclear and inconsistent. When the wording in a checklist is ambiguous or unclear, or when the wording in an operator's checklist differs from that in the checklist provided by the manufacturer, a flight crew may, in an effort to correct an abnormal or emergency condition, conduct procedures in ways not intended by the manufacturer, increasing the risk of entering into an undesired aircraft state. With the auto pilot on, the aircraft was unintentionally placed in a sideslip toward the wing tank with the greater quantity of fuel, and this opposite bank was not recognized by the flight crew. As a result, the lateral fuel imbalance was not controlled, and continued to increase. The fuel imbalance, which was unrelated to the damage sustained during the take-off roll, led the crew to declare an emergency and divert to a nearby airport for an emergency landing. Furthermore, the aircraft checklists did not require the flight crew to close the gravity crossflow valve following the attempted Gravity Crossfeed Procedure. As a result, the open valve occasionally made the fuel imbalance worse during the subsequent manoeuvring and was at one point more than 3 times the maximum permissible.

Following the occurrence, Jazz Aviation LP included additional warnings in its airport charts to highlight the risks of departing from within displaced threshold areas. For example, the San Diego International Airport charts now include a departure consideration informing flight crews of the threat of incorrect runway verification in reduced visibility and prescribes additional measures that should be used to verify the runway and the aircraft's alignment with the centreline. Jazz Aviation LP also issued a company memo regarding departures from displaced threshold areas. In addition, the air operator revised its line-up check procedure as well as its Gravity Crossfeed Procedure, which now contain more guidance on initiating a sideslip.

1.0 FACTUAL INFORMATION

The National Transportation Safety Board (NTSB) of the United States (U.S.) delegated the investigation of this occurrence to the TSB in accordance with International Civil Aviation Organization (ICAO) Annex 13.[1]

1.1 History of the flight

On 29 November 2021, the occurrence flight crew were scheduled to fly from Vancouver International Airport (CYVR), British Columbia (BC), to San Diego International Airport (KSAN), California, U.S., and back on the occurrence aircraft, the Mitsubishi Heavy Industries, Ltd. (MHI) CL-600-2D24 (Regional Jet Series 900) aircraft, which was being operated by Jazz Aviation LP (Jazz). At 1706,[2] the aircraft arrived at KSAN as flight JZA766. Directly after this inbound flight, the crew, which consisted of 2 flight crew members and 2 cabin crew members, began to prepare for the return flight (instrument flight rules flight JZA767) on the same aircraft.

At 1758, after 69 passengers had boarded and the aircraft had been loaded with more fuel (to a total of approximately 17 700 pounds[3]), the flight crew started the right engine while the aircraft was still parked at the gate. The aircraft pushed back from the gate at 1803. The left engine was started, and at 1809, the captain taxied the aircraft on Taxiway B for departure from Runway 27. At this time, 6 other aircraft were ahead of the occurrence aircraft awaiting departure from Runway 27, and an additional 9 aircraft were inbound to KSAN and would be landing in the opposite direction, on Runway 09.

Due to an anticipated delay in reaching the runway for takeoff, a number of aircraft, including the occurrence aircraft, shut down 1 engine during their taxi to the runway to conserve fuel. The flight crew shut down the occurrence aircraft's left engine at 1822.

At approximately 1830, the KSAN air traffic control (ATC) tower controller informed the next 3 aircraft in line (which included the occurrence aircraft) that their departure would begin in approximately 5 minutes. Two minutes after this notification, the flight crew of the occurrence aircraft restarted the left engine using Jazz's cross-bleed engine start procedure, completed the after-start checklist, and then began the before-takeoff checklist.

At 1841:16, the occurrence aircraft was given clearance to line up and wait on Runway 27. The captain initially taxied the aircraft along the taxiway centreline across the runway holding position marking, but then continued straight ahead, diverging to the right of the taxiway centreline until reaching the runway edge (Figure 1). During this time, the first officer was completing the before-takeoff and line-up checks and checklists. By 1841:46, the

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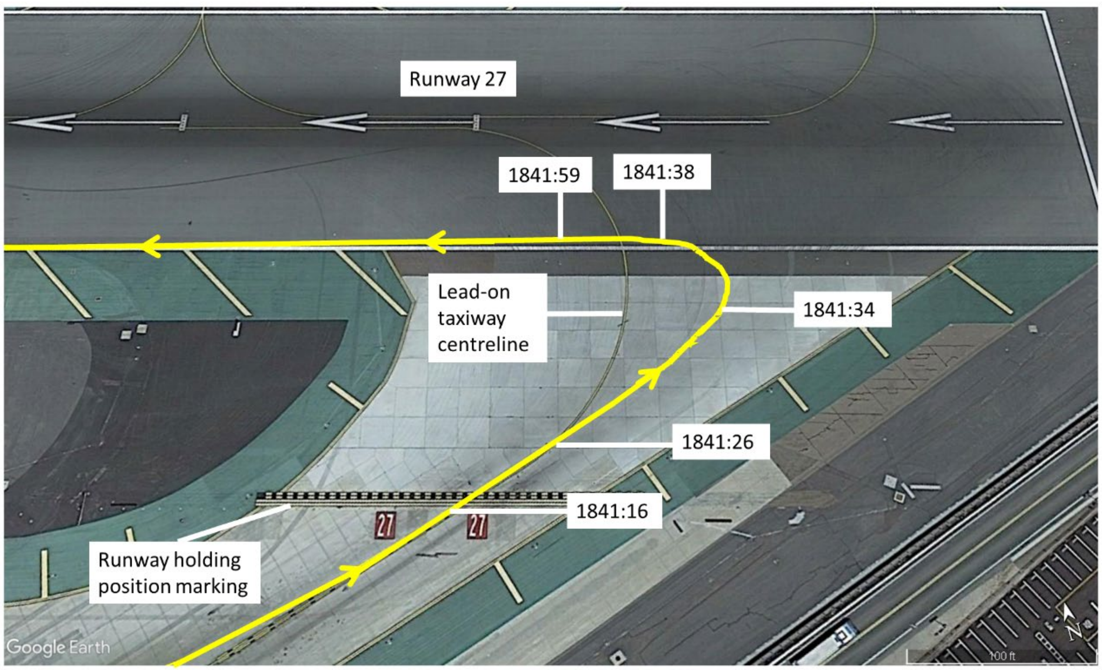
1 International Civil Aviation Organization (ICAO), Annex 13 to the *Convention on International Civil Aviation, Aircraft Accident and Incident Investigation*, Twelfth Edition (July 2020).

2 All times are Pacific Standard Time (Coordinated Universal Time minus 8 hours), unless otherwise indicated.

3 Fuel quantities are all approximate because the quantities recorded in the flight data recorder have an error range of ±16 pounds.

aircraft had turned onto the runway but was aligned with the left runway edge, unbeknownst to the flight crew. At 1841:53, the first officer read back the ATC take-off clearance and was then given control of the aircraft from the captain. The first officer assumed the role of pilot flying (PF), and the captain took on the role of pilot monitoring (PM). At 1841:59, the PF advanced the aircraft power levers and began the take-off roll approximately 1500 feet before the displaced threshold of Runway 27.

Figure 1. The occurrence aircraft's taxi route onto Runway 27, based on data from the flight data recorder (Source: Google Earth, with TSB annotations)



During the take-off roll, the wheels on the aircraft's left main landing gear struck and damaged 3 consecutive runway edge lights. The flight crew heard sounds and felt vibrations, but they thought they were rolling over embedded runway centreline lights and were thus unaware of the contact with the runway edge lights. Around this time, the PF visually identified the misalignment with the runway and began to correct toward the runway centreline. As the aircraft crossed the runway's displaced threshold, its lateral position on the runway had moved approximately 40 feet to the right (closer to the runway centreline). When the aircraft began to rotate, approximately 4650 feet from the point at which it had begun the take-off roll, it remained about 40 feet to the left of the runway centreline. At no point did the aircraft reach the centreline.

Following the takeoff, the aircraft climbed normally. Approximately 1 minute after takeoff, while climbing through 2500 feet above sea level (ASL), the PM set climb power.

About 3 minutes after departure, as the aircraft climbed through approximately 6500 feet ASL, the flight crew were presented with a "XFLOW PUMP" caution message on the aircraft's engine indication and crew alerting system (EICAS). The PM then actioned the XFLOW

PUMP Caution Message procedure in the aircraft's quick reference handbook (QRH).[4] The procedure's checklist instructs the flight crew to determine whether a lateral fuel imbalance between the left- and right-wing fuel tanks exists. The flight crew did not identify a significant imbalance so, as instructed by the checklist, they continued to monitor for an imbalance periodically as the aircraft continued to climb.

As the aircraft climbed through flight level (FL) 310, approximately 17 minutes after the "XFLOW PUMP" caution message had been displayed, the quantity of fuel in the left-wing tank began to increase while the quantity in the right-wing tank decreased. At this time, although not evident to the flight crew, fuel was transferring at a rate in excess of 5000 pounds per hour (lb/h). Shortly afterwards, the flight crew recognized this increasing imbalance and levelled out the aircraft at a cruising altitude of FL340. While the lateral fuel imbalance continued to increase, the flight crew attempted to use additional thrust on the left engine and less on the right engine to balance the fuel in the tanks.

Approximately 25 minutes after the initial "XFLOW PUMP" caution message had appeared, the fuel imbalance exceeded 800 pounds—the maximum permissible in-flight imbalance as specified by the manufacturer—and a subsequent "FUEL IMBALANCE" caution message activated on the EICAS display. This caution message has its own procedure outlined in the QRH.[5] The first step is to verify that the automatic crossflow is operating; however, the appearance of the "XFLOW PUMP" caution message indicated that it was not. So, the PM again completed the XFLOW PUMP Caution Message procedure checklist which, in the case of a fuel imbalance condition, instructs the flight crew to proceed to the Gravity Crossfeed Procedure.

Performing the QRH's Gravity Crossfeed Procedure includes placing the aircraft in a sideslip condition.[6][7] The PF applied right rudder pressure for the next 4 minutes (approximately), leading to a sideslip, while continuing to fly the aircraft on autopilot. During this procedure, the flight attendants experienced a left-wing-down motion and communicated with the flight crew to inquire about the abnormal flight attitude. In addition, the quantity of fuel in the left-wing tank continued to increase until the tank was full, while the quantity of fuel in the right-wing tank continued to decrease.

The QRH's Gravity Crossfeed Procedure concludes that if a fuel imbalance persists and cannot be controlled within limits, the engine fuelled by the tank containing the lower fuel quantity must be shut down. The flight crew requested a diversion to Los Angeles International Airport (KLAX), California, U.S., approximately 112 nautical miles (NM) away,

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4 Jazz Aviation LP, *CRJ 900 Quick Reference Handbook*, XFLOW PUMP Caution Message, Original (01 July 2011), p. ABNORMAL 10-16.

5 Ibid., FUEL IMBALANCE Caution Message, Original (01 July 2011), p. ABNORMAL 10-2.

6 A sideslip is a flight condition in which an aircraft is flown in a banked attitude but is prevented from changing its course over the ground because rudder pressure is applied in the direction opposite to the turn.

7 Jazz Aviation LP, *CRJ 900 Quick Reference Handbook*, Gravity Crossfeed Procedure, Revision 4 (01 August 2014), p. ABNORMAL 10-15.

and were instructer to turn left to begin the arrival procedure. During the left turn, the flight crew carried out the precautionary engine shutdown of the right engine. The PF continued to fly the aircraft, while the PM's duties for the minutes that followed included the coordination with ATC and Jazz dispatch for the diversion, the notification of the flight's cabin crew and passengers, and the planning and programming of the flight management computers for the arrival and approach. At this point, the imbalance had reached approximately 1700 pounds, with the greater amount in the left tank.

The flight crew declared a MAYDAY with ATC, and as the flight proceeded toward KLAX, the fuel imbalance continued to worsen, reaching a maximum recorded value[8] of 2464 pounds. Approximately 11 minutes before landing, fuel began to transfer back into the right-wing tank without any prompting or action from the flight crew. The fuel transfer continued for approximately 7 minutes, reducing the imbalance to approximately 1120 pounds.

Approximately 3 minutes before landing, following the aircraft's right turn onto the final approach course to KLAX, the aircraft was level, and fuel began transferring into the left-wing tank again. At the time of landing (approximately 1946), the fuel was recorded at 1568 pounds out of balance, with the higher fuel level in the left tank.

The flight crew brought the aircraft to a stop on the runway, where KLAX aircraft rescue and fire fighting services personnel found that the No. 1 tire from the left main landing gear was flat and reported the presence of smoke coming from the left main landing gear wheel. Water was sprayed on the wheels and the smoke dissipated.

All passengers and crew members deplaned via the airstairs onto the runway and were transported to the passenger terminal. The aircraft was towed to a maintenance hangar.

1.2 Injuries to persons

There were no injuries to passengers or crew members.

1.3 Damage to aircraft

After the aircraft had landed at KLAX, damage to the left tire on the left main landing gear was immediately noted by the attending emergency crews. This tire was flat and its outside sidewall was torn. Upon closer inspection of the aircraft by the emergency crews and aircraft flight crew, 2 puncture holes through the lower skin of the left-wing inboard flap were discovered.

Contract maintenance personnel replaced the left main landing gear wheels to allow the aircraft to be towed from the runway. Jazz maintenance personnel conducted functional and operational checks of the landing gear, and no further faults were found.

Following the occurrence, Jazz maintenance personnel noted no obvious indications of a fuel leak and validated the computer indications of fuel quantity by manually measuring the

8 As recorded by the aircraft's digital flight data recorder.

fuel quantity in each tank, which was later supported by data from the aircraft's flight data recorder (FDR).

As part of the examination of the fuel system, Jazz maintenance personnel inspected the maintenance diagnostic computer and found, while running an aircraft history operational check of the fuel quantity gauging computer (FQGC), that an internal fault code, B1-006805, had been recorded. The FQGC was replaced and an operational check was completed with no fault found. The occurrence FQGC was sent to the manufacturer for further analysis, but it was determined to have no system faults in its hardware. Jazz maintenance personnel found no other indications of mechanical faults in either the crossflow pump or gravity crossflow valve, and there was no record of reoccurrence subsequent to the occurrence flight.

On 04 December 2021, the occurrence aircraft was flown to Jazz's maintenance base at Calgary International Airport (CYYC), Alberta, under a ferry permit. The puncture holes in the left-wing inboard flap were repaired per a repair engineering order by the manufacturer.

The aircraft was returned to service on 09 December 2021.

1.4 Other damage

Since the flight crew, at the time of the occurrence, were unaware of the aircraft's contact with the runway edge lights, they did not communicate with ATC to report a possible contact.

The runway edge light debris was found at 0228 on 30 November 2021 by a member of the airport operations ground crew conducting a routine nightly inspection. Airport electricians immediately replaced the 3 damaged lights.

There was no indication of any negative impact on airport operations from the time the lights were damaged until the time they were discovered, a period of 7 hours and 46 minutes.

1.5 Personnel information

Table 1. Personnel information

	Captain	First officer
Pilot licence	Airline transport pilot licence	Airline transport pilot licence
Medical expiry date	01 May 2022	31 August 2022
Total flying hours	24 826	20 213
Flight hours on type	11 517	7157
Flight hours in the 7 days before the occurrence	22	16
Flight hours in the 30 days before the occurrence	48	55
Flight hours in the 90 days before the occurrence	162	202
Flight hours on type in the 90 days before the occurrence	162	202

Hours on duty before the occurrence	6	6
Hours off duty before the work period	120	49

The flight crew held the appropriate licences and met the recency requirements for the flight in accordance with existing regulations. Both pilots had been employed with Jazz for a number of years and had flown together numerous times. They had also both flown the CYVR-KSAN route regularly, sometimes together as a flight crew.

1.6 Aircraft information

Table 2. Aircraft information

Manufacturer	Bombardier Inc.*
Type, model, and registration	CL-600-2D24, Regional Jet Series 900, C-GJZV
Year of manufacture	2016
Serial number	15424
Certificate of airworthiness/flight permit issue date	30 November 2016
Total airframe time	11 227.4 hours
Engine type (number of engines)	General Electric CF34-8C5 (2)
Maximum allowable take-off weight	38 329 kg (84 500 lbs)
Recommended fuel types	Jet A, Jet A-1, Jet B
Fuel type used	Jet A

* Effective 01 June 2020, the aircraft type certificate was transferred to Mitsubishi Heavy Industries, Ltd.

1.6.1 General

The Regional Jet Series 900, originally developed by Bombardier Inc. and approved by Transport Canada (TC) in 2002, is a lengthened version of the Series 700 aircraft. The Series 900 can seat 76 to 90 passengers; the 35 aircraft owned by Jazz are configured for 76. There have been 487 Series 900 aircraft delivered to 24 different air operators worldwide.

1.6.2 Recent aircraft maintenance work

During the period between 26 November and the time of the occurrence, due to an unserviceable auxiliary power unit (APU), the aircraft was being operated under the restrictions of the aircraft's Minimum Equipment List (MEL).[9] The APU provides electrical power to the aircraft when its engines are not operating and provides a source of compressed air (from the APU bleed air) for the starting of the aircraft's 2 engines. Since the APU had become unserviceable, flight crews on the aircraft had been starting 1 engine through use of an air start unit while parked at the airport gates. The aircraft would then be pushed back from the gate, and the other engine would be started by performing a cross-

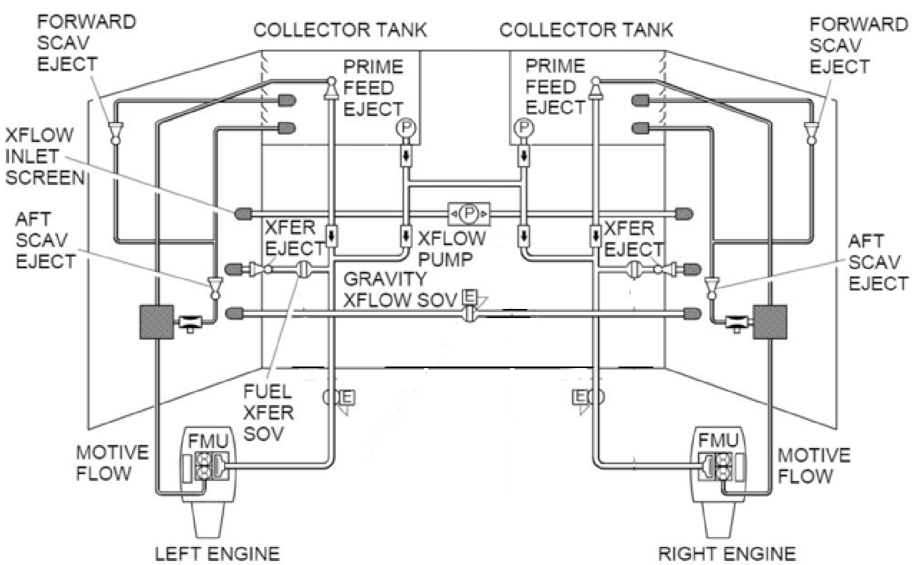
9 A minimum equipment list is "a document approved by the Minister pursuant to subsection 605.07(3) [of the *Canadian Aviation Regulations*] that authorizes an operator to operate an aircraft with aircraft equipment that is inoperative under the conditions specified therein, and may specify certain equipment that must be operative." (Source: Transport Canada, SOR/96-433, *Canadian Aviation Regulations,* section 101.01)

bleed start procedure (in which the bleed air from the running engine, rather than from the APU, is used). This process takes a few minutes longer than a start-up procedure that uses the APU, but it is a routine procedure at Jazz that is detailed in the company's standard operating procedures (SOPs).

1.6.3 Fuel system

The Regional Jet Series 900 fuel system (also common to the Series 700 and 1000 aircraft) consists of 3 integral tanks within the wing box structure: a tank in each of the wings and a centre tank (Figure 2). Fuel is able to be transferred between wing tanks by either a powered (electrically pumped) or gravity crossflow system. An FQGC measures the fuel quantity and temperature; however, slight variations in fuel quantity readings can exist due to changes in aircraft attitude. The FQGC also automatically controls fuel transfer between the wing tanks, as well as fuel transfers from the centre tank to the wing tanks via the left and right transfer ejectors. The EICAS in the cockpit shows a diagram of the fuel distribution system, and any fault detected by the FQGC is announced in the form of a visual message.

Figure 2. Regional Jet Series 900 fuel transfer and crossflow system (Source: Mitsubishi Heavy Industries, Ltd., Mitsubishi Heavy Industries Regional Jet Aviation Group, CSP C-013, *Flight Crew Operating Manual*, Revision 4 [16 February 2010], Chapter 28: Fuel System, p. 28-13-2.)



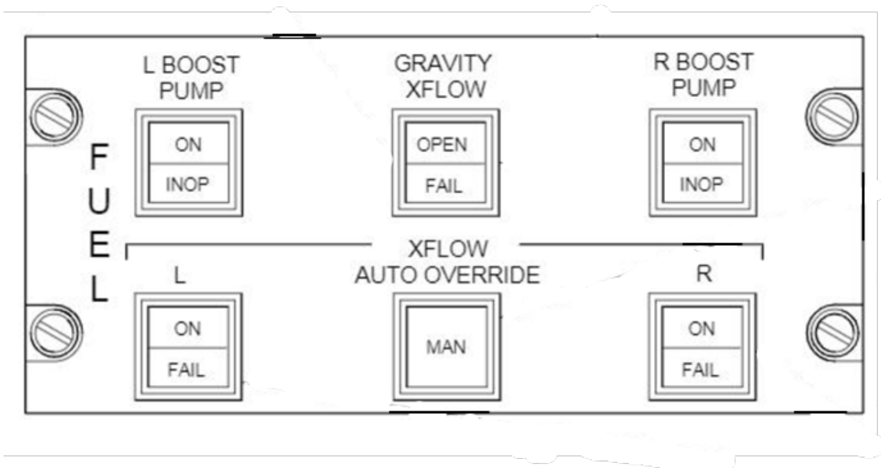
1.6.3.1 Transfer ejectors

Fuel transfer from the centre tank to the wing tanks is provided by transfer ejectors (labelled as XFER EJECT in Figure 2). The ejectors are not electrically operated pumps, but rather are powered only by fuel pressure tapped from the engine supply lines. The FQGC commands the transfer ejector shut-off valves to open when the associated wing tank fuel quantity falls to 93%, or approximately 7000 pounds, and commands them to close when the fuel quantity reaches 97%, or approximately 7200 pounds. The FQGC will continue cycling the transfer system on and off until the centre tank is empty.

1.6.3.2 Fuel crossflow system

Powered or gravity fuel crossflow allows fuel transfer between the wing tanks to correct fuel imbalances and to maintain lateral stability. Flight crews can control crossflow operations through the fuel control panel (Figure 3) located on the cockpit's overhead panel. The positions of the switches on the fuel control panel are not recorded on the aircraft's FDR.

Figure 3. Series 900 overhead fuel control panel (Source: Mitsubishi Heavy Industries, Ltd., Mitsubishi Heavy Industries Regional Jet Aviation Group, CSP C-013, *Flight Crew Operating Manual*, Revision 4 [16 February 2010], Chapter 28: Fuel System, p. 28-13-2.)



The switches are single-actuation push-button switches. Both the L and R BOOST PUMPs as well as the L and R XFLOW switches are in the off position when pressed out. Similarly, the GRAVITY XFLOW is closed when the switch is in the pressed-out position. When pressed in and lit up with white light, these switches are ON or, in the case of the GRAVITY XFLOW switch, OPEN. The XFLOW AUTO OVERRIDE switch, which is labelled as "MAN" and controls the FQGC mode, is in automatic (AUTO) mode when pressed out and manual (MAN) mode when pressed in and lit up.

The crossflow pump (XFLOW PUMP in Figure 2) provides powered crossflow operations in either automatic mode (when the XFLOW AUTO OVERRIDE push-button switch is in the OUT position) or manual mode (when the switch is in the IN position). In automatic mode, the FQGC controls the powered crossflow. When the FQGC detects a lateral imbalance of greater than 200 pounds for more than 30 seconds, the crossflow pump is activated automatically in the required direction to correct the imbalance. Also, in automatic mode, the FQGC actively monitors the position and operational status of the crossflow pump through a pair of Hall effect sensors.[10] These sensors create a feedback loop with the FQGC to sense the direction in which the fuel is transferring.

10 A Hall effect sensor is a type of magnetic sensor that detects the strength and direction of a magnetic field.

Conversely, a flight crew can control powered crossflow in manual mode by overriding automatic mode. In manual mode, the flight crew controls the flow by first pressing the XFLOW AUTO OVERRIDE switch and then selecting the direction of fuel through the crossflow pump by pressing either the L XFLOW or the R XFLOW switch. If XFLOW AUTO OVERRIDE is selected and neither L XFLOW or R XFLOW is selected, the auto transfer system is overridden, and powered crossflow does not occur.

According to Mitsubishi Heavy Industries Regional Jet Aviation Group (MHI RJ), the crossflow pump is able to transfer fuel at a rate of approximately 1700 to 2500 lb/h (approximately 28 to 42 lb/min), depending on fuel temperature and density.

In addition to the crossflow pump, all series of the Regional Jet have a gravity crossflow system that serves as a backup to powered fuel transfer. If the powered crossflow system fails, the flight crew can open the gravity crossflow shut-off valve (which connects the left- and right-wing fuel tanks) and allow fuel transfer by gravity between the tanks by pressing the GRAVITY XFLOW push-button switch on the overhead fuel control panel in the aircraft's cockpit. The switch and the valve it controls have no connection with the FQGC, and similarly, no connection with the crossflow pump or its corresponding switch. The EICAS will display a GRAV XFLOW FAIL message when the gravity crossflow shut-off valve is not in the selected position. The flight crew did not report the message being displayed during the occurrence flight.

The design requirement of the aircraft's gravity crossflow system establishes a transfer flow rate of at least 8000 lb/h (130 lb/min). When the system was in development, performance testing of the aircraft demonstrated that the system's average transfer flow rate was 3000 lb/h (50 lb/min) when on the ground with 0° roll angle and the engines at idle. In-flight performance checking demonstrated that a 5° sideslip angle resulted in a transfer rate of 19 200 lb/h (320 lb/min), and a 10° sideslip angle resulted in a transfer rate of 24 000 lb/h (400 lb/min). While these are the demonstrated performance abilities of the aircraft, actual flow rates are a function of:

- a difference of fuel head pressure between both main (wing) fuel tanks due to a fuel imbalance and/or the roll angle;
- the aircraft's lateral acceleration; and
- friction loss from the installation of the fuel tubes.

During the investigation, MHI RJ noted that a failure analysis conducted while the system was being tested had demonstrated that the gravity transfer flow rate is able to reduce the imbalance significantly in the situation of an inoperative crossflow pump. The transfer rate, as described in the MHI RJ QRH Gravity Cross-feed Procedure,[11] will be up to 100 lb/min.

11 Mitsubishi Heavy Industries, Ltd., MHI RJ Aviation Group, CSP C-022, *Quick Reference Handbook*, Revision 8 (27 September 2013), Gravity Cross-feed Procedure, p. ABNORM 9-9.

1.7 Meteorological information

During the flight crew's inbound flight to KSAN and while they were on the ground there, the weather at the occurrence flight's destination, CYVR, as well as at the alternate airport, Calgary International Airport (CYYC), Alberta, remained favourable to visual flight conditions.

The aircraft, on its inbound flight, landed at KSAN at 1703. At that time, the most recent aerodrome routine meteorological report (METAR)[12] at the airport indicated that the weather consisted of winds from 310° true (T) at 4 knots, visibility of 10 statute miles (SM), and few clouds at 200 feet above ground level (AGL).

Sunset at the airport occurred at 1642; the inbound flight therefore arrived during evening civil twilight.[13] At 1803, during the hours of darkness, the aircraft pushed back from the terminal gate to begin the taxi for takeoff on the occurrence flight.

While the flight crew prepared for the occurrence flight to CYVR, weather conditions at KSAN deteriorated due to an advancing fog bank. At 1749, the METAR for KSAN indicated calm winds, a visibility of 3 SM, mist, and a broken ceiling at 200 feet AGL. While the prevailing visibility was 3 SM, the observed visibility around the ATC tower was variable and ranged from ¾ SM to the west and southwest, up to 4 SM to the northeast and southeast.

At approximately 1842, when the aircraft departed on the occurrence flight, the weather conditions were continuing to deteriorate. The most recent METAR, which was issued at 1835 and broadcasted on the airport's automatic terminal information service (ATIS) frequency, indicated:

- winds from 300°T at 4 knots
- prevailing visibility of ½ SM (with an observed visibility of 2 SM toward the northeast and east and ¼SM toward the south and west)
- Runway 09 runway visual range (RVR) 1200 feet variable to 2000 feet
- fog
- broken ceiling at 200 feet AGL

Given the weather observation, the visibility conditions at various parts of the airport were highly variable during the aircraft's take-off roll. While the visibility at the western end of the runway had been degraded to about ¼ SM, visibility at the eastern end, where the aircraft began its takeoff, was degraded but not as low (at least ½ SM). At the time of takeoff, the flight crew did not have a clear view of the end of the runway or the airport's buildings.

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12 Issued at 1651, 12 minutes before the arrival of the inbound flight (JZA766).

13 Evening civil twilight is the period of time that begins at sunset and ends in the evening when the centre of the sun's disc is 6° below the horizon—approximately 25 minutes after sunset. (Source: Transport Canada, TP 14371E, *Transport Canada Aeronautical Information Manual* [TC AIM], GEN – General [06 October 2022], Section 1.5.2.)

Due to the in-flight fuel imbalance event, the aircraft diverted to KLAX. The METARs published there during the diversion and landing all indicated clear skies, light winds, and a visibility of 10 SM.

1.8 Aids to navigation

KSAN is serviced by multiple approaches to both Runway 09 and Runway 27. Each of these runways is serviced by a separate traditional localizer (LOC), with Runway 09 also equipped with a glide path for an instrument landing system (ILS). All systems were serviceable at the time of the occurrence.

1.9 Communications

While the occurrence aircraft was waiting for departure, 9 other aircraft approached Runway 09. The flight crew of the 6th aircraft to land on Runway 09 indicated to the KSAN tower controller, at approximately 1834, that they did not see the runway environment until they reached the minimum altitude on the approach.

At 1835, KSAN issued an updated weather report (as described in 1.7 *Meteorological information*), and it was broadcasted on the ATIS frequency. Approximately 1 minute later, the tower controller informed aircraft on the tower frequency that the new weather report was available on the ATIS.

The next 3 approaching aircraft were all notified by the tower controller to expect to see the runway environment at the minimum altitude on the approach. Of these 3 aircraft, 2 landed; the flight crew of the 3rd executed a missed approach at approximately 1839, and soon after, indicated to the tower controller that they did not see the runway environment from the minimum altitude.

The KSAN tower controller had no knowledge of the excursion until the broken lights were discovered by airport personnel 7 hours and 46 minutes later. Therefore, the tower could not alert the occurrence aircraft's flight crew while they were still in flight.

1.10 Aerodrome information

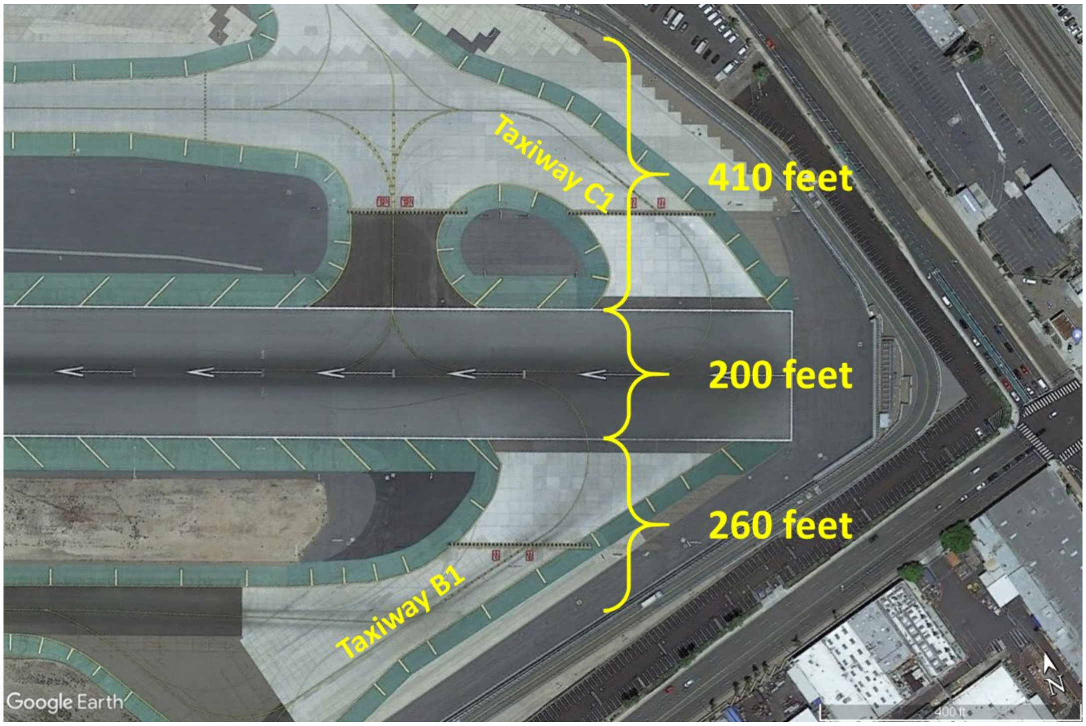
KSAN is a single-runway airport located on the northern shoreline of San Diego Bay and surrounded by the city of San Diego (Figure 4). KSAN is one of the busiest single-runway commercial service airports in the world and the 3rd-busiest airport in California. The airport's runway, Runway 09/27, is 200 feet wide and 9400 feet long. However, Runway 09 has a permanently displaced threshold of 1000 feet, and Runway 27's threshold is permanently displaced by 1810 feet. Runway 27 also incorporates an engineered materials arresting system (EMAS),[14] which is 315 feet long and located immediately west of the threshold of Runway 09.

Figure 4. View of San Diego International Airport and Runway 09/27 (Source: Google Earth, with TSB annotations)

The entry point of Taxiway B1 onto Runway 27 is directly across from that of Taxiway C1, which enters the runway from the north side. The runway itself is 200 feet wide, but the width of the paved surface at this intersection, where the occurrence aircraft initiated its takeoff, is approximately 870 feet. The pavement extends approximately 260 feet to the left of the runway's southern edge and 410 feet to the right of the runway's northern edge (Figure 5).

14 EMAS is made of "high energy absorbing materials of selected strength, which will reliably and predictably crush under the weight of [an] aircraft […]. When an aircraft rolls into an EMAS arrestor bed, the tires of the aircraft sink into the bed and the aircraft is decelerated by having to roll through the material. The objective […] is to bring an aircraft overrunning a runway to a stop." (Source: Transport Canada, Advisory Circular [AC] No. 300-007: Engineered Materials Arresting Systems for Aircraft Overruns, Issue 03 [24 April 2017], at tc.canada.ca/en/aviation/reference-centre/advisory-circulars/advisory-circular-ac-no-300-007 [last accessed on 22 May 2024]).

Figure 5. Map showing the width of the paved surfaces adjacent to Runway 27 at San Diego International Airport (Source: Google Earth, with TSB annotations)



Jazz conducts regularly scheduled daily flights between CYVR and KSAN. The investigation studied the typical arrival and departure patterns of the inbound (CYVR-KSAN) flights as well as the outbound return (KSAN-CYVR) flights for a 3-month period around the date of the occurrence. In the 158 individual flights studied, approximately 94% of the landings and takeoffs occurring at KSAN were conducted on Runway 27. Only 3 times in this period did an inbound flight land on Runway 09, with the return flight taking off from Runway 27.

1.10.1 Visual environments of runway thresholds and displaced thresholds

Canadian and U.S. standards for runway threshold markings are very similar. Runway threshold markings help identify the beginning of the runway that is available for landing. These markings are longitudinal stripes that are painted white and extend laterally across the approximate width of the runway. The specifications of the stripes are determined by the certification of the runway, by its width, as well as by the approach category servicing the runway.

In addition, the runway designation marking (known as the runway landing designator marking in the U.S.) is the painted runway number marking centred on the runway centreline and located 12 m from the top edge of the runway threshold marking.

In some instances, the landing threshold may be relocated or displaced; for example, when natural or fabricated obstacles interfere with runway approach paths and require limitations to their use. In the U.S.

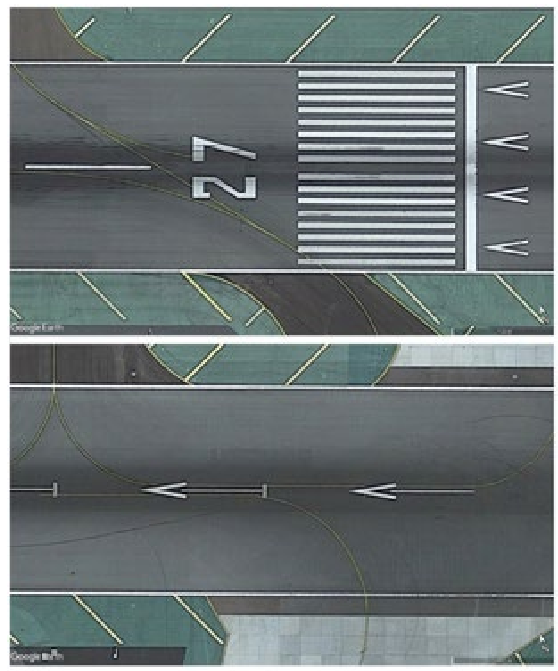
> [a] displaced threshold is a threshold located at a point on the runway other than the designated beginning of the runway. Displacement of a threshold reduces the

> length of runway available for landings. The portion of runway behind a displaced threshold is available for takeoffs in either direction and landings from the opposite direction. A ten feet wide white threshold bar is located across the width of the runway at the displaced threshold. White arrows are located along the centerline in the area between the beginning of the runway and displaced threshold.[15]

Standards in Canada indicate that the arrowhead must be 10 m long and the shaft at least 20 m.[16] Standards in the U.S. are similar, with required lengths of 13.5 m and 24 m, respectively (figures 6 and 7). The displaced portion of a runway can be used for taxiing and takeoff. It can also be used for rollouts after landing on the opposite end.

Figure 6. Runway threshold (top) and displaced threshold area (bottom) at Vancouver International Airport (Source: Google Earth)

Figure 7. Runway threshold (top) and displaced threshold area (bottom) at San Diego International Airport (Source: Google Earth)



Intersections between runways or taxiways, such as the intersection from which the occurrence aircraft began its take-off roll, have a visual environment similar to that of displaced threshold areas (in that neither has markings defining width). Many air operators have policies concerning intersection departures. For example, Jazz does permit takeoffs from intersections, but the policy is predicated on the flight crew being able to ascertain whether sufficient runway length exists.[17]

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15 Federal Aviation Administration, *Aeronautical Information Manual*, Chapter 2, section 2-3-3: Runway Markings.

16 Transport Canada, TP 312E, *Aerodromes Standards and Recommended Practices*, 5th Edition, Amendment 1 (effective 15 January 2020), Figure 5-6(a): Arrow markings, p. 100.

17 Jazz Aviation LP, *Company Operations Manual*, Revision 24 (15 November 2021), Subsection 4.5.6.2: Intersection Take-off, p. 4-5-8.

1.10.2 Taxiway centreline marking

Taxiway centreline markings provide flight crews with continuous visual guidance along a designated path. According to the U.S. Federal Aviation Administration (FAA) standard for airport markings, the centreline markings on a lead-on taxiway can terminate at the runway edge, but for taxiways that enter onto the runway in a displaced threshold area, the taxiway centreline markings continue onto the runway and extend parallel to the arrows that lead to the displaced threshold for at least 200 feet beyond the point of tangency or to the displaced threshold bar, whichever is less.[18]

Taxiway centreline markings thereby provide cues to flight crews for reaching the runway; however, they reduce slightly the length available for takeoff if a flight crew taxis to where these markings become tangent with the displaced threshold markings. At KSAN, the taxiway centreline marking on Taxiway B1 reaches tangency approximately 425 feet beyond the beginning of Runway 27.

During the occurrence, the aircraft entered Runway 27 from Taxiway B1, where the taxiway centreline marking extended to the centre of the runway. In addition, the Taxiway B1-Runway 27 intersection also has embedded lighting along a portion of the taxiway centreline marking. However, this is not taxiway centreline lighting, but rather, the runway status light (RWSL) system. RWSLs are a fully automatic advisory system (that is, they require no activation by air traffic controllers) designed to reduce runway incursions. When illuminated, they indicate to flight crews or airport vehicle operators that the runway is occupied or that an aircraft is approaching the runway. When the system detects an aircraft on the runway and in the vicinity of the intersection, the embedded lighting automatically turns red. At the time of this occurrence, RWSL systems were installed at 20 airports in the U.S. The RWSL system was functioning at KSAN on the night of the occurrence, and the red lighting illuminated toward the occurrence aircraft while the preceding aircraft was occupying the Runway 27–Taxiway B1 intersection at the beginning of its take-off roll. The red lights automatically extinguished, and shortly thereafter, the occurrence aircraft was cleared by ATC to take position on Runway 27.

1.10.3 Runway edge markings

Runway edge markings (known as runway side stripe markings in Canada) provide enhanced visual contrast between the runway edges and the surrounding terrain or runway shoulders and define the runway width. The side stripe markings consist of 1 parallel stripe on each edge of the runway. The Canadian aerodrome standard for runway markings states that side stripes are interrupted at intersections between 2 runways or at intersections

18 Federal Aviation Administration (FAA), Advisory Circular (AC) 150/5340-1M: Standards for Airport Markings, Change 1 (23 December 2020), Section 4.2: Taxiway Centerline Markings, p. 4-2.

between a runway and a taxiway (Figure 8).[19,20] By contrast, the U.S. standard[21] for runway edge markings specifies that runways shall have uninterrupted edge markings (Figure 9).

Figure 8. Runway side stripe markings at Vancouver International Airport (Source: Google Earth, with TSB annotations)

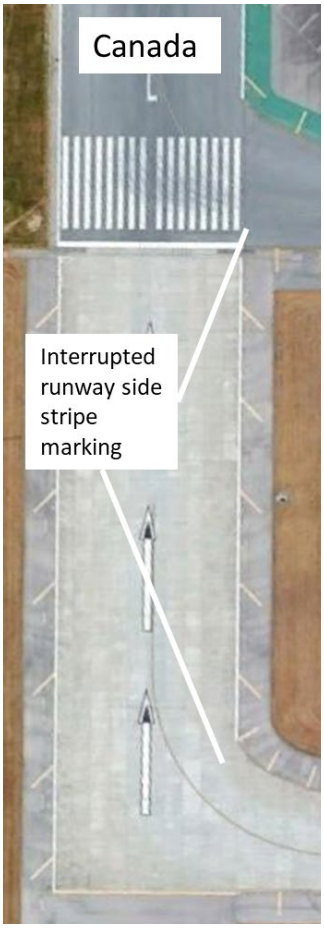
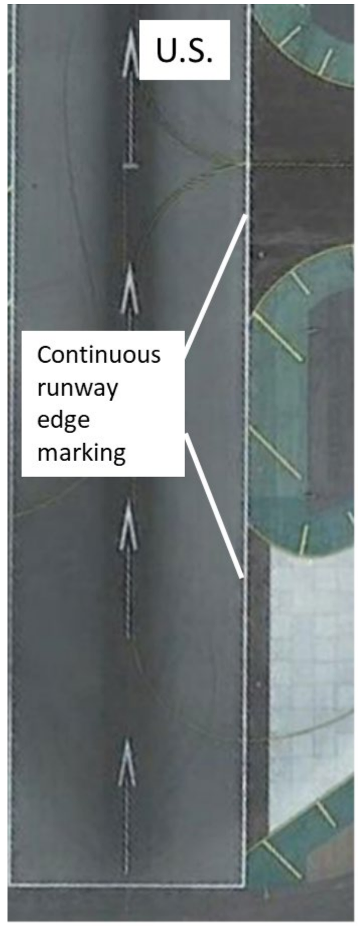


Figure 9. Runway edge markings at San Diego International Airport (Source: Google Earth, with TSB annotations)



The runway edge markings at KSAN had been most recently painted in May 2020—18 months before the current occurrence. Furthermore, in June 2021, the FAA had conducted its annual safety inspection at KSAN, in which an element was the inspection of runway markings for compliance with existing standards.

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19 Transport Canada, TP 312E, *Aerodromes Standards and Recommended Practices*, 5th Edition, Amendment 1 (effective date 15 January 2020), Section 5.2.11: Runway Side Stripe Marking, subsection 5.2.11.4, p. 105.

20 The investigation is aware of 1 runway in Canada that does not adhere to this standard: Runway 06L/24R at Toronto/Lester B. Pearson International Airport (CYYZ), Ontario. This runway had runway side stripe markings painted onto it before the publication of the most recent edition of TP 312 *Aerodrome Standards and Recommended Practices*, which established the current standard. Transport Canada Advisory Circular (AC) 302-018 (Grandfathering at Airports Pursuant to *Canadian Aviation Regulation* [CAR] 302.07) provides guidance to clarify that when airport parts and facilities are being maintained, they can be grandfathered to the same edition of TP 312 applicable at the time of initial certification (and with which they currently comply), but if replaced or improved, they must comply with the latest edition of TP 312.

21 Federal Aviation Administration (FAA), Advisory Circular (AC) 150/5340-1M: Standards for Airport Markings, Change 1 (23 December 2020), Section 2.8: Runway Edge Markings, pp. 2-16 to 2-17.

1.10.4 Runway shoulder markings

Runway shoulders are the areas adjacent to the defined runway edges that provide resistance to blast erosion and accommodate the passage of maintenance and emergency equipment. Paved shoulders assist in reducing the amount of dirt and debris that enters the runway, providing a smoother runoff area for runway side excursions and allowing for the passage of airport operations vehicles without the use of the runway surface.

While the U.S. standards[22] for runway geometry indicate that stabilized surfaces, such as turf or low-cost paving, are suitable for the shoulder, paved shoulder surfaces are required for runways that accommodate aircraft with a wingspan of 36 m or longer and a tail height of 13.7 m or higher (the approximate measurements of a Boeing 767 aircraft).

In the U.S., runway shoulders can have markings to further delineate the shoulder from the runway. If used, they consist of stripes oriented 45° from the runway centreline and painted yellow.[23]

Runway and taxiway shoulders at KSAN are painted dark green and striped yellow. The runway shoulder on the south side of Runway 27 in the vicinity of the Taxiway B1 entrance is 64 feet wide, 50 feet of which is painted and striped. However, there is also an unmarked and unpainted paved area that extends 125 feet between the shoulder of Runway 27 and the north edge of Taxiway B1. It covers the inside radius of the turn where Taxiway B1 meets Runway 27 (Figure 10). At the point where the occurrence aircraft aligned with the runway and came to a stop, the painted shoulder was approximately 180 feet ahead. Figure 12 in 1.10.5 *Runway lighting* provides a representation of the flight crew's visual environment in which the shoulder is visible.

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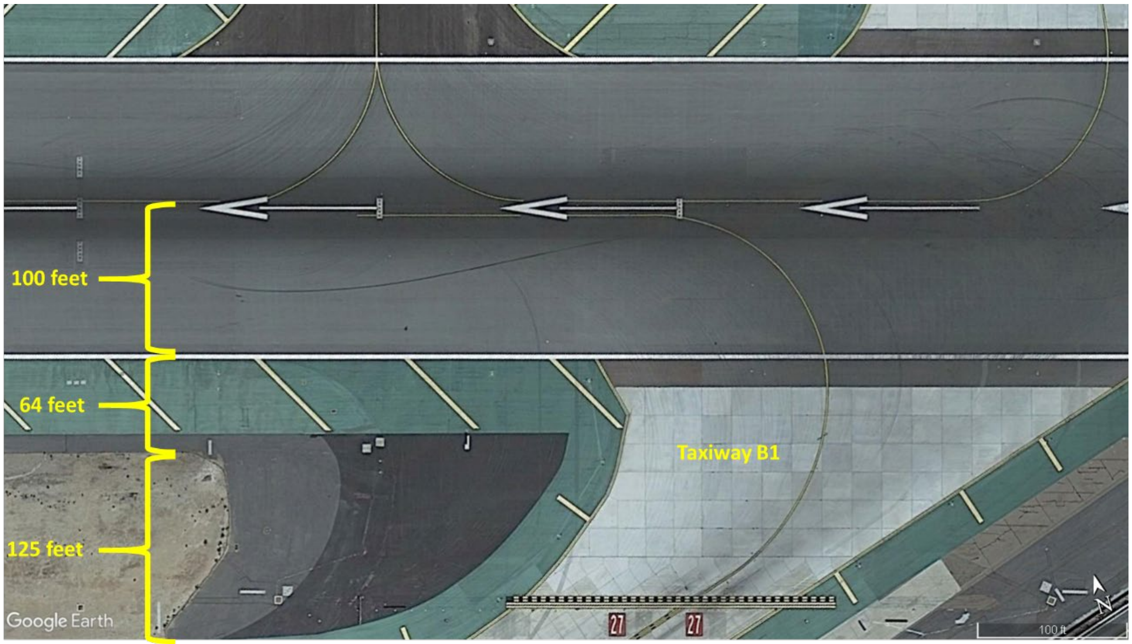
22 Federal Aviation Administration (FAA), Advisory Circular (AC) 150/5300-13A: Airport Design, Change 1 (26 February 2014), Section 304: Runway geometry, p. 54.

23 Federal Aviation Administration (FAA), Advisory Circular (AC) 150/5340-1M: Standards for Airport Markings, Change 1 (23 December 2020), Figure A-12: Runway Shoulder Markings, p. A-12.

Figure 10. Runway 27 shoulder configuration at Taxiway B1 (Source: Google Earth, with TSB annotations)



Canadian standards do not include provisions necessitating the addition of runway shoulders or their markings. The investigation assessed 18 Canadian airports regularly serviced by Jazz.[24] Of these, 9 had runway complexes with no defined shoulders, and the other 9 had defined runway shoulders of widths ranging from 5 feet to a maximum of 25 feet.

1.10.5 Runway lighting

In both Canada and the U.S., the standard for runway edge lighting is to emit white light. As an aircraft nears the end of the runway lighting, the colour changes from white to yellow, signifying the final 600 m (or 610 m in the U.S.) of the runway, which can include a displaced threshold. When a runway threshold is displaced, the runway edge lighting located in the area before the displaced threshold emits red light toward the aircraft on approach[25][26] and yellow in the opposite direction (Figure 11).

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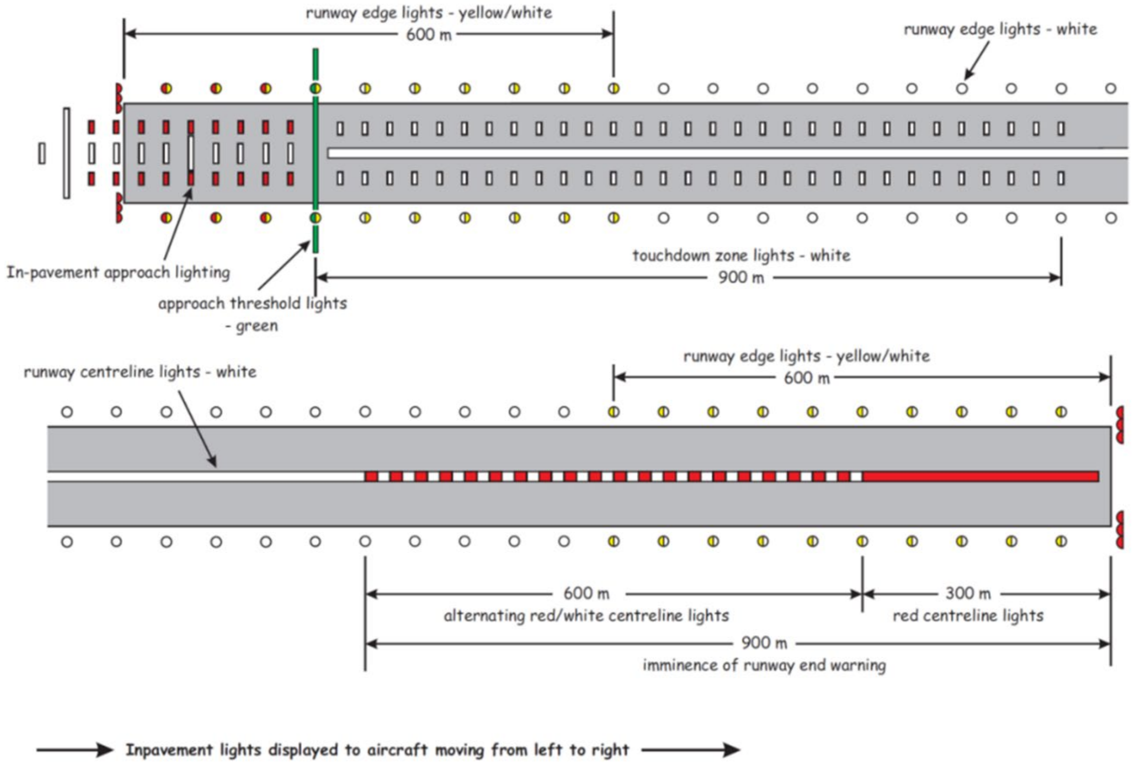
24 The airports are those regularly serviced by Jazz's MHI RJ Series 200 and 900 aircraft: Halifax/Stanfield International Airport (CYHZ), Sydney/J.A. Douglas McCurdy Airport (CYQY), Charlottetown Airport (CYYG), Saint John Airport (CYSJ), Québec/Jean Lesage International Airport (CYQB), Montréal/Pierre Elliott Trudeau International Airport (CYUL), Toronto/Lester B. Pearson International Airport (CYYZ), Windsor International Airport (CYQG), Sault Ste. Marie Airport (CYAM), Winnipeg/James Armstrong Richardson International Airport (CYWG), Saskatoon/John G. Diefenbaker International Airport (CYXE), Regina International Airport (CYQR), Edmonton International Airport (CYEG), Calgary International Airport (CYYC), Vancouver International Airport (CYVR), Victoria International Airport (CYYJ), Whitehorse/Erik Nielsen International Airport (CYXY), and Yellowknife Airport (CYZF).

25 Transport Canada, TP 312E, *Aerodromes Standards and Recommended Practices*, 5th edition, Amendment 1 (effective 15 January 2020), Section 5.3.12.5: Characteristics, p. 172.

26 Federal Aviation Administration (FAA), Advisory Circular (AC) 150/5340-30J: Design and Installation Details for Airport Visual Aids (12 February 2018), Section 2.3.2.1.2: Displaced Runway Thresholds, p. 2-4.

Figure 11. Runway edge and centreline lighting colours (Source: Transport Canada, TP 312E, *Aerodromes Standards and Recommended Practices*, 5th edition, Amendment 1 [effective date 15 January 2020], Figure 5-37: Runway edge, centreline and touchdown zone lighting, p. 173.)



All runway edge lights are placed in 2 parallel rows, each equidistant from the runway centreline, and with uniform spacing of not more than 60 m (or 61 m in the U.S.).

If a runway is equipped with runway centreline lighting, these lights emit a white light in the direction of the approaching aircraft. To warn flight crews of the impending end of a runway, the colouring changes to alternating red and white for the final 900 m, then to red for the final 300 m (Figure 11).[27,28]

Runway 27 at KSAN is equipped with runway edge and centreline lighting. Most edge lights are raised above the runway surface and on frangible bases, but a number of edge lights are embedded in the runway edge, including the runway edge lights that transect Taxiway B1 where it enters onto Runway 27. In addition, given the long displaced threshold area of the runway, the runway's approach lighting is also embedded within the paved surface. As such, the 1st runway edge light in front of the occurrence aircraft as it lined up on the runway edge was embedded in the runway surface, in the same fashion as the approach lighting on the centreline (Figure 12).

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27 Transport Canada, TP 312E, *Aerodromes Standards and Recommended Practices*, 5th edition, Amendment 1 (effective 15 January 2020), Figure 5-37: Runway edge, centreline and touchdown zone lighting, p. 173.

28 Federal Aviation Administration (FAA), Advisory Circular (AC) 150/5340-30J: Design and Installation Details for Airport Visual Aids (12 February 2018), Section 3.3.1.2: Color Coding, p. 3-2.

Figure 12. Approximate visual representation of the runway environment, as visible to the occurrence flight crew, while the aircraft was aligned with the left runway edge marking (Source: San Diego County Regional Airport Authority, with transparency adjustments made to the image by the TSB to recreate the visibility during the occurrence)

Runway 09/27 at KSAN has medium-intensity approach lighting on both ends. The majority of the approach lighting on each runway is embedded in the runway's surface, in the area before the displaced threshold. The embedded lights protrude slightly from the surface and can make for bumpy taxiing and take-off rolls. According to the configuration standard for lighting installation:

> the control of the approach lights and displaced threshold area centreline lights is interlocked to ensure that when the approach lights are "on", the displaced area centreline lights are "off", and vice versa.[29]

Runway 09 was being used for approaches during the time of the occurrence, meaning that the centreline lights in the Runway 09 displaced threshold area were off, but the ones in the Runway 27 displaced threshold area were on.

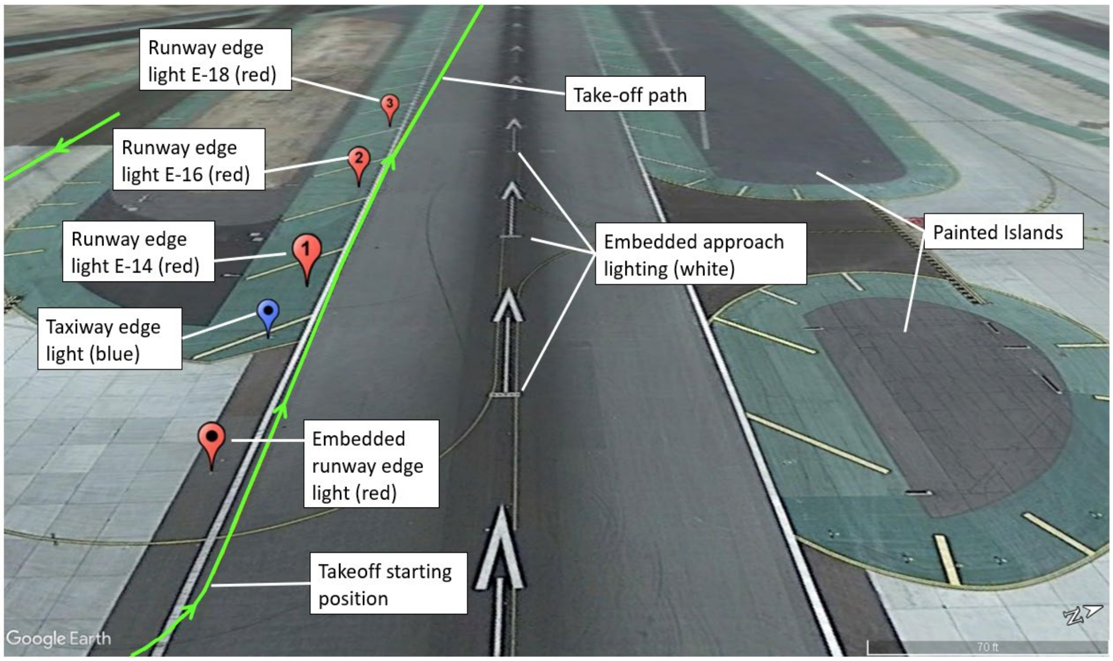
Canada and the U.S. have similar standards for the operation of airport lighting. Between sunset and sunrise, or when other specific environmental conditions persist, runway edge and centreline lights (if installed) must be on for departing aircraft. Approach lighting is required to be on only for the landing runway served by the lights. However, controllers can activate lights otherwise, as they deem necessary, and pilots can also request that approach lighting be activated.

[29] Ibid., Section 3.3.1.3.3, p. 3-2.

During the occurrence aircraft's takeoff, the runway edge and centreline lights were on. Since Runway 09 was being used for arrivals, the embedded approach lighting on Runway 27 in the area behind the displaced threshold was off.

During the take-off roll, the occurrence aircraft struck and severed 3 consecutive raised runway edge lights (labelled E-14, E-16, and E-18 in Figure 13).

Figure 13. Occurrenc aircraft's take-off path based on data from the flight data recorder in relation to Runway 27 edge lighting (Source: Google Earth, with TSB annotations)



1.10.6 San Diego International Airport departure and arrival operations using both ends of the runway

In degraded weather conditions, the use of Runway 09 for approaches and landings is often necessary due to it having a precision approach with lower published visibility and altitude limitations compared to those for Runway 27. Runway 27, on the other hand, is the preferred runway for departures due to the lower required climb gradient (aircraft depart toward the ocean instead of rising terrain) and less noise over the city. In a practice commonly referred to as "9/27 operations," the control tower collaborates with the approach/departure controller in a specific period in which successive departures take off, followed by another period in which successive arrivals will land. There are no detailed procedures for the switching of the approach lights for these periods and this runway configuration, and controllers are to follow the standards set forth by the FAA for airport lighting systems.[30]

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30 Federal Aviation Administration (FAA), Order JO 7110.65Z, *Air Traffic Organization Policy*, Change 2 (19 May 2022), Paragraph 3-4-5: Approach Lights.

1.10.7 San Diego International Airport tower aids

KSAN is 1 of 35 towered airports in the U.S. that use airport surface detection equipment – model X (ASDE-X). The system uses ATC radar, multilateration sensors, and satellite-based sensors to provide air traffic controllers with the position and identification of all aircraft and vehicles on the airport movement area. ASDE-X was developed to help reduce runway incursions, and at KSAN, it works in concert with the airport's RWSL system, which provides flight crews and vehicle operators with visual identification of a runway's status. ASDE-X also provides air traffic controllers with automatic alerts for potential runway conflicts.

However, given that it is not designed to send alerts for the lateral misalignment of an aircraft on a runway, the air traffic controller received no such alert. As a result, the air traffic controller, who was working at night and with degraded visibility conditions, remained unaware that the occurrence aircraft was misaligned for takeoff.

Furthermore, KSAN is not equipped with a foreign object debris detection system, which is designed to detect objects on runway surfaces and alert airport staff to their presence. Once the aircraft had completed the misaligned takeoff, the controllers and the airport operator therefore remained unaware of the missing runway edge lights and debris on the runway for the next 7 hours and 46 minutes.

1.10.8 San Diego International Airport runway side excursion history

The FAA was able to provide the investigation with details of known side excursion events at KSAN. These records show that in the 5 years preceding this occurrence, there were 6 runway side excursions at the airport. Two of them were the direct result of an aircraft mechanical issue. The remaining 4 side excursions indicate that each aircraft exited the runway as a result of flight crew visual perception of the paved surface environment, and specifically, the asphalt areas painted green with yellow stripes and contained within the runway shoulders, as well as the painted islands.

In the U.S., the National Aeronautics and Space Administration (NASA) maintains the Aviation Safety Reporting System (ASRS) which receives, processes, and analyzes voluntarily submitted incident reports describing occurrences or hazardous situations from pilots, air traffic controllers, and others within the aviation system. The ASRS contains 7 voluntary reports of side excursions that have occurred at KSAN since 1990. Two of the 7 occurrence reports describe flight crews exiting the runway onto the runway shoulders and painted islands while perceiving these areas as a taxiway. The other 5 occurrences describe nighttime runway misalignments in which flights crews attempted to take off, or successfully departed, while mistaking the runway edge markings and runway side lights within the Runway 27 displaced threshold area as the centreline.

The FAA Accident and Incident Data System[31] contains an additional occurrence[32] involving a flight crew conducting a nighttime takeoff from the area before the Runway 27 displaced threshold in which the aircraft was aligned with the runway edge and struck 4 runway edge lights during its takeoff.

1.11 Flight recorders

The aircraft was equipped with a digital FDR and a cockpit voice recorder (CVR).

Data was recovered from the digital FDR and processed at the TSB Engineering Laboratory in Ottawa, Ontario. The data contained 444 recorded parameters and covered more than 500 hours.

The CVR was removed by a Jazz contracted maintenance organization and shipped to the TSB Engineering Laboratory. The recording contained 2 hours and 4 minutes of recording from 4 channels. The laboratory noted that the recording quality of the cockpit area microphone was excellent. There were no crew communications data because the CVR was not isolated until approximately 4 hours after the aircraft had landed at KLAX. As a result, the occurrence flight was overwritten, and information that could have been valuable to the investigation was lost.

1.12 Wreckage and impact information

Not applicable.

1.13 Medical information

According to information gathered during the investigation, there was nothing to indicate that the flight crew's performance was degraded by medical factors.

1.14 Fire

Not applicable.

1.15 Survival aspects

Not applicable.

1.16 Tests and research

1.16.1 Runway threshold visual environment testing

To better appreciate the visual environment encountered by the occurrence flight crew when taking off within the displaced threshold area of Runway 27, the investigation

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31 Federal Aviation Administration (FAA), FAA Accident and Incident Data System, www.asias.faa.gov/apex/f?p=100:12:::NO (last accessed on 23 May 2024).

32 FAA Accident and Incident Data System number 20040108000379I.

simulated a representative runway model that approximated the runway shoulder, markings, and lighting at KSAN. The environmental conditions were varied between ½ SM visibility[33] and unlimited visibility; conditions were also varied between daytime and nighttime. Images captured from the displaced threshold area (Figure 14) demonstrated to the investigation the level of saliency of runway markings when a flight crew judges an aircraft's lateral alignment with the runway. They also showed how the paved runway shoulder contributes to the overall visual environment.

Figure 14. Simulated runway environments at the runway's left edge. Clockwise, from top left: daytime, at runway threshold; nighttime with reduced visibility, at runway threshold; nighttime, in displaced threshold area; daytime, in displaced threshold area. (Source: TSB)

1.16.2 Flight data analysis

The recorded flight data indicate that the occurrence aircraft departed from KSAN at 1842:38 (Appendix A). The flight data also show an engine thrust reduction to climb thrust by the flight crew approximately 1 minute later. At this time, the fuel load was laterally balanced. Over the next 2 minutes, the recorded fuel quantity in both the right-wing tank and the centre tank decreased, but the quantity in the left-wing tank remained steady.

Approximately 3 minutes after departure, the FQGC detected a minor lateral imbalance—the left fuel tank was approximately 220 pounds heavier.

The minor imbalance persisted as the aircraft continued to climb. During this period, the quantity of fuel in the right-wing tank fluctuated approximately around the scheduled thresholds for the FQGC utilization of the centre tank's transfer ejectors. However, in the same period, the fuel quantity in the left-wing tank remained relatively unchanged. Once the aircraft climbed above 10 000 feet ASL, FDR data show the aircraft was being flown in a

33 Approximately the lowest visibility the occurrence flight crew experienced as they began the takeoff from the runway area before the displaced threshold.

consistent left bank of approximately 1°, compared to an average left bank on the ground before takeoff of approximately 0.5°.

The investigation further calculated that the total amount of fuel consumed by both engines was consistent with the quantity of fuel transferred from the centre tank to the right-wing tank via the transfer ejectors. Since there is no route by which the fuel can travel from the centre tank directly to the engines, this calculation indicates that the total fuel consumed by both engines was generally being supplied by only the right-wing tank.

The significant lateral fuel imbalance began as the aircraft climbed through FL310. This portion of the flight coincides with the fuel consumption by the engines being reduced to a flow rate approximately equal to the crossflow pump rate of transfer. When the aircraft neared its cruise altitude of FL340, the lateral imbalance continued to worsen, reaching approximately 400 pounds. During this period, while the aircraft maintained a steady bank of 1° to the left, the 2 fuel amounts were diverging, with the left-wing tank slowly increasing in quantity, and the right-wing and centre tanks decreasing in quantity.

As the lateral imbalance reached approximately 700 pounds, the flight crew attempted to use differential engine thrust settings, using less thrust on the right engine and thus enabling less fuel flow. Following this attempt, the flight crew were presented with a "FUEL IMBALANCE" caution message because the imbalance had, at that time, reached the maximum permissible in-flight imbalance of 800 pounds. Calculations made by the investigation show that the amount of fuel consumed by the engines in this period was equal to the rate of change of fuel from the centre tank, and that the fuel amount in the left-wing tank was increasing at approximately the same rate as the fuel decrease in the right-wing tank.

When the flight crew continued with the original checklist (in the XFLOW PUMP Caution Message procedure), it led them to action the Gravity Crossfeed Procedure, which required them to perform a sideslip. With the autopilot system remaining on, the flight crew established the sideslip; however, they applied pressure to the right rudder (in the direction of the low-quantity fuel tank), which resulted in the autopilot banking the aircraft approximately 2.2° to the left (toward the higher-quantity fuel tank) for approximately 3 minutes. This manoeuvre resulted in the left-wing tank reaching its maximum quantity and additional fuel likely being forced through the tank vents and reaching the centre tank.

When the lateral fuel imbalance reached approximately 1400 pounds, the flight crew began to divert to KLAX. The flight crew were provided with a left turn and descent clearance by ATC, and meanwhile, the open gravity crossflow valve continued to exacerbate the lateral fuel imbalance. It was during this descending turn that the flight crew shut down the No. 2 engine as directed by the Gravity Crossfeed Procedure. After the turn, the aircraft maintained an average angle of bank to the left, in part due to the routing by ATC, but also due to a likely contribution of the left wing's weight, which, at this time, was approaching 2000 pounds heavier than the right wing. As a result, the left-wing tank remained at its maximum quantity, and despite the fact that only the left engine was operating, the only reduction in fuel quantity was from the right-wing tank.

As the data show, the left-wing tank continued to be full and the aircraft reached a peak lateral fuel imbalance of 2464 pounds when it was descending through approximately 10 000 feet ASL. Over the following 9 minutes, the aircraft's angle of bank was at times oriented to the right, including during an approximate 180° right turn with an angle of bank averaging approximately 15°. During this period, the lateral fuel imbalance was reduced to approximately 1120 pounds. In addition, as the aircraft rolled onto its final approach at KLAX, the angle of bank was again slightly to the left, and the aircraft landed with a lateral fuel imbalance of approximately 1600 pounds.

1.16.3 TSB laboratory reports

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

- LP179/2021 – CVR Download
- LP178/2021 – Flight Data Analysis

1.17 Organizational and management information

1.17.1 General

Jazz Aviation LP is a regional airline that operates 114 aircraft under *Canadian Aviation Regulations* (CARs) Subpart 705, including its fleet of MHI RJ Regional Jet Series 900 aircraft. In accordance with these regulations, the company has a safety management system (SMS).

1.17.2 Flight crew training

To maintain their flight qualifications, Jazz flight crews undergo annual ground training (technical training and crew resource management [CRM]) as well as flight training in a simulator and line checks. The occurrence captain had most recently completed his required recurrent training in July 2021 (4 months before the occurrence), and the first officer had done so 9 days before the occurrence.

Flight training in a simulator uses training and checking scripts—that is, scenarios including routes and failure sequences. Scripts rotate twice per year so that flight crews experience new training during each of their semi-annual simulator training sessions. Initial training scripts at Jazz include departures from runways with displaced thresholds, and the recurrent training script (as well as the flight checking) used throughout the 2nd half of 2018 included departures from Newark Liberty International Airport (KEWR), New Jersey, U.S., an airport that has displaced thresholds up to 2540 feet long. The occurrence flight crew members both received this training and checking in 2018.

Technical training for aircraft systems is taught to flight crews initially and during annual recurrent ground school training. Jazz's ground school course for the Regional Jet Series 900 includes a module for the fuel system and the related caution messages.

1.17.3 Threat and error management

Jazz flight crews receive initial and annual recurrent training on non-technical skills in the operator's in-house 1-day CRM training session. Flight crews are trained in non-technical skills in the morning. In the afternoon, the principles of threat and error management (TEM), covered during training, are applied and then discussed in the context of various scenarios. The scenario-based afternoon is also attended by staff from Jazz's cabin crews, dispatchers, and aircraft maintenance controllers. During TEM training, staff discuss the potential threats within scenarios and the ways to prevent any threats from developing into errors when an undesired aircraft state persists. The desired result from Jazz's scenario-based TEM training is for Jazz staff to be able to identify potential threats in the scenarios, as well as the errors that can result.

Jazz's TEM methodology is built upon the ICAO TEM model (further discussed in 1.18.3.3 *Crew resource management and threat and error management*). The operator's full CRM training program is updated yearly (but can be modified mid-cycle if critical data are identified) and developed using current information from safety investigation reports, the TSB Watchlist, internally identified data from flight training and line flying, and internal SMS reports and statistics. At the time of the occurrence, the most prevalent topics in Jazz's TEM training concerned flight deck automation management and manual flying, active monitoring of flight conditions by the PM, hard landings, and unruly passengers. Additional topics of concern, namely runway overruns and runway incursions, come from the TSB's Watchlist, and both are addressed in Jazz's TEM training scenarios. Misaligned takeoffs, considered by the operator to carry less risk than runway overruns and incursions, were not included in these scenarios.

A practical application of Jazz's TEM safety defence is the pre-flight briefings and approach briefings, in which flight crews are instructed to seek and identify potential threats (e.g., environmental conditions and airport hot spots). When the occurrence flight crew conducted the pre-flight briefing, they had no recent information pointing to misaligned takeoffs as a potential threat in the take-off environment and conditions in which they were about to operate, so this threat was not considered.

1.17.4 Jazz safety management system

Jazz reported that there were no SMS reports related to operational concerns or safety deficiencies at KSAN. Furthermore, there were no identified concerns, relevant to the occurrence, related to displaced thresholds, runway lighting, runway markings, or runway shoulders at any of the airports in Jazz's network.

1.17.5 Standard operating procedures and checklists

1.17.5.1 Runway lineup

Neither Jazz's Regional Jet aircraft operations manual (AOM) nor its company operations manual (COM) mandates that flight crews adhere to taxiway centreline markings when taxiing and entering a runway, unless operating on a contaminated surface. Therefore, deviating from the taxiway centreline marking for operational reasons (e.g., using greater runway length for takeoff) is at the discretion of the captain.

With respect to verification of runway alignment, the Jazz runway line-up check procedure in the AOM states:

> Once aligned with the runway centreline, Flight Crew shall positively verify the assigned runway either by visually observing the runway identifier on the runway surface, by reference to flight deck instrumentation (e.g. localizer alignment) or HSI [horizontal situation indicator] heading. When the RVR or reported visibility is less than 2600 or ½ mile respectively, only the runway identifier or localizer alignment may be used to positively verify the runway.[34]

During the occurrence aircraft's departure, the runway identifier was not in view because the takeoff was being conducted from the area before the displaced threshold of Runway 27. The captain therefore verified the runway using only the HSI compass heading, confirming that it was on the runway heading. This method was permissible according to the procedure, given that the most recent METAR issued for KSAN had indicated a visibility of ½ SM. Although the use of the HSI alone allowed the captain to verify that the aircraft was on the correct runway, it did not provide confirmation that the aircraft was correctly aligned with the centre.

The area before a displaced threshold is considered a portion of the runway available for takeoffs (and landing rollouts). There are no regulations in the U.S. or Canada prohibiting departures from those portions of the runway in visually degraded, or any other, conditions. Similarly, Jazz's AOM and COM provide no policies, procedures, or guidance material to pilots with respect to limitations or precautions when operating on runways with displaced thresholds.

1.17.5.2 Fuel crossflow operation

1.17.5.2.1 Normal procedures

Immediately before a departure and during Jazz's before-takeoff checks, the first officer actions the fuel crossflow system by pressing the XFLOW AUTO OVERRIDE switch, placing it in manual mode. Jazz's AOM illustrates the procedure as follows:

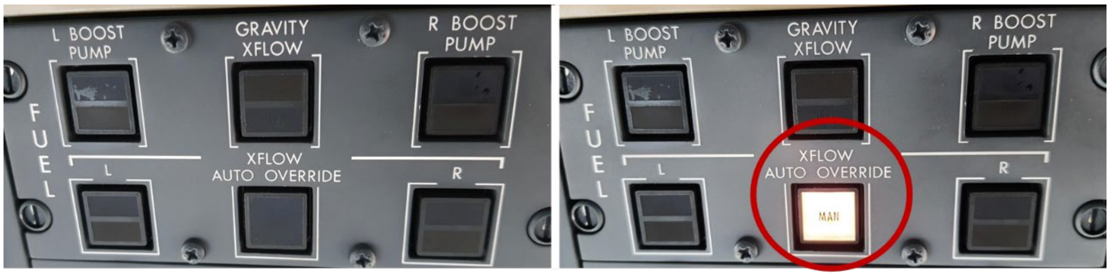
> **Fuel crossflow**
>
> - **/man, off**
>
> XFLOW AUTO OVERRIDE switchlight
>
> - select in
>
> Verify that the MAN XFLOW EICAS message is displayed. Ensure there is no **GRAV XFLOW OPEN** or L(R) XFLOW ON messages displayed.[35]

[34] Jazz Aviation LP, *CRJ AOM Volume II Aircraft Operating Manual*, Revision 19 (01 May 2021), Section 2.4.2: Line-Up Check, p. 2.4-5.

[35] Ibid., Section 2.4.1: Before-Takeoff Check, p. 2.4-3.

After a first officer performs the checks, he or she confirms them with the checklist, reading for this item “fuel crossflow manual off.” Per the AOM, the first officer is stating that the fuel crossflow is in manual mode and that there are no gravity crossflow or left or right crossflow messages displayed on the flight deck’s EICAS. When the XFLOW AUTO OVERRIDE push-button switch is pressed in, it becomes illuminated (Figure 15).

Figure 15. Fuel control panel before the XFLOW AUTO OVERRIDE switch is selected (left) and after the XFLOW AUTO OVERRIDE switch is selected (right) (Source: Third party with permissionand TSB annotations)



Following takeoff, the PM sets climb thrust, and then when workload permits, completes the after-takeoff checklist. This checklist requires the PM to deselect the XFLOW AUTO OVERRIDE switch (push button out and light off), placing the system back into automatic mode. During the occurrence flight, the captain was the PM and was required to action this checklist. The XFLOW AUTO OVERRIDE switch is not actioned again throughout the remainder of the flight unless it is required by abnormal or emergency checklist procedures.

1.17.5.2.2 Abnormal/emergency procedures

According to Jazz and MHI RJ procedures, when the “XFLOW PUMP” caution message is displayed, the PF will instruct the PM to carry out the XFLOW PUMP Caution Message procedure checklist, which instructs the flight crew to determine whether a fuel imbalance exists. If so, the instruction is to proceed to the Gravity Crossfeed Procedure, and if not, the flight crew is instructed to monitor fuel quantities.

When the flight crew determined that the lateral fuel imbalance existed and was unable to be corrected, the PM proceeded with the Gravity Crossfeed Procedure in the Jazz QRH:

GRAVITY CROSSFEED PROCEDURE

L XFLOW

- OFF

R XFLOW

- OFF

XFLOW AUTO OVERRIDE

- OFF

GRAVITY XFLOW

- OPEN

Steady-Heading Sideslip

- ACCOMPLISH[36]

This crossfeed procedure is virtually identical to the one published in the manufacturer's QRH.[37]

"OFF," the response to the instruction provided in the 3rd step of the procedure, is not 1 of the 2 available positions of the XFLOW AUTO OVERRIDE push-button switch, which are AUTO (push-button switch pressed out and not illuminated) and MAN (switch pressed in and illuminated).

When the PM reached this step, he completed the instruction of "OFF" by checking that the XFLOW AUTO OVERRIDE switch was deselected and pressed out, thereby causing the fuel crossflow to be in automatic mode. This switch position was logical to the PM because it was consistent with the adjacent L XFLOW and R XFLOW push-button switches, which were both in their respective off positions (i.e., pushed out and not illuminated).

The PM's action was, in fact, what the manufacturer had intended to prescribe in this step of the crossfeed procedure: the XFLOW AUTO OVERRIDE switch remains in the AUTO position, so that the FQGC's control over the fuel-transfer process would therefore be maintained.

The Jazz procedure then includes a note to flight crews: "Establish a bank angle of 10 degrees down on the low quantity side by use of the rudder pedal (rudder trim may be required), while maintaining a constant heading."[38] This note is slightly different from the instruction given in the QRH published by MHI RJ, which states: "Establish a bank angle of

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36 Jazz Aviation LP, *CRJ 900 Quick Reference Handbook*, Revision 15 (01 October 2020), Gravity Crossfeed Procedure, p. ABNORMAL 10-15.

37 Mitsubishi Heavy Industries, Ltd., MHI RJ Aviation Group, CSP C-022, *Quick Reference Handbook*, Revision 8 (27 September 2013), Gravity Cross-feed Procedure, p. ABNORM 9-9.

38 Jazz Aviation LP, *CRJ 900 Quick Reference Handbook*, Revision 15 (01 October 2020), Gravity Crossfeed Procedure, p. ABNORMAL 10-15.

10 degrees down on the low quantity side. Use rudder pedal/trim to maintain a constant heading/course."[39]

Although the difference is subtle, the 2 procedures are distinct. The Jazz procedure describes establishing the bank angle with the rudder, whereas the MHI RJ procedure is to establish a bank angle and then use the rudder to hold a heading/course.

A sideslip is normally performed to counteract the effect of drift when landing in a crosswind by holding the aircraft's longitudinal axis parallel with its flight path. However, the intention of the sideslip prescribed by the Jazz and MHI RJ QRHs is to bank the aircraft and use gravity to transfer the weight of the fuel from one side to the other. The application of rudder prevents the aircraft from turning.

The Gravity Crossfeed Procedure checklist goes on to state that if the fuel tank quantities balance as a result of the sideslip, the gravity crossflow valve is to be closed, and the crew can return to coordinated flight. If, however, the fuel quantities do not balance and cannot be controlled within limits, the engine on the side with the lower fuel quantity must be shut down.

The occurrence flight crew continued with the instruction in the Gravity Crossfeed Procedure checklist and actioned the In-Flight Engine Shutdown checklist.[40] Step 7 of this checklist instructs flight crews to place the fuel crossflow system into automatic mode, which is achieved by deselecting the XFLOW AUTO OVERRIDE switch so that it is pushed out, consistent with the position already selected during the Gravity Crossfeed Procedure.

The rest of the In-Flight Engine Shutdown checklist, as well as the subsequent Single-Engine Approach and Landing checklist,[41] provides no further instruction to a flight crew to close the gravity crossflow valve other than a note halfway through the In-Flight Engine Shutdown checklist explaining that flight crews "may have to perform the Gravity Cross-feed procedure when required and time permits."[42]

1.18 Additional information

1.18.1 Other occurrences and investigations of misaligned takeoffs

The TSB has previously reported on runway side excursions resulting from misaligned takeoffs. TSB records indicate 10 occurrences[43] in which flight crews lined up with and commenced a take-off roll on a runway edge rather than the runway centreline. All

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39 Mitsubishi Heavy Industries, Ltd., MHI RJ Aviation Group, CSP C-022, *Quick Reference Handbook*, Revision 8 (27 September 2013), Gravity Cross-feed Procedure, p. ABNORM 9-9.

40 Jazz Aviation LP, *CRJ 900 Quick Reference Handbook*, Revision 15 (01 October 2020), In-Flight Engine Shutdown, p. ABNORMAL 1-1.

41 Ibid., Single-Engine Approach and Landing, p. ABNORMAL 1-3.

42 Ibid., In-Flight Engine Shutdown, p. ABNORMAL 1-1.

43 TSB occurrences A23F0062, A23W0007, A18O0009, A11F0107, A09F0158, A09F0019, A09F0010, A07F0186, A06F0014, and A97A0185.

occurrences had in common operations in nighttime conditions, and 1 occurrence specifically noted degraded visual conditions.

One of the occurrences resulted in the 2006 TSB investigation[44] of the misaligned takeoff of a Canadian registered Airbus A319-114 from Harry Reid International Airport (KLAS), Las Vegas, U.S., which was bound for Montréal/Pierre Elliott Trudeau International Airport (CYUL), Quebec. That investigation found that the runway markings, combined with the PF's primary focus on the preceding aircraft's departure and his use of peripheral vision when orienting the aircraft onto the runway, contributed to the aircraft being aligned on the runway's asphalt shoulder rather than on the centreline and damaging runway edge lights during the take-off roll. Of note is the fact that this misalignment was not known to ATC or to the airport until 2 hours after the event, and during that time, potential debris from broken lights could have been a hazard to departing aircraft.

In 2009, the Australian Transport Safety Bureau (ATSB) researched the factors influencing occurrences of misaligned takeoffs. The published study identified 7 prevalent safety factors contributing to misaligned takeoffs, with the presence of each factor increasing the risk of an occurrence. The 7 factors are:

- night time operations
- the runway and taxiway environment, including confusing runway entry markings or lighting, areas of additional pavement on the runway, the absence of runway centreline lighting, and recessed runway edge lighting
- flight crew distraction (from within the cockpit) or inattention
- bad weather or poor/reduced visibility
- conducting a displaced threshold or intersection departure
- provision of air traffic control clearance when aircraft are entering the runway or still taxiing
- flight crew fatigue[45]

These factors can be categorized as either human factors, environmental factors, or operational factors. A key human factor identified in the research was distraction resulting in divided attention. Distraction causes a flight crew's attention to be divided, with a focus on completing tasks inside the cockpit at the expense of accurately assessing the external environment. This often occurs during the taxi, when the flight crew must have their eyes inside the cockpit for significant periods of time. As explained in the ATSB report,

> instead of maintaining a visual look out from when they enter the runway, their attention is drawn inside for some reason such as checking instruments, confirming aircraft configuration or performing checklist items. While multi-crew operations partially mitigate this risk by articulating and dividing aircraft handling and monitoring roles between the pilots, there are still times when both crew members

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44 TSB Aviation Investigation Report A06F0014.

45 Australian Transport Safety Bureau, ATSB Transport Safety Report, Aviation Research and Analysis Report AR-2009-033, *Factors influencing misaligned take-off occurrences at night* (June 2010), p. 19.

> may not be processing the external environmental cues accurately. This divided attention is often a necessary part of lining up or beginning the take-off roll […].[46]

The environmental factors outlined in the ATSB report include runway threshold markings. Colloquially known as piano keys, they assist flight crews by defining the width of the runway. As the report explains,

> aircraft using a displaced threshold will not be able to see the normal threshold markings, such as the runway number or 'piano keys', which provide important cues during the line up phase of flight. [47]

An operational factor highlighted in the report is the necessity of following any available lead-on taxiway centrelines and lights to maximize the flight crew's opportunity to correctly align the aircraft on the runway for takeoff, especially when ATC clearances are transmitted while the aircraft is lining up or when the aircraft is departing from an area other than a runway's threshold, with fewer cues for lateral runway alignment.

The ATSB provides examples of the occurrence reports it used in constructing the list of safety factors that increase the risk of a misaligned takeoff. One example[48] obtained from NASA's Aviation Safety Reporting System (ASRS) described the misaligned takeoff of a Cessna Citation X from KSAN that had lined up on the runway edge lights after entering the runway's displaced threshold area before the threshold of Runway 27. Observations from the flight crew in that occurrence highlighted the large amount of asphalted surface in that area and that the lack of centreline lighting contributed to their misaligned takeoff.

1.18.2 Other fuel imbalance occurrences

1.18.2.1 Jazz Aviation LP 2022 occurrence

During the course of the investigation, Jazz reported to the TSB a similar occurrence on a different aircraft flown by a different flight crew.[49] On 03 February 2022, the flight crew of a Jazz Regional Jet Series 900 departing from Winnipeg/James Armstrong Richardson International Airport (CYWG), Manitoba, were presented with a "XFLOW PUMP" caution message, followed by an increasing fuel imbalance. Jazz provided the TSB with the flight data of that event, and they were examined in concert with the data from the November 2021 occurrence investigated in this report.

While the data demonstrate that the actions of each flight crew were slightly different, the initiating event of the 2022 occurrence showed compelling similarities to that of the 2021 occurrence. The aircraft that had departed from CYWG transferred the fuel from the centre

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46 Ibid., p. 15.

47 Ibid., p. 17.

48 ASRS Database Online, Report no. 713117, akama.arc.nasa.gov/ASRSDBOnline/QueryWizard_Display.aspx?server=ASRSO (last accessed on 24 May 2024).

49 TSB Aviation Occurrence A22C0010.

to the wing tanks on a schedule relatively consistent with the specifications of the FQGC,[50] and the centre tank was empty approximately 8 minutes after departure.

About 14 minutes after departure, a lateral fuel imbalance of 200 pounds developed and continued for 30 seconds. Approximately 12 to 14 seconds later the "XFLOW PUMP" caution message displayed. Since the fuel in the centre tank had already been consumed, the flight crew were more easily able to monitor the changing imbalance condition. According to calculations, the rate of change in the fuel tanks was in excess of the amount of fuel being consumed by the engines. The flight data show that, in the 16 minutes following the caution message (until the imbalance was approximately 1000 pounds), the lateral transfer out of the right tank was between 2000 and 2200 lb/h (33 and 37 lb/m).

The flight crew carried out the precautionary engine shutdown as the imbalance reached approximately 1500 pounds. It could not be determined when the flight crew initiated the Gravity Crossfeed Procedure because the selection of the gravity crossflow valve is not a recorded parameter; however, approximately 1 minute after the engine shutdown, right rudder pressure was applied. As was the case in the 2021 occurrence, this resulted in the aircraft rolling into an angle of bank to the left. The lateral fuel imbalance reached a maximum of 2336 pounds during this manoeuvre, with an angle of bank of approximately 4°. The data show that this condition was maintained for less than 1 minute before the application of rudder in the opposite direction was initiated and maintained for approximately 4 minutes. During this time, the lateral fuel imbalance was reduced to only 224 pounds. The flight diverted to return to CYWG, but during the remainder of the flight, the lateral fuel imbalance rose again and fluctuated between approximately 500 and 1300 pounds. The flight landed safely, without further incident.

1.18.2.2 Other reported occurrences

TC publishes Civil Aviation Safety Alert (CASA) notices to convey important safety information and recommended action items. The investigation noted that there have been no notices related to potential crossflow pump issues on the Series 700, 900, or 1000 aircraft, nor have there been any airworthiness directives relating to this issue.

TC also collects service difficulty reports (SDRs) from aircraft maintenance engineers, owners, operators, and other sources reporting problems, defects, or occurrences that affect aircraft airworthiness in Canada. A reportable service difficulty is "a service difficulty that affects or that, if not corrected, is likely to affect the safety of an aircraft, its occupants or any other person." TC shared with the investigation all SDRs relating to Series 700, 900, and 1000 crossflow pumps. This collection highlighted 11 reported occurrences in Canada and the U.S. that were related to fuel imbalances. They occurred between March 2010 and February 2022.[51]

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[50] The 93% and 97% transfer ejector limits, as described in Section 1.6.3.1 *Transfer ejectors* of this report.

[51] Transport Canada, SOR/96-433, *Canadian Aviation Regulations,* subsection 101.01(1).

While 11 known and potentially similar occurrences exist, this number does not account for any other occurrences that have not been reported. According to the CARs, submitting SDRs is required.[52] However, TC has also explained that the definition of a reportable service difficulty is very broad due to the complexity of service difficulties and the many factors that could affect the safe operation of an aircraft. TC has further indicated that it is not possible to provide definitive guidance on every possible service difficulty and that it therefore becomes necessary to depend on the reporter or reporting organization's knowledge, experience, and good judgement to determine what constitutes a reportable service difficulty.[53]

The FAA provided the investigation with records showing 7 other known occurrences of lateral fuel imbalance, in the 10 years preceding the 2021 Jazz occurrence, involving Series 700, 900, and 1000 aircraft. These 7 occurrences all resulted in flight crews declaring an emergency and diverting the flights.

The investigation searched the ASRS for reported occurrences involving lateral fuel imbalance involving Series 700, 900, and 1000 aircraft. That database contains no reports of similar events.

Fuel imbalances can occur for a number of reasons. The 18 fuel imbalance reports noted above involved different circumstances than those observed in this occurrence.

In 2005, after receiving reports of spurious "XLFOW PUMP" caution messages occurring on Regional Jet Series 700 and 900's, Bombardier—the aircraft type certificate holder at the time—conducted an investigation and released a service letter[54] informing operators of the issue. The service letter identified that the fault was occurring when the XFLOW AUTO OVERRIDE switch was selected to manual simultaneously with the end of an automatic fuel imbalance correction. This information was included in Jazz's CRJ AOM,[55] in the before-takeoff checklist, where flight crews are required to make this manual selection.

Shortly after Bombardier released this service letter, the manufacturer of the aircraft's FQGC released a Service Bulletin[56] to address the issue. The service bulletin called for a change to the FQGC software, and the occurrence aircraft's FQGC had this update incorporated.

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52 Ibid., section 521.401: Form and Submission.

53 Transport Canada, Advisory Circular (AC) 521-009: Division IX – Service Difficulty Reporting, Issue 01 (07 September 2011), Section 4.2: Reportable Service Difficulties, at tc.canada.ca/en/aviation/reference-centre/advisory-circulars/advisory-circular-ac-no-521-009 (last accessed on 24 May 2024).

54 Bombardier Inc., Service Letter CRJ700/900-SL-28-014: "XFLOW PUMP" Message – Software Investigation (14 March 2005).

55 Jazz Aviation LP, *CRJ AOM Volume II: Aircraft Operating Manual*, Revision 19 (01 May 2021), Normal Procedures, p. 2.4-3.

56 Zodiac Intertechnique, Service Bulletin 738118-28-002: Fuel Quantity Gauging Computer (FQGC) P/N 738118-1-1 changed into P/N 738118-1-3, P/N 738118-1-2 changed into P/N 738118-1-3 (08 November 2006).

In 2012, in response to continued reports of spurious “XFLOW PUMP” caution messages, the manufacturer of the FQGC issued a service information letter in an attempt to collect field data related to the issue. The letter was updated and reissued in 2018, requesting that operators of Series 700, 900, and 1000 aircraft report events of “XFLOW PUMP” caution messages to the manufacturer. The purpose was to investigate the chain of events leading to these caution messages, including operational conditions at the moment the message is triggered. Minimal feedback was provided to the manufacturer by operators, and as a result, the relationship between the appearance of the “XFLOW PUMP” caution message and the operational conditions surrounding it could not be fully analyzed.[57]

1.18.3 Human factors

1.18.3.1 Vision in dark conditions

The visual system detects differences in the light reflected from an object (known as luminance) to see in light and dark conditions.[58] When light levels are higher, vision is achieved with the use of cones, which have receptors that detect colour. When light levels are lower, vision is achieved with the use of rods. Each rod has a receptor that detects only white, black, and shades of gray. A crossover portion of light level exists where both cones and rods are used, but colour is muted. In this crossover portion, the visual system automatically and involuntarily shifts between using primarily either cones or rods based on ambient light levels. Night flying typically occurs in this crossover portion of light level.[59]

Under dark conditions, a person has no obvious colour vision, and thus, coloured objects are less salient. Additionally, objects of low contrast to their backgrounds are difficult to distinguish. A perceptual side effect of low contrast is that a person may judge objects as being farther away than they actually are, contributing to misinterpretations of visual cues in the environment (e.g., the perception of distances). In addition, if the horizon shows no visual cues under dark conditions, parts of the eye can relax, making it difficult for the individual to notice faraway objects.[60]

1.18.3.2 Information processing in dynamic environments

Information processing is critical to human performance. It is described in stages, which are perceiving information, transforming information into different forms, acting on

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57 Zodiac Aerospace Services, Service Information Letter P93A25-28-002: Crossflow Pump P/N P93A25-602 (12 March 2018).

58 P. Wright and R. A. H. Scott, “Optics and vision”, in D. P. Gradwell and D. J. Rainford, *Ernstings’s Aviation and Space Medicine,* 5th Edition (CRC Press, 2016), p. 269.

59 Ibid., p. 270.

60 Karl H.E. Kroemer, *Fitting the Human: Introduction to Ergonomics/Human Factors Engineering*, 7th Edition (CRC Press, 2017), p. 98.

information, processing feedback information, and assessing the effects on the environment.[61]

1.18.3.2.1 Perception

Perception is the process by which humans acquire, process, and interpret information from the external world. The identification of an object in an environment is related not only to an individual's physical sensitivity to sensing properties such as light, sound, and temperature, but also to the individual's goals, knowledge, and expectations.[62] Objects are recognized more quickly when they are viewed in context, rather than when presented in isolation or in incoherent contexts.[63] In addition, objects and attributes that look similar to the target object can be perceived and understood as the object they resemble.

The way in which a person can perceive information through a mixture of sensing cues from the external environment and through their own goals, knowledge, and expectations can be described in the context of a runway departure. Each side of a runway, starting from the centreline, has an expanse of asphalt approximately 100 feet wide with an additional paved shoulder. The sight of the width of the asphalt and shoulder are cues from the environment that the aircraft is positioned on the centreline. Some runways in the U.S. have very large expanses of asphalt extending beyond the runway edge line on either side of the runway. In contrast, at airports in Canada, the paved shoulder beside a runway's edge is up to only 25 feet wide, and beyond the shoulder lies grass or some other textured surface. When a pilot sees a wide area of asphalt beside the aircraft, this cue can be interpreted as an indicator that the aircraft is positioned at the centreline when in fact, the aircraft may be positioned on the runway's edge. A collection of external cues is combined with a pilot's goals, knowledge, and expectations to form an understanding of position in space.

An individual's expectancies can be used to prevent misinterpretations when working in degraded conditions.[64] For example, expectancies created through training and experience contribute to how an individual perceives and interprets information in an environment and what information is perceived. Thus, knowledge of the fact that the environment in a displaced threshold area has different and fewer cues for identifying the runway centreline is important for flight crews operating in these areas. Furthermore, knowing how and why vision and perception can be negatively impacted in degraded or dark visual conditions is also useful for supporting operations under these conditions.

Sensory cues and information can be ambiguous depending on the environment in which they are sensed. A core aspect of processing sensory cues and information is resolving

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[61] C.D. Wickens and C.M. Carswell, "Information Processing," in G. Salvendy , *Handbook of Human Factors and Ergonomics,* 4th Edition (John Wiley & Sons, 2012), p. 117.

[62] Ibid., p. 122.

[63] C.D. Wickens and C.M. Carswell, "Information Processing," in G. Salvendy and W. Karwowski , *Handbook of Human Factors and Ergonomics,* 5th Edition (John Wiley & Sons, 2021), p. 120.

[64] Ibid., p. 121.

ambiguity. The brain resolves ambiguity in 2 ways: bottom-up processes and top-down processes, or a combination of both.[65] Bottom-up processing is when information flows up from lower levels to higher levels of analysis; simple characteristics of cues and information are integrated into larger images or forms on the basis of rules or knowledge held by the observer.[66] Top-down processing is when information flows down from higher levels to lower levels of analysis; prior knowledge and experience are used to direct lower level perceiving.[67]

When this concept is applied to a pilot perceiving a visual runway environment, a pilot sees the visual cues and information in the environment and uses bottom-up processing (i.e., perceptual sensors of the eye knowing where to look and what to look at) and top-down processing (i.e., knowledge from training and past experiences about the organization of the environment) to interpret the cues and information to understand the aircraft's position on the runway. Ambiguous cues and information in the external environment become more difficult to resolve and are more susceptible to misinterpretations when there is interference or degradation in the environmental cues and information (for example, in degraded visibility or dark conditions).

1.18.3.2.2 Transforming information and taking actions

Human information processing can be grouped into 3 levels: skill-based, rule-based, and knowledge-based.[68] Despite the distinction, many of the meaningful tasks that individuals perform represent, in reality, combinations of skill-, rule-, and knowledge-based levels of performance.

Rule-based performance involves the conscious perception of environmental cues, which trigger the application of rules learned on the basis of experience. These rules link environmental cues and goals of the task with actions to be performed.[69] Activities performed at the rule-based level use rules that have been committed to memory based on experiences and training. Problems in rule-based performance can occur when the information gathered, or the cues perceived in the environment, are inappropriately matched and either an action is missed or the wrong action for the situation is applied. A cue can go undetected or be misidentified when an individual is in a hurry or has a strong expectation of something occurring as a result of an action. Cues can also be missed when a

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65 G. Mather, *Essentials of Sensation and Perception* (Routledge, 2011), p. 127.

66 Ibid., p. 111.

67 Ibid.

68 J. Rasmussen, "Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-13, No. 3 (May/June 1983), p. 257.

69 C.D. Wickens and C.M. Carswell, "Information Processing", in G. Salvendy, *Handbook of Human Factors and Ergonomics,* 4th Edition (John Wiley & Sons, 2012), p. 143.

problem is not expected in a particular location, when the cue is ambiguous or degraded, and when cues are similar.[70]

Rule-based performance is closely related to recognition-primed decision making.[71] As explained in *Sources of Power: How People Make Decisions*,

> [t]he recognition-primed decision (RPD) model fuses two processes: the way decision makers size up the situation to recognize which course of action makes sense, and the way they evaluate that course of action by imagining it.[72]

In these types of situations, decision makers recognize situations as typical and familiar, and proceed to take action. Decision makers, as the author explains, understand which types of goals make sense, which priorities to set, which cues are important, and what can be anticipated next, as well as typical ways to respond in given situations.[73] When they recognize a situation as typical, they also determine a course of action likely to succeed and conduct rapid mental simulation to assess its fit for the situation. This decision-making model has come from research on how decisions are made in time-sensitive, dynamic, real-world settings.[74] Situation assessment is an important aspect of decision making in these real-world environments.[75]

When people make decisions and take actions based on this model, errors and poor outcomes can result from insufficient experience (e.g., when decision makers do not have experience with the situation) or inadequate information (e.g., if the information or cues needed to make a good assessment of the situation are unavailable or degraded), or due to errors in mental simulation (e.g., when people connect cues or signs of a problem to a different situation).[76]

1.18.3.3 Crew resource management and threat and error management

As TC Advisory Circular (AC) 700-042: Crew Resource Management explains, CRM

> integrates technical skill development with communications and crew coordination training and operational risk management by applying threat and error management (TEM) concepts.[77]

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70 J. Reason, *The Human Contribution: Unsafe Acts, Accidents and Heroic Recoveries* (CRC Press, 2008), pp. 38-39.

71 M.R. Lehto, F.F. Nah, and J.S. Yi, "Decision-making models, decision support, and problem solving", in: G. Salvendy, *Handbook of Human Factors and Ergonomics*, 4th edition (John Wiley & Sons, 2012), p. 211.

72 G. Klein, *Sources of Power: How People Make Decisions* (MIT Press, 1998), p. 24.

73 Ibid.

74 M.R. Lehto, F.F. Nah, and J.S. Yi, "Decision-making models, decision support, and problem solving", in: G. Salvendy, *Handbook of Human Factors and Ergonomics*, 4th edition (John Wiley & Sons, 2012), p. 211.

75 Ibid., p. 212.

76 G. Klein, *Sources of Power: How People Make Decisions* (MIT Press, 1998), p. 274-275.

77 Transport Canada, Advisory Circular (AC) 700-042: Crew Resource Management (CRM), (Issue 02: 14 March 2020), section 2.3 Definitions and Abbreviations; 1)b) at tc.canada.ca/sites/default/files/migrated/ac_700_042.pdf (last accessed on 04 June 2024).

The AC goes on to describe TEM, stating that it consists of

> the identification and analysis of potential hazards; the implementation of appropriate strategies to handle threats; and the implementation of steps to avoid, trap, or mitigate errors before they lead to undesired consequences such as an undesired aircraft state.[78]

TEM is a general safety principle for all aviation operations and has 3 components: threats, errors, and undesired aircraft states. The TEM framework is based on the concept that flight crews must manage threats and errors as a regular part of aviation operations because they can both potentially lead to an undesired aircraft state, at which point a flight crew must take action to avoid an unsafe outcome.[79]

A threat, as defined by the AC, is "any condition that increases the complexity of [an] operation […] [and] can decrease safety margins and lead to errors."[80] Threats can be either outside the control of the flight crew (external) or within the flight crew's control (internal). Examples of external threats are precipitation, system problems, and inadequate visibility, while hunger, eyesight, and hearing are all examples of internal threats. In the TEM model, threat management consists in recognizing the existence of a threat and developing a strategy to address it so that safety margins are not reduced.

An error is defined as a "mistake that is made when a threat is mismanaged."[81] Examples of errors are intentional non-compliance with procedures, miscommunications, and the execution of a procedure in the wrong order. The TEM model incorporates different error outcomes: inconsequential (no immediate effect on safety), undesired state (increased risk or unsafe operational conditions), and additional errors (the original error leads to another error).[82]

Error management is "[t]he process of correcting an error before it becomes consequential to safety […] [and] prevent[ing] future, similar errors by improving the resistance to errors in the system."[83] The latter can be achieved through improved strategies for dealing with external threats and better control over internal threats. Error management also relies on "resist and resolve" strategies, in which a flight crew resists certain practices that already exist within the system in an effort to prevent new errors and resolves existing errors in the system before they lead to unwanted consequences.[84]

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78 Ibid., section 4.1 General (9).

79 Ibid., Appendix E – Crew Resource Management Training Material.

80 Ibid., section (1)(d)(i)-(ii)

81 Ibid., section (1)(e)(i).

82 Ibid., section (1)(g).

83 Ibid., section (1)(f)(ii)(A)-(B).

84 Ibid., section (1)(h).

Some aspects of an environment increase operational complexity. However, if flight crews recognize threats and develop ways to manage them, errors can be prevented. As the AC explains,

> If an error occurs, there may be things already built into the system, such as inspections and operational checks, which resist the error to avoid a harmful outcome, or the person doing the work could recognize that he/she made an error and resolve the error quickly.[85]

Under TC's approach, the operator has key responsibilities in ensuring the effectiveness of CRM training within its organization:

> - […] an air operator [should treat] CRM as an integral part of its culture.
> - Company safety culture should support CRM throughout the organization, as well as among aircraft crew members.
> - CRM training should also address hazards and risks identified by the operator's safety management system (as applicable).
> - CRM embraces all operational personnel and should include initial indoctrination, annual practice, feedback and continuing reinforcement.
> - The operator is solely responsible for all activities related to the training of personnel both for in-house or any outsourced training program.[86]

To further support the effectiveness of CRM, operators should ensure that every stage of training incorporates it. CRM concepts should also be emphasized in checklists, briefings, abnormal and emergency procedures, and other areas of line operations.

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85 Ibid., section (1)(h)(iii)(A).

86 Ibid., section 6.2 Operator Responsibilities

2.0 ANALYSIS

During the occurrence aircraft's departure and flight, the aircraft experienced 2 separate and unrelated events leading to this safety investigation.

During the take-off roll, starting from the area before the displaced threshold of Runway 27 at San Diego International Airport (KSAN), California, United States, the aircraft's left main landing gear wheels struck 3 consecutive runway edge lights. The flight crew were, at that time, unaware of the runway side excursion and the minor damage it had caused.

Shortly after takeoff, while the aircraft was climbing to cruise altitude, the "XFLOW PUMP" caution message appeared. The caution message, combined with the subsequent lateral fuel imbalance, the declaration of an emergency with air traffic control (ATC), and the diversion to Los Angeles International Airport (KLAX), California, U.S., is considered a separate and unrelated issue to the takeoff misalignment. Therefore, the analysis will treat the 2 events as separate and unrelated.

2.1 Runway excursion on takeoff

2.1.1 Visibility

On the inbound flight to KSAN, the occurrence aircraft and flight crew landed on Runway 27 at 1703—during evening civil twilight hours. At the time of arrival, the visibility was 10 statute miles (SM) and few clouds were at 200 feet above ground level (AGL).

The aircraft later pushed back from the terminal gate at 1803, during nighttime hours, to begin taxiing for takeoff for the return flight (the occurrence flight) to Vancouver International Airport (CYVR), British Columbia. While the aircraft was parked at the terminal, weather conditions worsened. As the aircraft began to taxi for departure, prevailing visibility had decreased to 3 SM, with visibility in portions of the area around the airport as low as ¾ SM.

During the flight's nearly 40-minute taxi to Runway 27, the weather continued to deteriorate. By the time the aircraft was cleared for takeoff, the prevailing visibility was ½ SM in fog with portions as low as ¼ SM, and the Runway 09 runway visual range was 1200 feet variable to 2000 feet, with a ceiling of 200 feet AGL. The last aircraft to attempt a landing on Runway 09 before the departure of the occurrence flight conducted a missed approach and its flight crew noted that they could not see the runway environment from the minimum altitude on the approach. As the occurrence aircraft neared the runway for takeoff, the visibility in the area was significantly degraded.

Finding as to causes and contributing factors

The aircraft was operating at night and in fog, in an area where visibility was between ¼ SM and ½ SM. As a result, there were few visible cues available to the flight crew to identify and verify the aircraft's position on Runway 27 at KSAN.

2.1.2 Lighting

The similarities between the requirements for airport runway lighting in Canada and the U.S. support a common understanding of lighting installations when flight crews operate in either country. Given the lengthy area of runway before the displaced threshold of Runway 27 at KSAN, the runway's approach lighting is embedded on either side of the runway centreline and mostly flush with the runway asphalt surface. However, at the time of the occurrence, arrivals were active on the runway's opposite end, Runway 09, and thus, approach lighting was not active for Runway 27. This was consistent with ATC practices in both Canada and the U.S.

The runway lighting that could have been visible in the captain's peripheral vision included the runway's centreline lighting. It is likely that the spacing of the runway centreline lighting made it resemble the runway edge lighting installation on the right side of the runway. The captain's perception of this cue could have contributed to his understanding that the aircraft was aligned with the centre of the runway, in the area before the displaced threshold.

2.1.3 Markings

As the captain taxied from the runway holding position marking for Runway 27 toward the runway, he manoeuvred the aircraft to the right (east) of the taxiway centreline to increase the runway length available for the aircraft's take-off run. This action reduced the visual cues available to accurately identify the runway's centreline. Jazz Aviation LP (Jazz) did not have a standard operating procedure for adherence to the taxiway centrelines and permitted flight crews to deviate as necessary based on their assessment of individual situations.

The visual cues provided by the runway dimensions and markings, including side markings, are distinctively different in Canada from what they are in the U.S. In Canada, a runway's side stripe markings do not cross taxiways or other runways that intersect it. In the U.S., conversely, these markings—called runway edge markings—continue across such intersections. When the occurrence aircraft entered the runway, the first runway marking visible to the captain was the solid white left edge marking, which aligns with the runway's orientation. This was identified by the captain as the runway centreline.

Runway thresholds typically provide distinctive visual environments, established by runway threshold markings and runway numbers, that allow flight crews to distinguish the runway's width and orientation. However, when flight crews commence takeoffs from the area before a displaced threshold (or from an intersection elsewhere on the runway), they have fewer visual cues to assist in defining the runway's width, and thus, the centreline.

Finding as to causes and contributing factors

When taxiing to position on the runway, the captain taxied the aircraft off the taxiway centreline in order to increase the runway distance available for takeoff. As a result, he had to rely on other visual cues to determine the aircraft's position on the runway.

2.1.4 Width of paved take-off area

The runway shoulders along Runway 09/27 are significantly wider than the runway shoulders at Canadian airports regularly serviced by Jazz's Regional Jet fleet. Despite the benefits of paved runway shoulders, they have specifically been identified as a risk factor in an Australian Transport Safety Bureau safety report.

While the runway edge stripe helps pilots to discern the orientation of a runway, it also resembles a runway centreline. Therefore, when the captain taxied the aircraft onto Runway 27 and aligned it with the left runway edge marking, he perceived that he was on the runway centre.

At this point, the paved surface extended approximately 260 feet to the left of the aircraft and up to 610 feet to the right. This significant amount of paved surface on either side reinforced the captain's perception that the aircraft was on the runway's centre.

At the point where the captain brought the aircraft to a stop on the left runway edge marking, the visual environment ahead included a portion of the runway shoulder. The dark green painted portion of the shoulder was approximately 180 feet ahead of the aircraft. Unlike the runway shoulder areas at Canadian airports routinely serviced by Jazz's Regional Jet fleet, which are between 0 and 25 feet wide and immediately transition to grass or some other textured surface, the runway shoulder at KSAN was 64 feet wide with an additional 125 feet of paved and partially painted surface covering the area inside the curve where Taxiway B1 meets the runway.

At night, in degraded visual conditions, and with the approach lighting system being lit on the opposite end of the runway, the captain very likely observed no perceptible difference between the runway and the shoulder surfaces because the visual cues to allow the delineation of the 2 areas were not salient enough.

2.1.5 Captain's experience and expectation

The captain's experience and expectation affected the way he perceived the visual environment. For example, the disparity between the painted shoulders at KSAN and the natural grass that normally exists off the runway's paved surface at Canadian airports with which the captain was very familiar likely also reinforced the captain's perception that the aircraft was aligned with the centreline.

While the approach lighting for Runway 27 was not on at the time of the misaligned takeoff, the runway edge lighting and runway centreline lighting were active. As the captain brought the aircraft to a stop on the left runway edge marking, directly ahead was the runway edge lighting, and the first light in front of the aircraft was embedded in the runway surface in the same fashion as the approach lights around the centreline.

Per the standards, the edge lighting in the area before the displaced threshold is red when observed by flight crews aligned with Runway 27 either on the ground or in the air. When an aircraft is lined up to take off from the displaced threshold area on Runway 27, the runway centreline lights immediately ahead of the aircraft are seen as white. During the occurrence misalignment, although the captain would have seen red lights straight ahead and it would not have made sense for the runway centreline lights to be red in this area, it is possible that the visual presentation of the runway as a whole was close enough to the captain's expected visual environment. It is also possible that in the context in which they were seen, the red lights that the captain saw ahead of the aircraft were interpreted simply as lights, without taking the colour into account.

The size of the runway shoulder to the left of the runway edge lights ahead of the aircraft, combined with the captain's visual environment ahead on the left side of the runway's edge lights, likely matched the captain's expectation of the left half of the runway, to the left of the centreline lights. Given the darkness, the absence of lighting from the Runway 27 embedded approach light installation, and the degraded visual conditions, the captain's focus was generally on the area close to and directly ahead of the aircraft, rather than on a longer range. In the daytime and in non-degraded visual conditions, other non-salient peripheral cues are normally available in the area. However, given the visual conditions at the time of the occurrence, these cues were not available to the captain.

The investigation noted that in a 3-month period around the date of the occurrence, in which all inbound (JZA766) and outbound (JZA767) Jazz flights (158 flights total) were studied, 94% were using Runway 27. Only 3 times in that period did the inbound flight arrive on Runway 09 with the outbound flight departing from Runway 27. Despite the fact that the occurrence captain was experienced and had performed the Vancouver-San Diego route regularly, it is possible that he had never conducted a nighttime takeoff from the area before the displaced threshold of Runway 27 at KSAN while the embedded approach lights were off. As a result, his expectation and experience likely contributed to the misidentification of the runway edge lighting as the runway centreline lighting.

Given the collection of visual cues that were available on the night of the occurrence, the visual environment around the aircraft was perceived by the captain to be the centre of the runway in the area before the displaced threshold, and the cues signalling that the aircraft was instead aligned with the runway edge were too subtle to alert the captain that the aircraft was misaligned for takeoff.

Finding as to causes and contributing factors

When the aircraft was turning left to establish the runway heading in preparation for takeoff, the limited and ambiguous visual cues that were available likely met the captain's expectations. As a result, he perceived the left runway edge as the runway centreline and aligned the aircraft laterally with the left edge of the runway, rather than its centre.

2.1.6 Line-up procedure

According to Jazz's aircraft operations manual (AOM), a flight crew shall positively verify the assigned runway using 1 of 3 methods: observing the runway identifier (number) on the surface, using the horizontal situation indicator (HSI) to verify the heading, or using the localizer alignment to verify tracking and direction. The AOM further indicates that in conditions where the visibility is less than ½ SM or runway visual range 2600, only the runway identifier and the localizer alignment are acceptable means of verification. However, since the weather was reported on the KSAN automatic terminal information service (ATIS) frequency as ½ SM (not less than ½ SM) at the time of departure, and the departure was taking place from within the area before the displaced threshold, no runway identifier was available, and the captain completed this check by verifying only the cockpit HSI, which was permitted per the Jazz AOM.

While the HSI compass heading verification meets the intent of the line-up procedure as written—that is, to verify that the aircraft is on the correct runway—it does not defend against lateral misalignment on the runway. Conversely, the other 2 methods of runway identification can be safety defences against both a runway assignment error and a runway misalignment. However, only the verification of the localizer alignment is applicable to departures from positions other than the runway threshold (e.g., before a displaced threshold or at an intersection).

As demonstrated in the Australian Transport Safety Bureau's research into factors influencing misaligned take-off occurrences at night, as well as in previous TSB occurrence reports and the collection of runway misalignment information specific to Runway 27 at KSAN, misaligned takeoffs may be infrequent, though they are not uncommon. Because the airport operator does not keep records of misaligned takeoffs, it is unknown exactly how many occurred in the area before the KSAN Runway 27 displaced threshold. The true extent of the risk is therefore unknown.

Finding as to risk

If flight crews line up on runways in the area before the displaced threshold or conduct intersection departures under degraded visual conditions or at night and without confirming the aircraft's lateral position on the runway, there is an increased risk of runway misalignments or runway side excursions.

2.1.7 First officer's perception

Immediately before the takeoff of the occurrence flight, 9 aircraft arrived consecutively on Runway 09 in very short succession, with the last aircraft in the sequence conducting a missed approach because the flight crew was unable to acquire the required visual reference to land. At this time, the occurrence aircraft was 2nd in a line of 4 aircraft waiting to depart from the same runway in the opposite direction (Runway 27) before the next sequence of consecutive arrivals on Runway 09. KSAN being a single-runway commercial service airport, and one of the busiest in the world, the volume of arrivals and departures produces a fast cadence in the movement of aircraft. On the day of the occurrence, the fast cadence combined with the deteriorating weather likely resulted in a time pressure being perceived by the first officer.

When the air traffic controller instructed the flight crew of the occurrence aircraft to line up and wait, the first officer read back the instruction. He then proceeded with the before-takeoff checks followed by confirmation with the checklist and did the same for the line-up checks and checklist. When the aircraft entered the runway, the first officer, as a result of his cockpit duties, was likely switching his attention between the primary task of the cockpit checks and the task of performing monitoring and crosschecking. In this unfolding situation combined with the perceived time pressure, it was likely that the environmental cues in the runway environment were not salient enough for the first officer to detect the runway misalignment.

Finding as to causes and contributing factors

The complexity of instrument flight rules operations on a single runway surface, with arrivals on one end and departures from the other end, created an environment where the flight crew perceived a time pressure for the takeoff. As a result, the first officer was completing the line-up checks while the captain taxied to position, and the first officer therefore did not monitor the progress of the taxi.

The flight crew were given their take-off clearance as the occurrence aircraft taxied onto the runway's left edge marking and came to a stop. The first officer read back the clearance, and then the captain transferred control of the aircraft to the first officer. The cadence of these events, combined with the perception of a time pressure due to the rapid and continuous sequence of arrivals and departures, resulted in the first officer tending to the outside visual environment for only a very limited amount of time.

During this limited time spent verifying readiness for takeoff, the visual cues in the runway environment likely matched what was expected: a row of lights directly ahead, another row of lights aligned 100 feet to the right, and a paved surface to the left of the aircraft's heading. In addition, the end of the runway and the airport buildings were not clearly visible due to the darkness and degraded visual conditions.

Given the first officer's familiarity with both KSAN and flying with the occurrence captain, there was an added expectation that the aircraft was lined up on the centreline when the captain confirmed the runway alignment and transferred control of the aircraft to him. The degraded visual conditions at night and the short amount of time spent monitoring the visual environment resulted in the available visual cues not being salient enough to alter the first officer's expectation that the aircraft was aligned with the centre of the runway.

Findings as to causes and contributing factors

Due to the reduced visual cues and perceived time pressure felt by the first officer, he did not recognize that the aircraft's nose was aligned with the left edge of the runway when he assumed the role of pilot flying shortly before the take-off roll commenced.

During the take-off roll, the aircraft's left main landing gear wheels contacted and severed 3 runway edge lights, causing damage to the aircraft's tires and flaps.

The aircraft's contact with the runway edge lights was not recognized by the flight crew because they perceived the sounds and vibrations to be normal contact with the embedded runway centreline lights and consequently continued with the departure.

2.1.8 Undetected foreign object debris

At KSAN, the ATC tower's airport surface detection equipment – model X (ASDE-X) provides increased cues to controllers, allowing them to more accurately identify all aircraft and vehicles on the airport movement area. However, the system is not designed to alert controllers to the hazardous situations leading to misaligned takeoffs. Therefore, during nighttime operations in degraded visual conditions, with no alerts to a potential runway misalignment, it is unlikely that the tower controller had sufficient cues to identify the occurrence aircraft's misalignment on the runway.

In this occurrence, damage to the aircraft was minor. It required the replacement of the left main landing gear wheels and patching to repair the puncture holes in the left inboard flap. While the flight crew were unaware of the damage to their aircraft, the airport operator and controllers were also unaware of the damage to the runway lighting and the debris that remained on the runway because KSAN does not have a foreign object debris detection system. During the nearly 8 hours between the misaligned takeoff of the occurrence aircraft and the time at which the San Diego County Regional Airport Authority became aware of the event, debris left by the broken lights remained in the runway environment, posing a hazard for other aircraft taking off.

Finding as to risk

If foreign object debris on runways is not detected and identified in a timely manner, there is a risk that it will result in aircraft damage during critical phases of flight.

2.1.9 Threat and error management

Training in crew resource management (CRM) and threat and error management (TEM) is provided each year to all Jazz flight crew and cabin crew members, as well as dispatchers and aircraft maintenance controllers. During TEM training, staff discuss potential threats and ways to prevent threats from developing into errors when an undesired aircraft state persists. This training is conducted using scenarios based on information about relevant threats and errors in everyday operations. According to Jazz procedures, common or prevalent threats are typically identified by flight crews during standard pre-flight briefings.

Jazz designs biannual simulator training and checking in part using relevant threats and errors identified through numerous internal and external sources. While Jazz CRM and TEM training sessions include strategies intended to help flight crews manage distraction and attention, this occurrence demonstrates that a crew member's duties in the cockpit can become complex and require more attention as the aircraft is entering the runway. The necessity of completing cockpit checks and checklists while also monitoring the aircraft's surroundings results in a need to switch attention between tasks. These competing demands can cause a flight crew member to be partially absent or unaware when monitoring the aircraft's position and can, as a result, lead the flight crew member to misunderstand a situation.

TEM has been shown to be an effective addition to flight crew training and is required for all commercial aviation operations in Canada. In this occurrence, the flight crew identified a threat (limited runway length) and managed it by deviating from the taxiway centreline marking to use more runway space. However, this mitigation, though routinely successful in reducing the risk of an overrun, also reduced the visual cues available to the flight crew for aligning the aircraft to the centre of the runway. Because the crew had not considered a misaligned takeoff as a prevalent potential threat that could emerge in the environment and conditions in which the flight was to be operated, this threat remained unaddressed and unmanaged.

2.2 Fuel imbalance leading to the in-flight shutdown of the right engine

2.2.1 Fuel imbalance

Shortly before the aircraft entered the departure runway, the first officer completed the before-takeoff checks, which required him to press the XFLOW AUTO OVERRIDE push-button switch to select "MAN" (manual position). This push-button switch is located on the overhead panel directly below the GRAVITY XFLOW push-button switch (Figure 15, Section 1.17.5.2.1 *Normal procedures*). Expanded procedures in the operator's AOM require that once this push-button switch is pressed, the first officer should then verify that the MAN XFLOW message is displayed on the engine indication and crew alerting system (EICAS) and that there is no GRAV XFLOW OPEN message displayed. The after-takeoff checklist, which is normally completed after setting climb thrust when workload permits, requires the flight crew to press the XFLOW AUTO OVERRIDE push-button switch again to return it to the AUTO position.

The Regional Jet Series 700 and 900 aircraft previously had a known issue where selection of the crossflow pump to manual would trigger a spurious "XFLOW PUMP" caution message if the selection to manual were made while the automatic transfer is about to stop. The spurious caution message issue was addressed by the manufacturer of the fuel quantity gauging computer (FQGC) in 2006 by incorporating a software update. This update had been incorporated into the occurrence aircraft's FQGC. However, more recent information from the FQGC manufacturer indicates that the spurious messages continue to occur. The source of the repetitive issue could not be determined due to limited data.

On the occurrence flight, the XFLOW PUMP caution was recorded at approximately 6500 feet in the initial climb, very close to the time the pilot monitoring (PM) (the captain) was completing the after-takeoff checks, which involved pressing the XFLOW AUTO OVERRIDE push-button switch. If this switch had inadvertently been left on AUTO for takeoff, this action would have set the push-button switch to MAN (manual), instead of returning the selection to AUTO.

The close timing of the XFLOW AUTO OVERRIDE push-button switch selection, possibly to manual, and the appearance of the caution message are consistent with the conditions that were previously known to occasionally result in a spurious warning. Therefore, because there was no post-occurrence indication of a pump failure, it is likely the "XFLOW PUMP" caution message the flight crew received was spurious, rather than a genuine indication of a pump failure, even though the aircraft's FQGC had been updated with software designed to address this spurious issue.

As the aircraft continued to climb, recorded data indicates that it maintained a very slight bank angle to the left of approximately 1°. The crew was likely unaware of this bank angle because the angle was so slight and was similar to the static bank angle the aircraft experienced on the ground before takeoff. During this period of steady bank, the quantity of fuel in the left-wing tank remained steady or slowly increased, whereas the quantity of fuel in the centre and right-wing tanks continued to decrease.

As the flight continued, the flight crew monitored the fuel imbalance as instructed in the XFLOW PUMP checklist. Approximately 17 minutes after the "XFLOW PUMP" caution message, while the aircraft was climbing through flight level (FL) 310, the net fuel transfer from the right-wing to left-wing tank was greater than 5000 pounds per hour (lb/h). This rate of transfer is only possible with the gravity crossflow open given that it significantly exceeds the capability of the crossflow pump. This high rate of transfer preceded the "FUEL IMBALANCE" caution message by approximately 8 minutes, and the flight crew's subsequent completion of the Gravity Crossfeed Procedure. While this recorded rate of transfer indicates that the gravity crossflow valve was open, the crew had not yet conducted any procedure that called for this valve to be opened.

The gravity crossflow valve is a completely manual selection and is not controlled by the aircraft's FQGC. For the valve to be open at that time, it either had failed or had been inadvertently selected open by the flight crew. The push-button switch selections on the fuel control panel are not recorded on the aircraft's flight data recorder, so it could not be determined with certainty that the flight crew opened the gravity crossflow; however, no mechanical faults were found with the valve, and the issue has not since reoccurred. The EICAS will display a message if the gravity crossflow shut-off valve fails, but there was no report of the message being displayed in this occurrence.

Furthermore, the gravity crossflow push-button switch is located directly above the XFLOW AUTO OVERRIDE switch on the overhead fuel control panel. The switches are in close proximity to one another and the recorded transfer rates indicate that the gravity crossflow must have been open. Therefore, the most likely scenario is that the valve was opened inadvertently by the flight crew pressing the push-button switch at some point before the high transfer rates occurred. The only 2 normal procedures that require the flight crew to press any push-button switch on the overhead fuel panel is when the XFLOW AUTO OVERRIDE switch is selected during the before-takeoff and after-takeoff checklists. It is, therefore, possible that the mis-selection occurred at either of these times.

Finding as to causes and contributing factors

During the completion of either the before-takeoff or after-takeoff checklists, it is likely that the flight crew inadvertently pressed the gravity crossflow push-button switch instead of the co-located crossflow auto override push-button switch. As a result, during the flight, fuel periodically transferred between the aircraft's wing tanks by gravity when the aircraft was banked left or right, leading to a worsening fuel imbalance condition.

2.2.2 Flight crew guidance

2.2.2.1 Guidance for switch selection

In the Jazz quick reference handbook (QRH), the abnormal checklist for the "XFLOW PUMP" caution message informs flight crews that if no lateral fuel imbalance exists, they are to monitor fuel quantities, and conversely, that if an imbalance does exist, they should then proceed with the Gravity Crossfeed Procedure in the QRH. Upon addressing the original caution message, the flight crew determined that the imbalance, which was less than 200 pounds at the time, was minor. As the aircraft climbed through FL310, the lateral fuel imbalance began to worsen. The flight crew attempted to troubleshoot, but the lateral fuel imbalance continued and reached the 800-pound limitation while the aircraft was at its cruise altitude of FL340. This exceedance was accompanied by a "FUEL IMBALANCE" caution message on the EICAS. This caution message is associated with its own abnormal checklist. However, given the chronology of the messages, the PM returned to the original abnormal checklist for the crossflow pump, and thus continued to the Gravity Crossfeed Procedure.

The steps of the Gravity Crossfeed Procedure in the Jazz QRH instructed the PM to place the left and right crossflow push-button switches (L XFLOW and R XFLOW) in the "OFF" position (switches out and not pressed in). Next, it instructs the flight crew to place the XFLOW AUTO OVERRIDE switch (whose push button is labelled "MAN") into the "OFF" position. However, "OFF" is not 1 of the 2 available positions: AUTO (switch out) or MAN (switch pressed in).

Despite the unclear instruction, the PM ensured that the XFLOW AUTO OVERRIDE switch was in the AUTO position (with the switch out). This action was consistent with the logical position and appearance of the switch in relation to the other switches that are on the same panel and mentioned immediately before in the checklist steps, and it corresponded to the manufacturer's intended instruction as well as its design of the checklist and logic of the switch position. According to the manufacturer's design, the switch is supposed to be in automatic mode and the "MAN" push-button switch is to be pushed out, thereby maintaining the FQGC's control over the fuel-transfer process.

2.2.2.2 Guidance for sideslips

The flight crew continued with the Gravity Crossfeed Procedure checklist and reached the step that directed them to accomplish a steady-heading sideslip. While this manoeuvre is a common strategy for remaining aligned with a runway centreline when landing in a crosswind, it is not a flight manoeuvre normally used at cruise altitude. Entering a sideslip requires banking the aircraft with the ailerons and using rudder force to resist the turning moment, thereby holding the aircraft in a banked attitude but with a steady heading. This attitude, combined with the open gravity crossflow valve, will transfer fuel between the left- and right-wing tanks. However, the Gravity Crossfeed Procedure checklist in the Jazz QRH has a note (provided to enhance a flight crew's understanding of the checklist) that tells the flight crew to establish a bank angle by use of the rudder pedal. This instruction differs slightly from the checklist in the manufacturer's QRH, which specifically instructs flight crews to establish a bank first and then use the rudder as necessary to prevent the turning moment.

In addition, the checklist does not necessitate or instruct that the autopilot be turned off for the sideslip manoeuvre. While this does not preclude the ability to enter the aircraft into a sideslip, an interpretation of the wording in the Jazz checklist can imply something different from the instruction in the manufacturer's checklist. The Jazz checklist instructs flight crews to establish a bank angle down on the low-quantity side by use of the rudder. An application of the rudder on the low-quantity side induces a yaw moment to that direction. With the autopilot engaged, the system will react to maintain a steady course by applying a bank angle, but to the opposite side, which has the higher quantity of fuel.

Finding as to risk

When the wording in a checklist is ambiguous or unclear, or when the wording in an operator's checklist differs from that in the checklist provided by the manufacturer, a flight crew may, in an effort to correct an abnormal or emergency condition, conduct procedures in ways not intended by the manufacturer, increasing the risk of entering into an undesired aircraft state.

The recorded flight data demonstrate that the occurrence flight crew continued to operate with the autopilot engaged, and when the aircraft entered into the sideslip, the 1st control input was right rudder (on the low fuel quantity side). This translated into a bank angle to the left, averaging 2.2° for the next 3 minutes, approximately. Given that the flight crew were dealing with a seemingly novel situation, at night, the angle of bank in the opposite direction went undetected, thereby transferring even more fuel to the left-wing tank, which quickly reached its maximum quantity.

The application of the rudder opposite to that which was required was not unique to the occurrence flight crew. As the investigation learned from a 2nd occurrence of fuel imbalance approximately 2 months later involving a different Jazz aircraft and flight crew, that flight crew also continued flying with the autopilot engaged and applied rudder pressure on the low-quantity side. While this did induce a rapid and significant transfer of fuel to the side that already had a greater quantity of fuel (which quickly led to a lateral imbalance in excess of 2300 pounds), the flight crew recognized the condition and corrected it, thus reducing the fuel imbalance to only approximately 200 pounds. Although this flight crew recognized the condition in less than 1 minute, they, unlike the occurrence flight crew, did so in daytime conditions and at an angle of bank of about 4°.

Findings as to causes and contributing factors

While operating at night with the autopilot on, the aircraft was placed in a sideslip toward the wing tank with the greater quantity of fuel, and this opposite bank was not recognized by the flight crew. As a result, the lateral fuel imbalance was not controlled, and continued to increase.

The fuel imbalance, which was unrelated to the damage sustained during the take-off roll, led the flight crew to declare an emergency and divert to a nearby airport for an emergency landing.

As the flight crew made the decision to divert to KLAX, ATC provided them with a left turn to reverse course. This sustained flight attitude, with the left wing (which carried the tank with the higher quantity of fuel) low and the open gravity crossflow valve, almost certainly continued to exacerbate the lateral fuel imbalance.

The Gravity Crossfeed Procedure checklists in both QRHs state that if a lateral fuel balance can be established, the crew is to return to coordinated flight and close the gravity crossflow valve. However, if a lateral fuel balance cannot be controlled within aircraft limitations, the engine on the side with the lower fuel quantity shall be shut down as a precaution. The occurrence flight crew completed this procedure per the In-Flight Engine Shutdown abnormal checklist in the Jazz QRH.

Step 7 in the In-Flight Engine Shutdown abnormal checklist instructs flight crews to place the fuel crossflow system into automatic mode, applying the same switch position (switch out) that is to be selected for normal flight, and the same switch position interpreted by the captain as required during the Gravity Crossfeed Procedure. A note mid-checklist states that flight crews may have to perform the Gravity Crossfeed Procedure when required and if time permits.

In the rest of the In-Flight Engine Shutdown checklist, and in the subsequent Single-Engine Approach and Landing checklist, there are no further instructions to close the gravity crossflow valve. When this valve remains open, all remaining fuel on board is available to the operating engine; however, in this occurrence as a result of the valve remaining open and fuel continuing to transfer to the left wing tank, which was physically lower than the right wing tank, the lateral fuel imbalance exceeded 2400 pounds during the diversion to KLAX.

The recorded flight data demonstrate that following the peak lateral imbalance, the aircraft's angle of bank was at times to the right (including in a prolonged 180° right turn with an angle of bank of approximately 15°) on final approach to KLAX. During this portion of the flight, the lateral fuel imbalance was reduced to approximately 1120 pounds before increasing again once the aircraft was established on final approach. It continued to increase until landing.

Finding as to causes and contributing factors

The checklists did not require the flight crew to close the gravity crossflow valve following the attempted Gravity Crossfeed Procedure. As a result, the open valve occasionally made the fuel imbalance worse during the subsequent manoeuvring and was at one point more than 3 times the maximum permissible.

3.0 FINDINGS

3.1 Findings as to causes and contributing factors

These are conditions, acts or safety deficiencies that were found to have caused or contributed to this occurrence.

1. The aircraft was operating at night and in fog, in an area where visibility was between ¼ statute mile and ½ statute mile. As a result, there were few visible cues available to the flight crew to identify and verify the aircraft's position on Runway 27 at San Diego International Airport.

2. When taxiing to position on the runway, the captain taxied the aircraft off the taxiway centreline in order to increase the runway distance available for takeoff. As a result, he had to rely on other visual cues to determine the aircraft's position on the runway.

3. When the aircraft was turning left to establish the runway heading in preparation for takeoff, the limited and ambiguous visual cues that were available likely met the captain's expectations. As a result, he perceived the left runway edge as the runway centreline and aligned the aircraft laterally with the left edge of the runway, rather than its centre.

4. The complexity of instrument flight rules operations on a single runway surface, with arrivals on one end and departures from the other end, created an environment where the flight crew perceived a time pressure for the takeoff. As a result, the first officer was completing the line-up checks while the captain taxied to position, and the first officer therefore did not monitor the progress of the taxi.

5. Due to the reduced visual cues and perceived time pressure felt by the first officer, he did not recognize that the aircraft's nose was aligned with the left edge of the runway when he assumed the role of pilot flying shortly before the take-off roll commenced.

6. During the take-off roll, the aircraft's left main landing gear wheels contacted and severed 3 runway edge lights, causing damage to the aircraft's tires and flaps.

7. The aircraft's contact with the runway edge lights was not recognized by the flight crew because they perceived the sounds and vibrations to be normal contact with the embedded runway centreline lights and consequently continued with the departure.

8. During the completion of either the before-takeoff or after-takeoff checklists, it is likely that the flight crew inadvertently pressed the gravity crossflow push-button switch instead of the co-located crossflow auto override push-button switch. As a result, during the flight, fuel periodically transferred between the aircraft's wing tanks by gravity when the aircraft was banked left or right, leading to a worsening fuel imbalance condition.

9. While operating at night with the autopilot on, the aircraft was placed in a sideslip toward the wing tank with the greater quantity of fuel, and this opposite bank was not recognized by the flight crew. As a result, the lateral fuel imbalance was not controlled, and continued to increase.

10. The fuel imbalance, which was unrelated to the damage sustained during the take-off roll, led the flight crew to declare an emergency and divert to a nearby airport for an emergency landing.

11. The checklists did not require the flight crew to close the gravity crossflow valve following the attempted Gravity Crossfeed Procedure. As a result, the open valve occasionally made the fuel imbalance worse during the subsequent manoeuvring and was at one point more than 3 times the maximum permissible.

3.2 Findings as to risk

These are conditions, unsafe acts or safety deficiencies that were found not to be a factor in this occurrence but could have adverse consequences in future occurrences.

1. If flight crews line up on runways in the area before the displaced threshold or conduct intersection departures under degraded visual conditions or at night and without confirming the aircraft's lateral position on the runway, there is an increased risk of runway misalignments or runway side excursions.

2. If foreign object debris on runways is not detected and identified in a timely manner, there is a risk that it will result in aircraft damage during critical phases of flight.

3. When the wording in a checklist is ambiguous or unclear, or when the wording in an operator’s checklist differs from that in the checklist provided by the manufacturer, a flight crew may, in an effort to correct an abnormal or emergency condition, conduct procedures in ways not intended by the manufacturer, increasing the risk of entering into an undesired aircraft state.

4.0 SAFETY ACTION

4.1 Safety action taken

4.1.1 Jazz Aviation LP

Jazz Aviation LP (Jazz) Flight Operations has examined the 35 airports in the United States and the 41 airports in Canada in its network and identified those that require risk-mitigation measures to minimize the risk associated with the presence of displaced thresholds. As a result of this work, which focused on 42 runways in the U.S. and 13 runways in Canada, additional warnings have been included in Jazz's airport charts to highlight the risks of departing from within these displaced threshold areas. For example, the San Diego International Airport (KSAN) charts now include a departure consideration informing flight crews of the threat of incorrect runway verification. It states that:

> a. Runways 9 and 27 have displaced thresholds for landing which affects the lighting and runway markings available for lining up and starting the takeoff roll on the full runway. Exercise caution when departing in reduced visibility or at night to ensure the aircraft is on the runway centerline.
>
> b. At night or in low visibility, request ATC [air traffic control] to select runway lights to the departing runway if taking off opposite to landing traffic.
>
> c. **Use the localizer for runway and centerline verification** [emphasis in original] due to the location of the runway identifiers at the displaced thresholds.
>
> d. Use the white arrows on the runway centerline between the beginning of the runway and the displaced threshold to further confirm runway centerline alignment.[87]

In addition to conducting a study of airports in its network and making changes to its airport charts, Jazz issued a company memo to all pilots, for all aircraft types, concerning departures from the areas before the displaced threshold on a runway. This memo referenced this occurrence and the current investigation and informed flight crews of the threats that exist during departures from runway areas other than the threshold, and the mitigations in place to minimize these threats.

Jazz Flight Operations also published an amendment to section 2.4.2 (Line-Up Check) of the *CRJ AOM Volume II Aircraft Operating Manual*. The revision states that both pilots must verify the departing runway using either

> the runway identifier on the runway surface, localizer alignment […], Ownship position on the taxi charts or Airport Moving Map (AMM) in the Jeppesen app. The

[87] Jazz Aviation LP, KSAN [charts] (01 April 2022), Departure Considerations.

> HSI (horizontal situation indicator) heading may be used for runway verification only if all other methods for runway verification are not available.[88]

However, the procedure adds that in low-visibility operating conditions, “relying only on the HSI heading is not permitted.”[89] The new text further instructs flight crews to “[e]xercise caution and use all available cues when verifying the runway and runway centerline”[90] at airports with displaced thresholds or converging runway thresholds.

Jazz made a change to the CRJ 900 QRH Gravity Crossfeed Procedure (ABNORMAL 10-15). Revision 16 includes concise wording on initiating a sideslip and requires that the autopilot be disengaged as part of the procedure.

Immediately after the occurrence, Jazz submitted a service difficulty report to Transport Canada (TC) detailing the events involving the crossflow pump, the fuel quantity gauging computer, and the resultant fuel imbalance. In a similar fashion, Jazz immediately submitted another service difficulty report to TC following the 2022 fuel imbalance occurrence in Winnipeg.

This report concludes the Transportation Safety Board of Canada’s investigation into this occurrence. The Board authorized the release of this report on 22 May 2024. It was officially released on 05 July 2024.

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88 Jazz Aviation LP, *CRJ AOM Volume II Aircraft Operating Manual*, Revision 20 (01 August 2022), Section 2.4.2: Line-Up Check, p. 2.4-5.

89 Ibid.

90 Ibid.

APPENDICES

Appendix A – Fuel imbalance sequence of events

Time	Event
1842:38	Aircraft rotates and departs from runway at San Diego International Airport (KSAN), California, United States.
1843:50	First reduction in engine thrust. Per the Jazz Aviation LP quick reference handbook (QRH), this event coincides with the pilot monitoring switching the fuel crossflow system from manual to auto mode.
1845:15 – 1845:17	Fuel system reading indicates an imbalance of approximately 220 pounds.
1845:45 – 1845:47	30-second threshold for activation of the crossflow pump met.
1845:49	Fuel system reading indicates imbalance of approximately 192 pounds.
1845:57	Illumination of "XFLOW PUMP" caution message. No significant imbalance exists, but the flight crew continue to monitor fuel quantities via the flight deck displays.
1847:45	Right-wing tank reading indicates approximately 93% quantity, triggering fuel quantity gauging computer (FQGC) activation of the transfer ejector, which moves fuel from the centre tank to the right-wing tank.
1854:37	Right-wing tank reading indicates approximately 97% quantity, triggering FQGC deactivation of transfer ejector.
1900:49	Right-wing tank reading indicates approximately 93% quantity, triggering FQGC activation of the transfer ejector, which moves fuel from centre tank to right-wing tank.
1901:00	Approximate time when the fuel imbalance becomes divergent, with left-wing tank slowly increasing and right-wing tank decreasing.
1903:05	Lateral imbalance of 300 pounds.
1904:32	Lateral imbalance of 400 pounds.
1905:37	Lateral imbalance of 500 pounds.
1906:39	Lateral imbalance of 600 pounds.
1906:44	Aircraft levels out at a cruise altitude of flight level (FL) 340.
1907:33	Lateral imbalance of 700 pounds.
1909:56	Flight crew attempt to use differential engine thrust settings (less thrust on right engine and more on left engine).
1911:00	Lateral imbalance of 800 pounds. Flight crew receive the "FUEL IMBALANCE" caution message since the imbalance has now reached the design limitation of the aircraft. Flight crew continue with XFLOW PUMP Caution Message procedure in QRH checklist, which directs them to action the Gravity Crossfeed Procedure.
1911:25	With the gravity crossflow valve open, flight crew apply right rudder pressure to initiate a sideslip. This application causes the autopilot to apply a bank angle to the left to compensate and maintain a steady course. During the next 3 minutes, aircraft maintains an average angle of bank of approximately 2.2° to the left.
1914:03	Left-wing tank reaches its maximum quantity.
1914:17	Flight crew begin to divert flight to Los Angeles International Airport (KLAX), California, United States, and are given air traffic control (ATC) clearance to initiate a left turn and begin descending.

1916:11	Flight crew continue following the QRH, which instructs them to carry out a precautionary shutdown of the engine on the low fuel quantity side. This is accomplished during the descending left turn.
1935:19	During descent through approximately 10 000 feet above sea level, aircraft fuel reaches its point of maximum imbalance: 2464 pounds.
1944:01	Aircraft completes right turn to line up with final approach to KLAX. Fuel imbalance reduced to 1120 pounds after previous 9 minutes of manoeuvring, which included numerous small turns to the right.
1946:33	Aircraft lands at KLAX with a recorded lateral fuel imbalance of approximately 1568 pounds.