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

AVIATION INVESTIGATION REPORT A15F0165

Severe turbulence encounter

Air Canada
Boeing 777-333ER, C-FRAM
Anchorage, Alaska, 85 nm ENE
30 December 2015

Canada

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Summary

On 30 December 2015, the Air Canada Boeing 777-333ER (registration C-FRAM, serial number 35250) was operating as flight 088 (ACA088) from Shanghai/Pudong Airport, China, to Toronto/Lester B. Pearson International Airport, Ontario. At 1924 Coordinated Universal Time, 8 hours into the flight, ACA088 encountered severe turbulence at flight level 330, approximately 85 nautical miles east-northeast of Anchorage, Alaska, United States. During the encounter, 21 passengers were injured, 1 of whom was seriously injured. ACA088 diverted to Calgary International Airport, Alberta, and landed approximately 2 hours and 45 minutes later. Damage to the aircraft was limited to interior furnishings and a V-clamp for ducting on the Number 2 air conditioning system that failed.

Le présent rapport est également disponible en français.

Table of contents

1.0 Factual information

1.1 History of the flight

On 30 December 2015, the Air Canada Boeing 777-333ER operating as flight 088 (ACA088) was preparing to depart Shanghai/Pudong Airport (ZSPD), China, for Toronto/Lester B. Pearson International Airport (CYYZ), Ontario, with 19 crew members and 332 passengers[1] on board. The planned duration of the flight was 13 hours and 40 minutes. Air Canada dispatch created the route and issued the operational flight plan (OFP) at about 0645 Coordinated Universal Time.[2] This flight plan was printed by the flight crew at 0846. There were no amendments to the planned route.

The flight was scheduled for a 1005 departure, but was delayed due to the aircraft arriving late on the inbound flight from Toronto. ACA088 pushed back from the gate at 1059 and departed Shanghai at 1123.

Owing to the length of the flight, ACA088 had 4 flight crew members: the operating captain and first officer, an augment first officer, and a relief pilot. The flight crew determined their work schedule prior to departure. In this case, the plan was for the operating captain and first officer to carry out the takeoff and establish cruise, and the augment first officer and relief pilot would take over and fly for 3 hours. The operating captain and first officer would then take over for the next 3 hours, and the crews would alternate in this manner for the remainder of the flight. All flight crew members were licensed in accordance with Air Canada policies and the *Canadian Aviation Regulations* (CARs).

There were 15 flight attendants on board ACA088, including 2 in-charge flight attendants. This complement ensured that at least 1 in-charge flight attendant would be on duty at all times. At the time of the occurrence, 7 flight attendants and 1 in-charge flight attendant were using the cabin crew rest facility.

The Number 1 air conditioning system[3] had experienced occasional overheating on recent flights, including the inbound flight to Shanghai. Maintenance personnel inspected the system on the ground in Shanghai, but they found no problems and released the aircraft for the flight. During the first few hours of the occurrence flight, the Number 1 system indicated an overheat condition. The flight crew successfully reset the system and the flight continued with both air conditioning systems functioning, although the Number 1 system had a fluctuating duct pressure reading.

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[1] 330 fare-paying passengers and 2 lap-held infants (children under 2 years of age).

[2] Because the aircraft passed through multiple time zones on the occurrence flight, all times in this report are given in Coordinated Universal Time (UTC) or (Z).

[3] The Boeing 777 has 2 air conditioning systems that provide pressurization, heating and cooling air for the cabin. Adequate pressurization and air conditioning can be maintained with only 1 system functional.

At about 1635, the operating captain and first officer received a significant meteorological information (SIGMET) bulletin from Air Canada dispatch via the aircraft communications addressing and report system (ACARS). The SIGMET, referred to as SIGMET I2, forecast an area of occasional severe turbulence along the route of flight for ACA088 between flight level (FL) 260[4] and FL400. This information was also being communicated through the U.S. Federal Aviation Administration (FAA) Anchorage Air Route Traffic Control Center (ARTCC).

At 1745, the operating captain and the first officer were relieved by the augment first officer and the relief pilot, and the 4 flight crew members discussed SIGMET I2. The augment first officer assumed the duties of pilot flying in the right seat, and the relief pilot assumed the duties of pilot monitoring in the left seat. As pilot monitoring, the relief pilot was also responsible for radio communications.

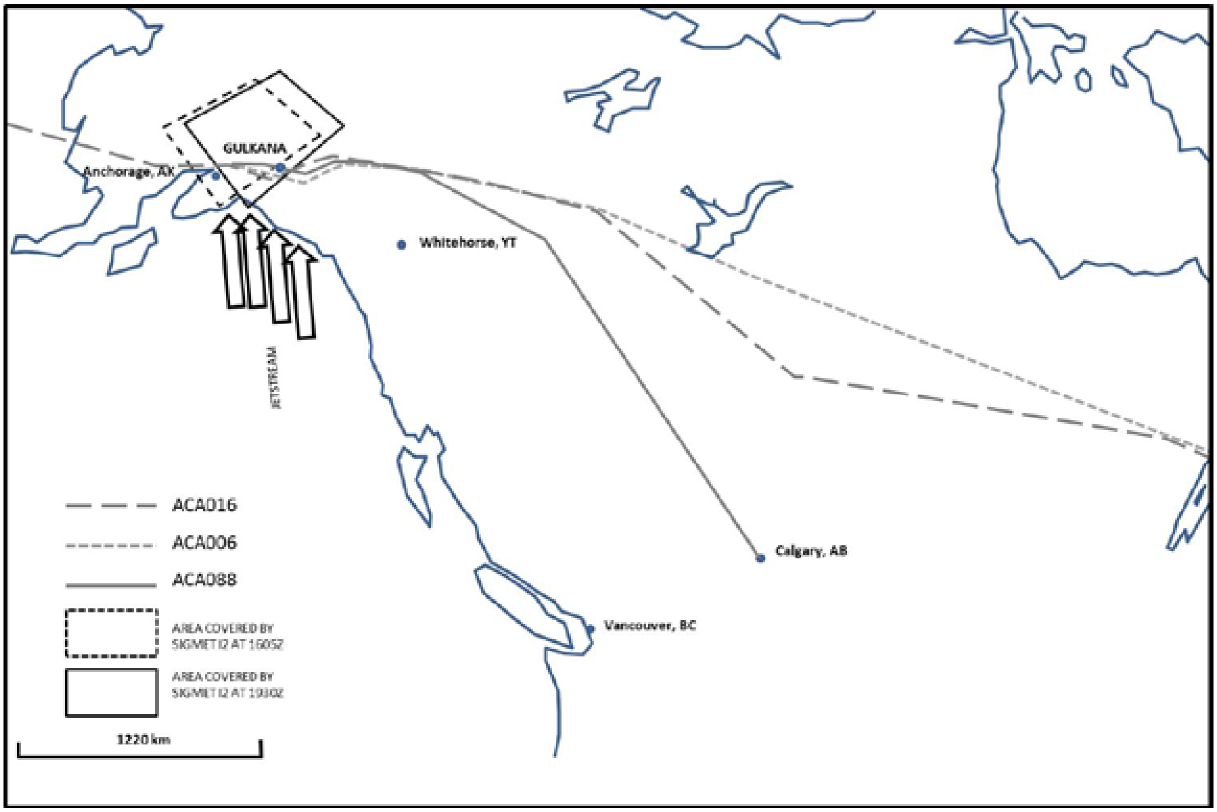
The relief pilot contacted the Anchorage West controller to ask about flight conditions for ACA088's route of flight and altitude. The Anchorage West controller told them that there were reports of light to moderate turbulence associated with the jet stream, but that there had been no reports of moderate or severe turbulence at FL330 at that time.

An Air Canada Boeing 777 operating as flight 016 (ACA016) was 90 minutes ahead of ACA088 on the same route of flight. A third Air Canada flight, a Boeing 787 operating as flight 006 (ACA006), was at FL390[5] on the same track and was about 60 minutes behind ACA016 and 30 minutes ahead of ACA088 (Figure 1).

4 Flight level 260 is the equivalent to 26 000 feet above sea level with an altimeter setting of 29.92 inches of mercury.

5 The Boeing 787 was able to cruise at a higher flight level due to its performance capabilities.

Figure 1. Routes of flight of ACA016, ACA006, and ACA088, showing area of turbulence forecast in SIGMET I2



At about 1755, ACA016 encountered moderate to severe turbulence at FL350 near the GULKANA waypoint, in the area covered by SIGMET I2. This information was relayed to the Anchorage ARTCC in a pilot weather report (PIREP). Air Canada dispatch retrieved the PIREP from its flight following software, but was not aware that it had come from ACA016. PIREPs indicate only the type of aircraft from which the report is made, not the air carrier. Air Canada dispatch then disseminated the PIREP via ACARS to ACA088. This PIREP was also communicated to ACA088 by the Anchorage ARTCC.

ACA016 had first encountered severe turbulence at FL350 and had been cleared by the Anchorage ARTCC for flight between FL330 and FL370. ACA016, for its part, encountered less turbulence at FL330, but elected to climb back to FL350 to get above a cloud layer.

At 1810, ACA016 encountered severe turbulence a second time at FL350, and again it descended to FL330; during this event, a flight attendant sustained a minor injury. ACA016 relayed this information to Air Canada dispatch via ACARS and clarified it an hour later through a satellite phone call at 1905. During this 5-minute phone call, the severity and duration of the turbulence and the airspeed fluctuations were discussed, and it was concluded that FL330 was the better altitude in terms of ride quality. Air Canada dispatch relayed this information to ACA088 at 1909.

At 1822, ACA006 received an ACARS message from Air Canada dispatch that described the intensity of the turbulence and airspeed deviations experienced by ACA016. At 1850, ACA006 sent an ACARS message directly to ACA016 to ask about the turbulence that

ACA016 had encountered. ACA016 responded that the turbulence had lasted 15 to 20 minutes with a 5-minute gap; a diversion to the south was strongly advised. The suggestion to divert to the south was not shared with Air Canada dispatch or ACA088.

The duration of the turbulence ACA006 encountered was similar to that experienced by ACA016, but its intensity was considered to be only moderate, not severe.

At approximately 1850, or about 35 minutes before ACA088 entered the area of known moderate to severe turbulence, ACA088's augment first officer called the in-charge flight attendant and said that they were approaching the jet stream, and that significant turbulence had been reported by the preceding aircraft, which was flying at a higher altitude. The augment first officer then directed the cabin crew to stop service and secure the cabin—actions that were in accordance with the Air Canada *Flight Operations Manual*.[6]

The in-charge flight attendant directed the flight attendants to secure all service carts, secure all loose items in the galley, suspend service, make announcements to the passengers, and walk the cabin to visually check that seat belts were fastened and loose items were stowed. The lighting in the cabin remained in the sleep mode, on a dim/low light setting.

While securing the cabin, several announcements were made in English, French, and Mandarin. The announcements were consistent with Air Canada company procedures (refer to section 1.17.3 of this report).

At 1922, the Anchorage ARTCC informed ACA088 of reports of moderate to severe turbulence at FL280 and FL350, and of moderate turbulence at FL390 between ACA088's current position and the GULKANA waypoint. The ACA088 flight crew chose to stay on the flight-planned track at FL330 based on the information obtained from Air Canada dispatch, Anchorage ARTCC, and visual cues suggesting that FL330 would have the least turbulence.

Just before ACA088 entered the area of turbulence, a passenger seated in row 1 of business class got up to use the washroom. At this time, all flight attendants were seated with their lap and shoulder harnesses fastened. The in-charge flight attendant told the passenger to return to their seat, but the passenger insisted on using the washroom. As the passenger was returning to their seat, the aircraft encountered turbulence for the first time, and the passenger was thrown into the ceiling and then onto the floor.

After this first turbulence event, ACA088 altered course 30° to the right.

The first turbulence event had lasted 2 minutes and was described as moderate to severe. This was followed by a second turbulence event of approximately 8 minutes of light to moderate turbulence. Immediately after this, a third turbulence event of moderate to severe turbulence occurred, lasting 7 minutes and 30 seconds (Figure 2). It was during this third event that most of the injuries were sustained.

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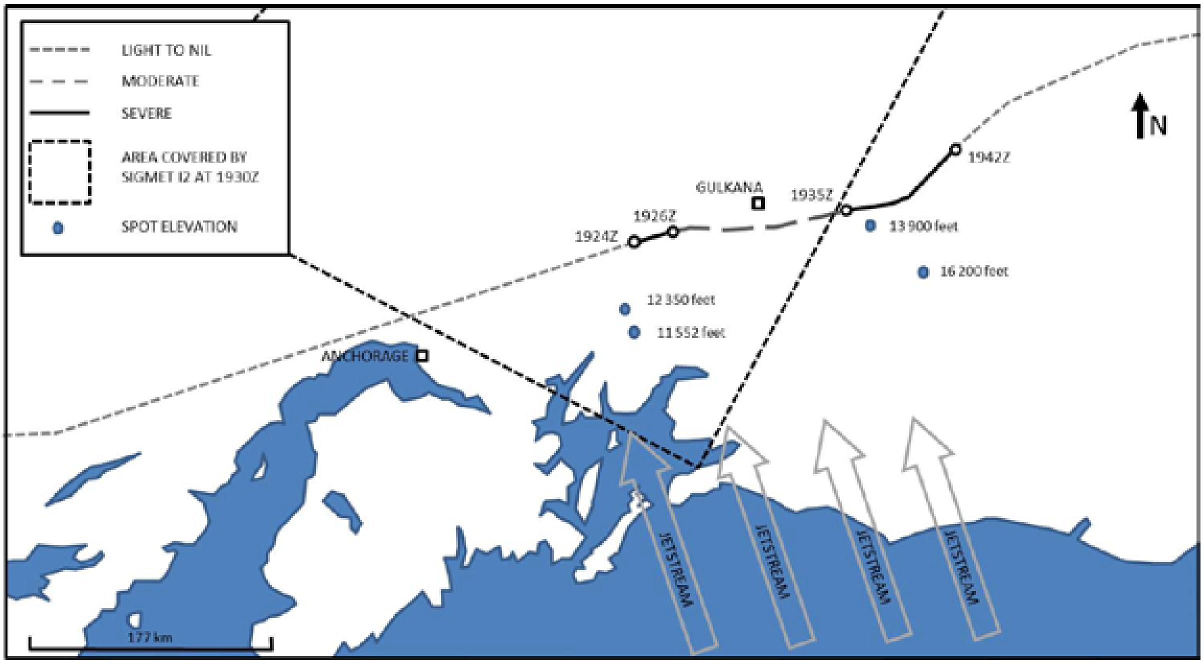
6 Air Canada, *Flight Operations Manual* (2015), section 7.1.22.2, "Seatbelt Usage during Turbulence."

Figure 2. Location, time and severity of turbulence encountered by ACA088



Between 1926 and 1935, the flight crew observed a BLEED LEAK R message on the engine indicating and crew alerting system, which indicated that the Number 2 air conditioning system had failed. Because the Number 1 air conditioning system had been overheating earlier, the flight crew was concerned about losing all pressurization if it failed again while the Number 2 system was inoperative. A loss of pressurization would require a descent to at least 13 000 feet, and at that time, the safe altitude for terrain clearance was 18 600 feet.

Once the turbulence subsided, the operating captain and the first officer returned to the flight deck. The door was difficult to open due to items (paperwork, tunics, etc.) being strewn around the flight deck. Once these 2 flight crew members gained access to the flight deck, the augment first officer and the relief pilot took the jump seats and remained on duty to assist the operating captain.

The augment first officer subsequently went to the cabin to help assess the cabin and give the captain an overview of the situation to help determine the next course of action. While in the cabin, the augment first officer reassured passengers and answered questions, which helped calm them.

A periodontist who was travelling on board helped the cabin crew provide first aid to the injured. The number of injured and the nature of their injuries were recorded and relayed to the operating captain, who in turn informed Air Canada dispatch and discussed diversion options. A diversion to Vancouver, British Columbia—the closest suitable destination—would require higher altitudes in order to avoid mountainous terrain. It was decided that altering course to skirt the high mountain terrain and fly at a lower altitude was paramount because the aircraft was operating on only 1 air conditioning system.

ACA088 continued on track toward the Northwest Territories and northern Alberta and then to Calgary, Alberta. Edmonton, Alberta, had been considered as the alternate airport, but Calgary was chosen for reasons of terrain avoidance, maintenance, and the convenience it provided for continuing passengers. In addition, the aircraft would be making an overweight landing: the longer runway at Calgary would allow for lower brake temperatures during rollout.

Prior to landing, the passengers were informed that emergency medical services would board at the gate to assess the injured and to deplane them first. Deplaning took about an hour.

1.2 *Injuries to persons*

Most injuries were sprains, strains, bruising, and scrapes. Injured passengers were located throughout the cabin (Appendix A). One passenger in business class received cuts from broken glassware, and 1 seriously injured passenger required an extended stay in hospital. The injuries resulted from passengers coming into contact with aircraft furnishings, the ceiling, and the floor of the interior.

Photo 1. Passenger service unit damage at seat 35K

The moderate to severe turbulence events featured a significant negative *g* force, followed quickly by a positive *g* force. The height of the ceiling of the Boeing 777 is 2.4 metres in the aisles and 1.6 metres at the window seat. Several passenger service units were damaged when passengers were thrown upward into the ceiling during the negative *g* event (Photo 1). The passenger who was seriously injured was seated near the L4 door (Appendix A) and was thrown upward and then downward onto the floor area by the door.

Most of the passengers who were physically injured were aware that they were required to wear their seat belts, but chose not to. Two of these passengers were asleep and did not hear the announcement.

No child restraint systems were used on board the aircraft, nor was their use required by regulation. The 2 infants on board were being held in their caregivers' arms and were not injured. The cabin crew attended to 3 passengers described as children (between the ages of 2 and 13). No physical injuries or issues associated with seat belt usage were reported.

Table 1. Injuries to persons

	Crew	Passengers	Others	Total
Fatal	–	–	–	0
Serious	–	1	–	1

Minor	–	20	–	20
None	19	311	–	330
Total	19	332	–	351

1.3 *Damage to aircraft*

Damage to the aircraft was limited to interior furnishings and a V-clamp for ducting on the Number 2 air conditioning system that failed.

1.4 *Other damage*

Not applicable.

1.5 *Personnel information*

Table 2. Personnel information

	Captain	First officer	Augment first officer	Relief pilot
Pilot license	Airline transport pilot licence	Airline transport pilot licence	Airline transport pilot licence	Airline transport pilot licence
Medical expiry date	01 Dec 2016	01 Feb 2016	01 Jan 2017	01 Mar 2016
Total flying hours	22 529	13 906	19 738	5221
Flight hours on type	5061	5814	1459	1453
Flight hours in the last 7 days	12	13	12	12
Flight hours in the last 90 days	159	84	62	132
Hours on duty prior to occurrence	11	11	11	11
Hours off duty prior to work period	24	24	24	24

The flight crew were certified and qualified for the flight in accordance with existing regulations.

1.6 Aircraft information

Table 3. Aircraft information

Manufacturer	The Boeing Company
Type, model and registration	777-333ER, C-FRAM
Year of manufacture	2008
Serial number	35250
Certificate of airworthiness issue date	25 June 2008
Total airframe time	39 452 hours
Engine type (number of engines)	General Electric, GE90-115B (2)
Maximum allowable take-off weight	351 534 kg
Recommended fuel types	Jet A, Jet A-1
Fuel type used	Jet A-1

The aircraft was certified, equipped, and maintained in accordance with existing regulations and approved procedures. The weight and centre of gravity were within the prescribed limits.

1.7 Meteorological information

1.7.1 General

There are unique challenges to operating long-haul flights, one of which is predicting the weather. Weather forecasts for these long-haul routes can be obtained as much as 20 hours ahead of arrival time. The further into the future a weather forecast is made, the less accurate it will be. To ensure flight safety, airlines use a dispatch and flight following system that allows weather information to be sent to the flight crew by one or more of the following methods:

- very high frequency (VHF) radio
- high frequency (HF) radio
- satellite telephone
- ACARS.

Dispatch can also relay information through air traffic control.

Before departure, the flight crew of ACA088 received the operational flight plan (OFP), which included the weather for the route of flight. The weather information was created by a third party for Air Canada. The enroute portion of it includes plan-view charts that show wind information and air temperature at various flight levels; a profile view for wind information and temperature for the route of flight; pilot reports from Air Canada flights; and significant weather charts. All of these charts are monochromatic to facilitate printing at the many different locations at which Air Canada operates. The OFP did not include any specific turbulence charts or charts that showed mountain wave activity.

The route of flight for a trans-Pacific flight from Asia to North America typically follows a great circle route[7] (or as near to a great circle route as possible), which transverses the polar regions. In winter, the 2 air masses that dominate the North Pacific routes are the arctic and polar air masses. It is not unusual for significant weather charts to show areas of moderate turbulence over this area in the winter months.

The OFP produced for ACA088 deviated from the ideal great circle route by 550 nautical miles (nm) in order to avoid the polar regions, which were susceptible to increased solar flare activity[8] for the time of the flight. The route chosen required the flight to cross a jet stream travelling from south to north over Alaska. ACA088's route had to bisect the jet stream at some point; avoiding it completely would have required an extensive deviation and was therefore impractical. The significant weather chart in the OFP depicted the location of the jet stream and an area of associated moderate turbulence along the route of flight near southern Alaska (Appendix B).

As the flight progressed, the original forecast for moderate turbulence was updated to severe turbulence by SIGMET I2 and then confirmed with PIREPs. The ACA088 flight crew was able to receive this and other weather information throughout the flight.

1.7.2 Jet streams

The mixing zone between air masses can produce significant weather and, for aircraft in cruise, it is often in the form of jet stream turbulence. The jet stream is a narrow band of strong wind caused by the temperature difference between 2 air masses. The jet stream typically features winds of 80 to 120 knots, but the wind can be as high as 240 knots.[9] Clear air turbulence (CAT) associated with the jet stream is often found in the vicinity of the tropopause.[10] For ACA088, the forecast height of the tropopause was between FL290 and FL330. The jet stream encountered in this occurrence was forecast to be 130 knots, with CAT forecast between FL290 and FL330. Information from ACA088's digital flight data recorder (DFDR) recorded a wind speed as high as 120 knots in the vicinity of Anchorage. A few minutes before ACA088 encountered the first event of severe turbulence, the recorded wind speed fell to 70 knots.

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7 A great circle route is the shortest distance between 2 points over the Earth's surface.

8 The Air Canada *Flight Dispatch Manual* (section 5.25.4, "Pre Departure Considerations") states that, for extended twin-engine operations, planned routes should avoid known or expected areas of solar flare activity, cosmic radiation or radio blackouts on polar routings.

9 Federal Aviation Administration, Advisory Circular (AC) 00-30C: Clear Air Turbulence Avoidance (22 March 2016).

10 The tropopause is "[t]he boundary between the troposphere and the stratosphere, where an abrupt change in lapse rate usually occurs. It is defined as the lowest level at which the lapse rate decreases to 2 °C/km or less, provided that the average lapse rate between this level and all higher levels within 2 km does not exceed 2 °C/km." *International Meteorological Vocabulary* (2nd ed.). Geneva: Secretariat of the World Meteorological Organization, 1992. p. 636.

Turbulence can be avoided strategically by planning routes based on forecast conditions, and tactically by altering routes and/or altitudes based on weather updates, cloud formations, PIREPs and by observing changes to the outside air temperature (OAT). The static air temperature (SAT) recorded on ACA088's DFDR showed a 15 °C decrease in temperature in the 25 minutes leading up to the turbulence.

Another condition that can increase the severity of turbulence associated with the jet stream is geographic features. If the jet stream crosses mountainous terrain at right angles, mountain waves and associated severe turbulence are often encountered on the downwind or lee side of the mountains. The effect of the mountains can result in turbulence over a large altitude range.

The routes of flight for ACA088, ACA016, and ACA006 were all in the vicinity of the southern coastal mountains of Alaska. The area covered by SIGMET I2 was located downwind of the area where the jet stream was expected to cross the southern coastal mountains.

With regard to turbulence created by the jet stream in mountainous areas, the FAA advisory circular "Clear Air Turbulence Avoidance" states the following:

> 6.7.2 Jet streams stronger than 110 kts (at the core) have potential for generating significant turbulence near the sloping tropopause above the core, in the jet stream front below the core, and on the low-pressure side of the core.
>
> 6.7.3 Wind shear and its accompanying CAT in jet streams are more intense above and to the lee of mountain wave ranges. CAT should be anticipated whenever the flightpath traverses a strong jet stream in the vicinity of mountainous terrain.[11]

The flight crew of ACA088 were last exposed to information on jet streams and turbulence in training taken in 2011 and 2012.[12] Air Canada dispatchers had also received training on CAT weather and jet streams.[13] Neither training package specifically discussed the conditions produced by jet streams crossing mountainous terrain.

1.8 Aids to navigation

Not applicable.

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11 Federal Aviation Administration, Advisory Circular 00-30C: Clear Air Turbulence Avoidance (22 March 2016).

12 Flight crews receive recurrent training annually, with topics rotating on a 3-year cycle. This means that flight crews receive training on a particular topic (e.g., jet streams and clear air turbulence) once every 3 years.

13 The Air Canada flight crew and dispatcher training programs are extensive and meet Transport Canada requirements under CAR 705.124 (2) and CASS 725.124.

1.9 Communications

Air Canada operates a Transport Canada (TC)–approved Type A operational control system to support its flight operations. The operations centre in Toronto provides weather briefings, load control, and flight following for Air Canada flights. A flight is released when a dispatcher approves the OFP and the pilot-in-command accepts it. OFPs should be issued no later than 90 minutes before the estimated time of departure.

The OFP contains route of flight information, load control information, weather, Notices to Airmen (NOTAMs)[14] and other pertinent information relating to that flight. The captain is responsible for reviewing the information, making corrections or changes in coordination with dispatch and, having accepted the flight plan, briefing the other flight crew and cabin crew members on it.

The Air Canada *Flight Dispatch Manual* states the following:

> The Flight Dispatcher is responsible for planning over routes and at altitudes that meet the requirements of:
>
> - Passenger safety/comfort
> - Air Traffic Control
> - Aircraft operating performance and limitations, such as FMS and non-FMS routes.
> - Terrain Clearance
> - Preferred routes in Canada and the United States, unless it has been otherwise approved by the ATC facility. (CFCF [central flow control function] or YYZ Flow Control)
> - Fuel efficiency, for flights over two (2) hours thirty (30) minutes MFT/R [minimum fuel track with restrictions] or MCT/R [minimum cost track with restrictions] should be considered the primary flight planning method wherever possible
> - Schedule integrity[15]

The *Flight Dispatch Manual* is clear in stating that the cost-saving considerations for determining a route can be "overridden by other operational factors; e.g. turbulence/weather avoidance."[16]

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14 A Notice to Airmen (NOTAM) is a notice distributed by means of telecommunication containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations. Source: Transport Canada, Advisory Circular (AC) 100-001: Glossary for Pilots and Air Traffic Services Personnel (05 June 2016).

15 Air Canada, *Flight Dispatch Manual* (01 December 2014), section 5.15.1, page 135.

16 Ibid., section 5.15.12, page 158.

The section of the *Flight Dispatch Manual* that deals with severe turbulence states the following:

> Severe and extreme turbulence has the potential of seriously damaging the structural integrity of an airliner, apart from the impact on passenger comfort and in-flight service. Careful study of SigWx [significant weather] charts is required and areas of known *severe* turbulence should - if possible – be avoided, by either circumnavigating or selecting a different flight level.
>
> Clear Air Turbulence (CAT) may also be expected when:
>
> - Horizontal wind gradient >40kt/100NM
> - Horizontal OAT gradient >4°/100NM
> - Route is close to the polar side of a jet stream
> - Route is close to an altitude trough of low pressure.
> - Consistent shear rates >7[[17]]
>
> The dispatcher shall be aware of the effects of turbulence and shear rate on aircraft performance at or close to its maximum altitude.
>
> Note:
>
> There are flight planning scenarios, such as the North Atlantic and the North Pacific during the winter, where high shear rates are endemic and cannot reasonably be avoided.
>
> Once the flight is underway the Flight Crew shall be kept up to date of any changes in areas of turbulence and any SIGMETS and/or PIREPS received for those areas shall be forwarded to the Flight Crew with minimal delay.[18]

Air Canada standard operating procedures include a procedure for transmitting pilots' turbulence reports via ACARS. The procedure is contained in the *Boeing B777 Quick Reference Handbook (QRH) – Normal*. Pilot reports are collected and incorporated into the PIREP system used by Air Canada dispatchers and pilots for pre-flight planning and enroute weather decision making. The turbulence report page in the QRH specifies 7 levels of turbulence intensity and 3 levels of turbulence frequency. The flight crews of ACA006 and ACA016 did not use the PIREP feature of the ACARS to report the turbulence. The flight crew of ACA088 used the turbulence scale described in the QRH but sent that information to dispatch in a generic ACARS message.

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17 The shear rate value is determined by evaluating the difference in wind speed and direction for the wind 2000 feet above and below the planned altitude. A larger shear number is to be used as an indicator of the potential for clear air turbulence only. It does not indicate the strength of turbulence. The shear rates indicated on the operational flight plan for ACA088 at HAMND and GULKANA waypoints were level 4.

18 Air Canada, *Flight Dispatch Manual* (01 December 2014), section 5.24.3, page 202.

1.10 Aerodrome information

Not applicable.

1.11 Flight recorders

1.11.1 Digital flight data recorder

The DFDR recorded 25 hours of data, which was of good quality. The DFDR does not record the position of the seat belt switch on the flight deck overhead panel.

The DFDR recorded 2 significant turbulence events from the accelerometers in the aircraft (Appendix C). The severity of turbulence is not a measurement on the DFDR. To determine the severity of turbulence, the time between the changes in acceleration must be taken into consideration. In the first event, the peak vertical acceleration forces recorded were + 1.7 *g*[19] and + 0.14 *g*. In the second event, peak vertical acceleration forces recorded were + 2.21 *g* and -1.32 *g*.

During the second event, aircraft roll varied between 10° and 15° to the left and right. No significant pitch or yaw deviations were recorded. Before the aircraft entered turbulence, the recorded altitude was 33 000 feet. Altitude varied from 32 868 feet to 33 383 feet in the 21 minutes of turbulence. Recorded computed airspeeds fluctuated from 261 to 320 knots, with a momentary stick shaker activation 27 seconds after the start of the first event.

The turbulence encountered by ACA016 was similar to, but not quite as severe as, the turbulence encountered by ACA088 90 minutes later. The DFDR from ACA016 was analyzed by the TSB Laboratory, and when the 2 flights were compared, the acceleration data showed 31 instances where vertical acceleration forces were changing at a higher rate for ACA088 than for ACA016.

1.11.2 Digital cockpit voice recorder

The digital cockpit voice recorder (CVR) installed in ACA088 records 2 hours of information on a loop. ACA088 landed in Calgary 2 hours and 45 minutes after the turbulence event. As a result, the event was overwritten, including any cabin announcements that were made before and during the turbulence. The International Civil Aviation Organization (ICAO) is proposing amendments to Annex 6 to the Convention on International Civil Aviation that would require newly manufactured transport category aircraft over 27 000 kg to be equipped with 25-hour CVRs starting in 2021.

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[19] *g* is the acceleration of gravity or 9.8 m/s^2.

1.12 *Wreckage and impact information*

After ACA088 arrived in Calgary, Air Canada maintenance personnel conducted a severe-turbulence inspection[20] of the aircraft. When they opened the access door to the Number 2 environmental control systems (ECS) bay, a V-clamp[21] fell from the aircraft. Inspection of the V-clamp revealed that the T-bolt band loop had failed, which resulted in the clamp opening and the duct coming off the connection to the flow control shutoff valve. This was determined to be the cause of the BLEED LEAK R message observed by the flight crew on the engine indicating and crew alerting system during the turbulence.

V-clamps are duct-coupling devices used on pneumatic ducting systems and bleed-air components. They are assembled by applying torque to the coupling nut and generating an inward radial force on the clamp. The radial load created by band tension is transmitted as an axial load on the mating flanges due to the wedging action of the V-clamp.[22]

The standard installation procedure for the V-clamp is as follows:

1. Apply an initial torque of 50 to 60 inch–pounds to the coupling nut.
2. Tap the outside of the clamp with a soft-faced hammer, starting at the opposite side of the T-bolt and moving toward the T-bolt. Do this for both sides of the clamp.
3. Re-torque the coupling nut to 50 to 60 inch-pounds, and hammer the outside of the clamp as in Step 2.
4. Repeat until less than a half turn of movement is required to attain the required torque on the coupling nut.

This procedure ensures that the clamp is seated on the flanges of the ducts. Boeing does caution that the clamps should not be tightened until all ducts are aligned correctly, to prevent leaks and damage to the system.[23]

On a properly torqued V-clamp, 0.5 inch or more of thread should be exposed on the T-bolt. On the failed V-clamp, 1.01 inches of thread was exposed. The maintenance instructions do not indicate a maximum number of inches of thread that should be exposed.

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20 The severe-turbulence inspection is described in Chapter 5-51-04 of the Boeing Aircraft Maintenance Manual.

21 V-clamp manufacturer: Voss Aerospace. Voss Part Number: VC1683A-550-A-E. Boeing Part Number – BACC10LE550E

22 Machine Design [online], "Clamping and coupling with V-band retainers," available at: http://machinedesign.com/archive/clamping-and-coupling-v-band-retainers (last accessed 04 January 2017).

23 The Boeing Company, Boeing Service Bulletin 777-21-0145: Air Conditioning – Cooling – Environmental Control Systems Pack Air Supply Ducts Coupling Replacement (Revision 1, 31 March 2011).

The failed V-clamp had been installed on the occurrence aircraft since the aircraft was constructed. On 02 December 2015, the clamp was handled by maintenance personnel as part of interchanging flow control valves for troubleshooting.

After the occurrence, the V-clamp was sent to the TSB Laboratory for further analysis. The examination indicated that the clamp failed as a result of fatigue cracking that had developed in the clamp band. Hoop stresses were found oriented circumferentially along the band. These stresses were generated by tightening the T-bolt during clamp installation or maintenance.

Boeing has had reports of several previous failures of this clamp at this location and adjacent locations resulting in BLEED LEAK L/R and BLEED LOSS L/R messages on the engine indicating and crew alerting system. Boeing performed vibration testing on several failed clamps and was able to duplicate the failure; however, the failures did not initiate at the spot welds as they did in the occurrence aircraft. The testing did show sensitivity to T-bolt location relative to the butterfly valve shaft on the flow-control shutoff valve. As an interim action, Boeing investigated rotating the V-clamp to avoid the area of higher load created by the airflow downstream of the butterfly valve on the flow-control shutoff valve. On 05 January 2015, Boeing published revised maintenance procedures to orient the T-bolt so that it was positioned 90° ± 5° from the centreline of the butterfly valve shaft.

On the occurrence aircraft, the orientation of the failed V-clamp could not be determined because it had fallen out of the aircraft. However, the V-clamp on the Number 1 environmental control system was oriented as per the revised procedure.

In response to previous instances of coupling failure, Boeing had developed a new coupling capable of withstanding greater loads that uses rivets instead of spot welds. The new clamps were introduced in new production in March 2010. On 31 March 2011, Boeing released Revision 1 of Service Bulletin 777-21-0145 to the 777 fleet, informing operators that the stronger clamp was available for installation on old aircraft. According to the service bulletin

> Accomplishment of this service bulletin will prevent premature breakage of couplings on the Environmental Control Systems (ECS) pack air supply ducts. Damaged or broken couplings could cause cooling pack duct leakage for the duration of a flight and possibly result in the loss of an ECS pack or a flight diversion.[24]

Neither V-clamp on the occurrence aircraft had been upgraded to the new, stronger version recommended in the Boeing service bulletin.

1.13 *Medical and pathological information*

Not applicable.

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24 Ibid.

1.14 Fire

There was no fire.

1.15 Survival aspects

Not applicable.

1.16 Tests and research

1.16.1 Seat belts

Information collected during the investigation was consistent with the seat belt sign being on, multiple announcements being made in 3 languages, and flight attendant cabin walk-throughs being completed before the aircraft entered the turbulence.

After landing in Calgary, the aircraft was inspected to verify that the seat belt signage and chimes were operational throughout the cabin and to check the functionality and security of seat belts on the seats where passengers were injured. This involved checking the webbing, the latches and the anchor points to the seat structure. There were no deficiencies in the seat belts noted and no reports of seat belts failing. The seat belt signage and chimes also functioned normally.

1.16.2 Child safety restraint systems

In 2015, following its investigation into the December 2012 low-energy rejected landing and collision with terrain occurrence in Sanikiluaq, Nunavut (TSB Aviation Investigation Report A12Q0216), the TSB found that infants and children who are not properly restrained are at risk of injury and possibly death, and may cause injury or death to other passengers in the event of an accident or encounter with turbulence. It further concluded that, if new regulations on the use of child restraint systems are not implemented, then lap-held infants and young children are exposed to undue risk and are not provided with a level of safety equivalent to that afforded adult passengers. Therefore, the Board recommended that

> The Department of Transport work with industry to develop age- and size-appropriate child restraint systems for infants and young children travelling on commercial aircraft, and mandate their use to provide an equivalent level of safety compared to adults.
>
> **TSB Recommendation A15-02**

In part, TC's response to the recommendation stated

> During fiscal year 2016/2017, the department will initiate an in-depth regulatory examination of the issue. The department would issue a notice that would articulate its intent to determine the most effective means of addressing the recommendation and would then outline its plan and consult industry stakeholders.
>
> Transport Canada will continue to participate in and support international efforts to improve passenger safety, particularly through the ICAO passenger

> Safety Working Group and follow-on activities with a view to harmonization with international partners.

The TSB assessed TC's response in April 2016. In part, the assessment stated that

> The Board is encouraged to note that Transport Canada is planning to take some short and medium term actions, while initiating an in-depth review to address the safety deficiency. However, the Board also notes that the International Civil Aviation Organization (ICAO) has recently published guidance to regulators on implementing regulations for child restraint systems. The availability of this material may be useful in accelerating the regulatory examination.
>
> Although Transport Canada's proposed actions in the medium and long term, may have some benefits, the TSB cannot evaluate if these actions will provide specific solutions that will ensure infants and young children are provided an equivalent level of safety compared to adults.

Therefore, the response to Recommendation A15-02 was assessed as Satisfactory Intent.

1.16.3 Passenger behaviour and seat belt use

1.16.3.1 Comparative studies

Regardless of transportation type, passengers may or may not use seat belts. Even though it has been a legal requirement to wear a seat belt in road vehicles for many years, TC recognizes that the best compliance rate for Canadian vehicle occupants in all seating positions is still only about 95%. The data indicates that, at best, 5% of vehicle occupants still do not wear a seat belt,[25] even with an immediate obvious threat to life and enforced monetary and licence penalties.

In the United States, "while the daytime seat belt use rate for front seat occupants […] is 87 percent, seat belt use is significantly lower in states without primary enforcement laws and for back seat passengers."[26] Further, "in 2013, nearly 50 percent of the more than 20 000 fatally injured vehicle occupants were found to be unrestrained."[27]

In China, where most of the passengers on ACA088 originated, these statistics are even lower.[28] Patterns and trends in urban seat belt use in road vehicles were observed for 95 933 occupants in front and rear seating positions over the years 2005 to 2007 in 2 cities in eastern China, which are adjacent to Shanghai: Nanjing (Jiangsu Province) and Zhoushan (Zhejiang

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25 Transport Canada, TP 15145E, *Road Safety in Canada* (2011).

26 National Transportation Safety Board [online], "Strengthen Occupant Protection," available at: http://www.ntsb.gov/safety/mwl/Pages/mwl4-2016.aspx (last accessed 06 January 2017).

27 Ibid.

28 Routley, V., Ozanne-Smith, J., Li, D., Yu, M., Wang, J., Zhang, J., Tong, Z., Wu, M., Wang, P. & Qin, Y. (2008). "China belting up or down? Seat belt wearing trends in Nanjing and Zhoushan," *Accident Analysis & Prevention*, Vol. 40, Issue 6 (November 2008), pp. 1850–1858.

Province). Seat belt use was around 47% to 49% for drivers, 1% to 9% for front seat passengers and even lower for back seat passengers. These levels declined significantly from year to year. There was common agreement in focus groups in a subsequent study[29] that there should be fines for drivers and warnings for front seat passengers, but that seat belts were not really required in the back seat, regardless of road type. Lack of comfort and inconvenience were cited as principal reasons for not wearing seat belts.

1.16.3.2 Influencing behaviour

A study by the Australian Transport Safety Bureau[30] identified that the overall effectiveness of cabin safety communications is weak.

> Passenger overconfidence, poor perceptions regarding relevance, low passenger compliance, mixed levels of understanding, communications that fail to capture interest, and the presence of destructive social norms were all found to be inhibiting communication effectiveness.

There are 3 main ways in which passengers may be socially influenced to wear their seat belts: conformity, compliance, and obedience.[31,32]

1. **Conformity**. Conformity is a passive form of social influence. If the social norm in a cabin is that seat belts are typically fastened, a passenger may fasten their seat belt only because they feel they should or because they fear social disapproval if they do not. If the social norm is to ignore safety communications, a passenger may decide to remain unrestrained. This latter instance may be driven by the flight experience of the passenger and/or their need to be perceived as a relaxed, confident flyer.[33]

2. **Compliance**. In the absence of any need to conform in (1), a passenger may fasten their seat belt because they voluntarily agree to do so in response to an active request. The action does not require the passenger to actually agree with or believe in the importance of seat belts. Compliance can be affected by the passenger's motivations and/or their perception of the crew requesting the behaviour.

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29 Routley, V., Ozanne-Smith, J., Li, D., Yu, M., Wang, J., Zhang, J., Qin, Y. & Zhao, M. "Focus on seat belt use in China." *Traffic Injury Prevention*, Vol. 11, Issue 6 (December 2010), pp. 578–586.

30 Parker, Andrew D., *Public Attitudes, Perceptions and Behaviours towards Cabin Safety Communications* (Sydney, Australia: Australian Transport Safety Bureau, June 2006).

31 Baron, R.A., and Byrne, D.E. "Social Influence: Changing Others' Behavior." *Social Psychology: Understanding Human Interaction* (6th Edition). Boston: Allyn and Bacon, 1991.

32 Oxford bibliographies [online], "Conformity, compliance and obedience," available at: http://www.oxfordbibliographies.com/view/document/obo-9780199828340/obo-9780199828340-0075.xml (last accessed 04 January 2017).

33 Routley, V., Ozanne-Smith, J., Li, D., Yu, M., Wang, J., Zhang, J., Qin, Y. and Zhao, M. "Focus on seat belt use in China." *Traffic Injury Prevention*, Vol. 11, Issue 6 (December 2010), pp. 578–586.

3. **Obedience**. Regardless of any need to conform (1) or agreement to comply (2), a passenger may fasten their seat belt as a result of an active instruction from an authority figure, which implies a consequence if that order is not obeyed.

If a passenger has no motivation to socially conform (1), honour the crew's request (2), or obey commands (3), they may also be influenced as follows:

4. **Persuasion**. Persuasion is an active attempt to change a passenger's attitudes, beliefs, or feelings and, potentially, their behaviour. This may include education on the risks and hazards of turbulence and the benefits of seat belt use as mitigation. Once persuaded, a passenger may wear a seat belt because they believe it is the best course of action, regardless of whether they are asked to or whether it is legally required.

To increase seat belt and child restraint use in motor vehicles, the U.S. National Transportation Safety Board (NTSB) recommends a 3-pronged approach: legislation and enforcement (which may increase obedience in [3] above), and education (which may influence attitudes and beliefs in [4] above).[34] For the seat belt studies in China, crash video clips on the non-use of seat belts were judged by participants as potentially effective for promoting seat belt use, especially if scenarios were associated with relatively low speeds.[35]

The NTSB has recommended legislation and enforcement for increasing in-car seat belt use.[36] A review of scientific studies relating to seat belt use in the U.S. shows that primary enforcement (ticketing an individual directly for not wearing a seat belt) is more effective at increasing seat belt use compared to secondary enforcement (ticketing an individual only if they have violated another regulation).[37]

1.16.3.3 Safety guidance

The FAA issued a special safety information letter in 2011, highlighting that "turbulence is the leading cause of in-flight injuries" and that "there is a regulatory requirement for seatbelt compliance."[38] The International Air Transport Association (IATA) also issued guidance for

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34 National Transportation Safety Board [online], "Strengthen Occupant Protection," available at http://www.ntsb.gov/safety/mwl/Pages/mwl4-2016.aspx (last accessed 06 January 2017).

35 Routley, V., Ozanne-Smith, J., Li, D., Yu, M., Wang, J., Zhang, J., Tong, Z., Wu, M., Wang, P. & Qin, Y. (2008). "China belting up or down? Seat belt wearing trends in Nanjing and Zhoushan," *Accident Analysis & Prevention*, Vol. 40, Issue 6 (November 2008), pp. 1850–1858.

36 National Transportation Safety Board [online], "Strengthen Occupant Protection," available at: http://www.ntsb.gov/safety/mwl/Pages/mwl4-2016.aspx (last accessed 06 January 2017).

37 Task Force on Community Preventive Services, "Recommendations to reduce injuries to motor vehicle occupants: increasing child safety seat use, increasing safety belt use, and reducing alcohol-impaired driving." *American Journal of Preventive Medicine*, Vol. 21, Issue 4, Supplement 1 (November 2001), pp. 16–22.

38 Federal Aviation Administration, Information for Operators (InFO) 11001: Seat Belt Use and Passenger Injuries in Turbulence (06 January 2011).

turbulence management in 2012,[39] which highlighted the importance of having a proactive seat belt policy for effective turbulence management. This included pre-flight safety information; the use of seat belts during the flight; and the combined use of the seat belt sign, passenger announcements, compliance checks, and flight-crew intervention before and during turbulence. TC subsequently issued a special Advisory Circular in 2014[40] on the use of safety belts while in flight and a recommendation that seat belt announcements should be customized with the anticipated severity and duration of the turbulence, as well as additional information on the risks of turbulence.

There is no requirement in the CARs to provide passengers with any specific on-board information concerning turbulence or its effects.

1.16.4 TSB Laboratory reports

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

- LP038-2016 – Bleed Air Duct Clamp
- HF 014/2016 – Survivability: Aircraft Seat Belt Use

1.17 Organizational and management information

1.17.1 Seat belt sign and passenger announcements

IATA[41] and TC recommend that the seat belt sign only be used for takeoff, landing, and turbulence, to avoid desensitizing passengers to its use. As required by the CARs[42] and Air Canada procedures, the seat belt sign was illuminated on ACA088 before the turbulence event.

Air Canada procedures, based on the CARs, instruct cabin crew to provide the following briefings to passengers:

> 3.1 After Take-Off
>
> 3.1.1 Seatbelt and Smoking Regulations
>
> Ladies and Gentlemen, we encourage you to wear your seat belt at all times […].
>
> 3.2 Turbulence
>
> 3.2.1 Light Turbulence

39 International Air Transport Association, *Cabin Operations Safety Toolkit: Guidance for Turbulence Management*, December 2012.

40 Transport Canada, Advisory Circular (AC) 605-004, "Use of Safety Belts and Shoulder Harnesses On Board Aircraft" (Issue 2, 28 November 2014).

41 International Air Transport Association, *Cabin Operations Safety Toolkit: Guidance for Turbulence Management* (December 2012).

42 Canadian Aviation Regulation 605.25 – General Use of Safety Belts and Restraint Systems, and Commercial Air Services Standard 725.43 – Briefing of Passengers.

> Due to light turbulence, please fasten your seat belt.
>
> 3.2.2 Exceeding Light Turbulence
>
> Due to turbulence, please stow your baggage and fasten your seat belt.[43]

The wording of CAR 605.26 and Air Canada procedures directed to flight and cabin crew concerning seat belt use include words such as "must," "ensure," "required use," and "direct all persons on board." The information relayed to passengers includes softer words such as "we encourage you to wear your seat belt" and "please fasten your seat belts." These announcements are all typically made by cabin crew. Further, instructions for fastening seat belts on the passenger safety card are placed under the heading "for your safety."

As a comparison, CAR 602.06 prohibits smoking on board an aircraft and CAR 602.04 prohibits the consumption of alcoholic beverages not supplied by the operator. These regulations include authoritative words such as "prohibited" and "must." However, unlike messages regarding the use of seat belts, the smoking- and alcohol-related messages relayed to passengers use directive language. Following takeoff, the cabin crew informs passengers that "federal regulations *prohibit* smoking on board," and "Air Canada *does not permit* the use of e-cigarettes." [emphasis added][44]

The Air Canada smoking message is supplemented with a consequence: "passengers may be met by authorities if they do not comply"[45] as well as information that smoke detectors are installed in washrooms. Seat belt announcements do not contain any indication of consequence or enforcement.

As required by the CARs and Air Canada procedures, the cabin crew made a passenger announcement on ACA088 approximately 35 minutes before the initial light turbulence. No additional information on turbulence or its effects was provided either before or during the flight.

1.17.2 Flight crew

The Air Canada *Flight Operations Manual* provides guidance to flight crews and cabin crews on operations in turbulence. This manual categorizes turbulence into 3 categories: light, moderate, and severe. For severe turbulence, the flight operations manual requires the seat belt sign to be turned on, an announcement made to discontinue service, passengers to be informed to take their seats and fasten their seat belts, the in-charge flight attendant to be advised of the anticipated timing, and the in-charge flight attendant to be advised when it is safe to resume duties.

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43 Air Canada, In-Flight Service Publication 378, "On Board Announcements" (30 September 2015).

44 Ibid.

45 Air Canada, In-flight Service Publication 356, "Safety and Emergency Procedures" (01 January 2015).

When an aircraft enters turbulent air, the Air Canada Boeing 777 *Aircraft Operating Manual* requires that, above 25 000 feet, the aircraft be slowed to Mach 0.82 or to 280 knots indicated airspeed, whichever is lower. The DFDR indicated that a speed of Mach 0.82 was input by the flight crew on the mode control panel at about 1900, and the aircraft slowed shortly afterward.

1.17.3 Cabin crew

With regard to turbulence, the Air Canada *Safety and Emergency Procedures Cabin Personnel Manual* reflects the same guidance as the flight operations manual and requires the cabin crew to stop service, make announcements, ensure that passengers remove infants from bassinets, stow equipment and hot liquids, check for security in the cabin, advise the in-charge flight attendant that the cabin is secure, sit down and fasten seat belt and shoulder harnesses, and not get up until the in-charge flight attendant states that it is safe to move about the cabin.[46]

For the different intensities of turbulence, Air Canada cabin crews are given the following flight crew and cabin crew actions to be taken:

1. In-flight crew rest: *Seat belts must be fastened at all times in crew rest areas, including when lying down.*
2. Turbulence (light): *Select seat belt sign on* > *Make announcements* > *Conduct visual checks (ensure seat belts are fastened). Service may be conducted.*
3. Turbulence (moderate or severe): *Select seat belt sign on* > *Discontinue service* > *Make announcements. Conduct visual checks (ensure seat belts are fastened). Sit down and fasten seat belt and shoulder harness.*
4. Turbulence (moderate unanticipated): *Select seat belt sign on* > *Discontinue service* > *Make announcements* > *Conduct visual checks (ensure seat belts are fastened). Sit down immediately. PA should be a directive, e.g. "FAs and passengers be seated immediately with your seat belts fastened."*
5. Turbulence (severe unanticipated): *Select seat belt sign on* > *Secure carts* > *Make announcements* > *Sit down immediately. Captain PA should be a directive, e.g. "FAs and passengers be seated immediately with your seat belts fastened."* [No compliance checks].
6. *In-charge FA will direct passengers to return to their seat and fasten seat belt.*
7. *Crew members must sit down and fasten their seat belts immediately when turbulence levels are such that their personal safety is at a risk.*[47]

Airline crews have limited means to compel passengers to comply with instructions to secure their seat belt. The only legal recourse for non-compliance with seat belt instructions is in

[46] Ibid.

[47] Ibid.

CAR 705.175(*b*)(iii), which relates to passenger interference, or non-compliance, with crew members' directions. If there is a "repeated failure of a passenger to comply with a crew member's safety instructions," then the passenger may be subject to prosecution by TC under section 7.41 of the *Aeronautics Act*.

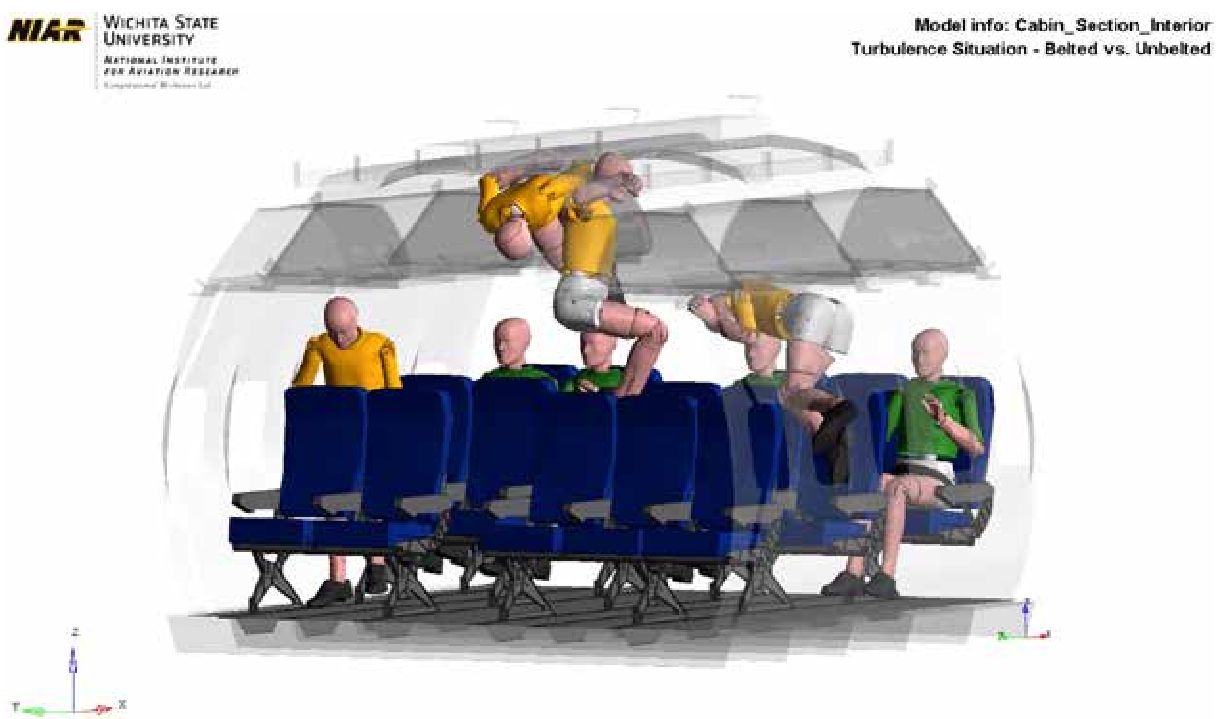
1.18 Additional information

Not applicable.

1.19 Useful or effective investigation techniques

The TSB worked with the National Institute for Aviation Research's Computational Mechanics Lab to develop an animation based on a portion of the acceleration data collected by ACA088's DFDR. The acceleration forces recorded were used to depict, in a generic aircraft cabin, what effects the forces associated with severe turbulence would have on passengers who were wearing seat belts and those who were not (Figure 3).

Figure 3. Screen capture of animation demonstrating the effects of severe turbulence on restrained passengers (green) and unrestrained passengers (yellow) in an aircraft, based on acceleration data collected from ACA088's digital flight data recorder



The 12 passengers in the animation were represented by digital versions of the Hybrid II 50th Percentile Anthropomorphic Test Device (ATD). The ATDs represent the size and weight of an average adult male with range of motions, centre of gravity, and sub-assembly masses determined by anthropometric studies. Each ATD had a modelled weight of about 170 pounds.

The cabin was modelled on a generic single-aisle transport category aircraft with a seat pitch of 34 inches. The cabin was rendered with common commercial aircraft seats with a single nylon webbing seat belt.

The entire model (12 ATDs and interior components) contained 1.5 million elements. To create an animation in a reasonable time and cost, all elements were modelled as rigid components. As a result, all the contact/impact loads are very noisy and could be unrealistic due to the rigid-to-rigid contact definition. However, their movement in the cabin environment is realistic based on the vertical and lateral acceleration data used.

2.0 Analysis

2.1 Flight planning

Planning routes and altitudes for long-haul flights presents many challenges, including weather forecasts. Forecast reliability decreases with each additional hour of flight time, especially forecasts more than 12 hours into the future.

For Air Canada flight 088 (ACA088), the flight crew's weather package indicated an area of moderate turbulence, which was usual for this route of flight at that time of year. There was no information in the pre-departure weather package that would have prompted the captain to consider a different route.

2.2 Turbulence

ACA088 entered an area of moderate to severe turbulence that was caused by the jet stream traversing the southern coastal mountains of Alaska. The 2 encounters of severe turbulence were consistent with the jet stream flowing over 2 prominent mountainous areas located 85 nautical miles (nm) and 191 nm east-northeast of Anchorage.

The significant meteorological information (SIGMET) I2 forecast severe turbulence through a large altitude range (flight level [FL] 260 to FL400) in an area where mountain wave activity could be created by the jet stream. The flight crew of Air Canada flight 016 (ACA016), which was 90 minutes ahead of ACA088, concluded that FL330 was likely the best altitude for flight through this area. This conclusion was made when ACA016 happened to be at this altitude and in the area between the prominent mountain ranges, where there was less mountain wave activity created by the jet stream.

The acceleration forces encountered resulted in passengers who were not wearing seat belts contacting various furnishings and surfaces in the cabin causing a variety of injuries, including 1 serious injury.

Air Canada flight 006 (ACA006), the Boeing 787 at FL390 that was 30 minutes ahead of ACA088 on the same route of flight did not encounter severe turbulence because its operational capabilities allowed it to fly significantly higher than the tropopause.

2.2.1 Air Canada training

When determining the best route and altitude through the area of potential moderate to severe turbulence, neither Air Canada dispatchers nor the flight crew of ACA088 fully appreciated the combined effects of the jet stream and the mountainous terrain. Training material given to both pilots and dispatchers did not contain information on the increased likelihood of turbulence through a wide range of altitudes when jet streams cross mountainous terrain.

If training material does not contain complete information pertaining to all of the factors that contribute to turbulence, then there is a risk that the best course of action will not be taken.

2.2.2 *Flight following and pilot reporting*

Once a flight is en route, Air Canada dispatch monitors the weather for the flight and communicates any significant changes, as necessary. In this occurrence, the forecast for moderate turbulence became a forecast for occasional severe turbulence (as indicated in SIGMET I2), and this was confirmed once ACA016, which was 90 minutes ahead of ACA088, encountered turbulence at FL350 and made a pilot weather report (PIREP).

This information was relayed to ACA088 in time for the flight crew to determine how best to avoid the turbulence. The information the flight crew had received from Air Canada dispatch and Anchorage Air Route Traffic Control Centre (ARTCC), as well as the visual cues, suggested that FL330 was the best ride. As a result, and because they had not received any course deviation information, the flight crew decided that FL330 and the current course was the best option. With a view to preventing injury, the augment first officer ordered the cabin and flight deck to be secured ahead of the turbulence.

The information from ACA016 about a more southerly route being a possible mitigation for the severe turbulence was never relayed to ACA088's flight crew. Whether this southerly deviation would have been smoother is unknown; however, if flight crews and dispatchers do not receive all pertinent information relating to flight conditions, optimal decisions on a course of action may not be made, increasing the risk of exposure to adverse conditions.

In this occurrence, none of the flight crews used the turbulence-reporting feature on the position report page of the aircraft communications addressing and report system (ACARS). The reporting system has several scales that allow a detailed report to be made, which is then captured by the flight planning system for future use. Neither the flight crew of ACA088 nor the Air Canada dispatcher fully appreciated the level and intensity of the turbulence. A detailed turbulence report, such as the one provided by the ACARS, could have helped them understand the severity and duration of the turbulence. If systems such as ACARS are not utilized to their full capacity, then there is a risk that more detailed information about flight conditions will not be available.

2.2.3 *Cabin preparation*

With approximately 35 minutes' notice, the cabin crew of ACA088 began to secure the cabin in preparation for turbulence. Due to the cabin crew's efforts, approximately 94% of the passengers were not injured and no flight attendants were injured. However, 21 (6%) of the passengers were not wearing their seat belts and were consequently injured.

Seat belts were visually checked by cabin crew. However, on ACA088, this was done in low-light cabin conditions, which may have impaired detection of unfastened seat belts. Seat belts are generally dark-coloured and difficult to see in low light. Furthermore, several passengers were using blankets, which may have hidden the seat belts entirely.

If cabin lighting is not sufficiently bright, then there is a risk that cabin crew members will miss unfastened seat belts due to the lack of contrast of the seat belt material and concealment by blankets.

2.2.4 *Passenger seat belt compliance*

It was not possible to determine with certainty how many passengers were not wearing their seat belts. The degree of acceleration forces the aircraft and passengers experienced during the severe turbulence made it likely that anyone unrestrained would have been injured.

The following reasons for non-compliance with the seat belt instructions were identified by the investigation:

- Context: the cabin was in night mode, shades were down, and people were trying to sleep, be comfortable and lie down.
- Passenger: a passenger in business class needed to use the washroom.
- Perceived risk: the cabin was dark and calm, reducing the expectation of injury.
- Perceived hazard: passengers did not know about or have experience with the effects of turbulence.
- Perceived consequence: passengers did not perceive the consequences of not wearing a seat belt.

The various influences on the passengers' decisions to not wear their seat belts are discussed below.

2.2.4.1 *Conformity*

Cultural attitudes toward seat belt use in road vehicles may influence seat belt use in aircraft: i.e., infrequent seat belt use may create a norm of non-compliance. Even if the perceived social norm is that a seat belt should be worn, there are no seat belt lights or alarms to indicate to other passengers that someone is not wearing a seatbelt, and there are no perceived secondary effects on other passengers. Consequently, social disapproval is easily avoided. This is in contrast to smoking, where non-compliance with smoking bans does affect other passengers, is immediately obvious, and social disapproval is typically imminent.

If there is no visual or audible indicator associated with not wearing a seat belt, then there is an increased risk of non-conformity with respect to seat belt use.

2.2.4.2 *Compliance*

Passengers are more likely to pay attention to and comply with cabin safety information if they perceive it as relevant. Before the turbulence, the following conditions were present:

- cabin crew were still moving about the cabin, suggesting to passengers that the turbulence was not imminent;
- approximately 35 minutes had passed from when turbulence preparations had started to when the severe turbulence began;
- passengers were 8 hours into the flight and in the middle of their sleep routine; and
- the cabin lights were turned down low for sleeping.

These factors may have influenced passengers' perceptions of an imminent risk and, in turn, the probability of initial and sustained compliance. Transport Canada advises that seat belt announcements should be customized with the anticipated severity and duration of the turbulence.

If seat belt announcements do not contain sufficient detailed information on anticipated turbulence, then there is a risk that passengers will not immediately comply and maintain compliance with an instruction to fasten seat belts.

2.2.4.3 Obedience

In its guidance on turbulence management, the International Air Transport Association states that passengers tend to respond more to seat belt announcements when they are made by the flight crew, as opposed to the cabin crew.[48]

In Air Canada's guidance material for unanticipated severe turbulence, the captain is required to provide a directive public announcement to flight attendants (FA) and passengers: for example, "FAs and passengers be seated immediately with your seat belts fastened."

In this occurrence, because the turbulence was anticipated, announcements were made by the cabin crew as per Air Canada's procedures. However, these announcements used less directive language than the language used by the flight crew. If safety announcements made by cabin crew do not use language that conveys the expectation of compliance, there is a risk that passengers will perceive these announcements to be less authoritative, which may result in non-compliance.

2.2.4.4 Persuasion

Passengers' attitudes and behaviours are strongly influenced by their ability to assess risk and their confidence in their own abilities to respond in an emergency. Once on board an aircraft, passengers are not provided with any specific information or education on the probability or effects of turbulence. And when the aircraft is in cruise flight, there is no immediate sensory feedback to indicate risk to the passenger, especially when the surrounding environment is dark and calm. This is in contrast to both takeoff and landing, which are accompanied by physical and visual sensory information that enables the passenger to perceive yaw, pitch, speed and potential impact forces—similar to those experienced when travelling in a car. Furthermore, passengers are not provided any information about the potential injury they could cause to other passengers if they are unrestrained in the cabin during turbulence.

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[48] International Air Transport Association, *Cabin Operations Safety Toolkit: Guidance for Turbulence Management* (December 2012).

The U.S. Federal Aviation Administration uses business-card-sized cards to provide information to passengers about the risks of turbulence. Transport Canada advises customizing seat belt announcements with additional information on the risks of turbulence.

If passenger safety briefings lack information on the effects turbulence can have on individual passengers, their possessions, and on others, then there is a risk that it will reduce the probability of seat belt use.

2.2.4.5 *Enforcement*

Another influence on passenger compliance is the notion of enforcement. The language used in messages from cabin crew can influence a passenger's perception of the consequences that may be incurred due to non-compliance.

Messages related to smoking on board aircraft are clear that there will be serious consequences should a passenger choose to smoke. In contrast, the language used for messages related to seat belt usage is less assertive and does not convey any sense of consequences should a passenger choose not to wear their seat belt.

Airline crews have limited means to compel passengers to comply with instructions to fasten their seat belt. If passengers do not expect consequences and enforcement for non-seat belt use, passengers may not perceive the use of seat belts as mandatory, when so directed.

2.2.4.6 *Combined approach*

Seat belt use is affected by the combined issues associated with conformity, compliance, obedience and persuasion. Addressing only one of these factors is unlikely to improve usage.

Fear or risk may be ineffective as the only persuasive tool, as the act of boarding an aircraft itself implies that the passenger has already established a perception that air travel is safe. However, most passengers believe that, if an accident occurs, survivability is low. This combination results in the perception by passengers that a hazardous scenario is unlikely, but that, if one does occur, they have little control over the consequences. This may affect attitudes toward safety communications and safety behaviours in the cabin.

A more recent review of behaviour indicates that the probability of compliance (which is voluntary) or obedience (which is mandatory) relies on many factors other than the actual request or instruction, such as the behaviour being sacrificed (sitting comfortably without a belt) and the perceived effect on the larger group (social responsibility). Because long-haul flights affect personal welfare in terms of comfort and sleep deprivation, instruction may not be sufficient to overcome these basic needs. Similarly, because individual seat belt use is not detectable to others and passengers are not informed of the hazard they become to others while unrestrained, instruction may not be sufficient to overcome this lack of perceived social responsibility.

Studies into car seat belt use indicate that education and publicity alone do not achieve reliable passenger behaviour, without supplementation of authority and enforcement.

If the approach to improve seat belt use does not include an understanding of the cultural and social norms of passengers, education to increase awareness, improved attitudes and an associated enforcement program to ensure corresponding changes in behaviour, then there is a risk that passengers will not wear their seat belts.

2.3 V-clamp installation

Service experience indicated that the original V-clamps on the air conditioning ducts were sensitive to orientation. Proper installation of the V-clamp is critical. Ducting tubes and components to be joined must be aligned with each other before installing the coupling. Flanges must also be oriented correctly before the coupling is installed, for good joint performance.

Results of the V-clamp examination indicated that the final overstress fracture of the clamp band likely happened during the turbulence event. The clamp failed as a result of fatigue cracking developed in the clamp band. These stresses were generated by tightening the T-bolt during clamp installation or maintenance.

Damaged or broken couplings could cause leaks in the air conditioning system duct for the duration of a flight and possibly result in the loss of an environmental control system pack or a flight diversion. If V-clamps are not installed using the proper procedure and torque, then there is a risk of V-clamp failure and subsequent partial loss of an air conditioning system and cabin pressurization.

3.0 Findings

3.1 Findings as to causes and contributing factors

1. Air Canada flight 088 entered an area of moderate to severe turbulence that was caused by the jet stream traversing the southern coastal mountains of Alaska.

2. The acceleration forces encountered resulted in passengers who were not wearing seat belts contacting various furnishings and surfaces in the cabin causing a variety of injuries, including 1 serious injury.

3.2 Findings as to risk

1. If training material does not contain complete information pertaining to all of the factors that contribute to turbulence, then there is a risk that the best course of action will not be taken.

2. If flight crews and dispatchers do not receive all pertinent information relating to flight conditions, optimal decisions on a course of action may not be made, increasing the risk of exposure to adverse conditions.

3. If systems such as an aircraft communications addressing and report system are not utilized to their full capacity, then there is a risk that more detailed information about flight conditions will not be available.

4. If cabin lighting is not sufficiently bright, then there is a risk that cabin crew members will miss unfastened seat belts due to the lack of contrast of the seat belt material and concealment by blankets.

5. If there is no visual or audible indicator associated with not wearing a seat belt, then there is an increased risk of non-conformity with respect to seat belt use.

6. If seat belt announcements do not contain sufficient detailed information on anticipated turbulence, then there is a risk that passengers will not immediately comply and maintain compliance with an instruction to fasten seat belts.

7. If safety announcements made by cabin crew do not use language that conveys the expectation of compliance, there is a risk that passengers will perceive these announcements to be less authoritative, which may result in non-compliance.

8. If passenger safety briefings lack information on the effects turbulence can have on individual passengers, their possessions, and on others, then there is a risk that it will reduce the probability of seat belt use.

9. If passengers do not expect consequences and enforcement for non-seat belt use, passengers may not perceive the use of seat belts as mandatory, when so directed.

10. If the approach to improve seat belt use does not include an understanding of the cultural and social norms of passengers, education to increase awareness, improved attitudes and an associated enforcement program to ensure corresponding changes in behaviour, then there is a risk that passengers will not wear their seat belts.

11. If V-clamps are not installed using the proper procedure and torque, then there is a risk of V-clamp failure and subsequent partial loss of an air conditioning system and cabin pressurization.

3.3 Other findings

1. The Air Canada flight 088 flight crew's decision to secure the cabin and reduce to turbulence penetration speed contributed to preventing significant numbers of injuries in the cabin and potential damage to the aircraft.

4.0 Safety action

4.1 Safety action taken

4.1.1 Air Canada

The following safety actions have been completed in response to this occurrence.

On 04 April 2016, Air Canada commenced a program to replace V-clamps on the B777 fleet in accordance with Boeing Service Bulletin 777-21-0145R01, "Air Conditioning – Cooling – Environmental Control Systems Pack Air Supply Ducts Coupling Replacement."

Air Canada Flight Dispatch has issued ACA Standard Operating Procedures (SOP) Bulletin #16/16R1: SUBJECT FDM 6.3.3 *Flight Watch Tasks and Responsibilities*. This bulletin includes the following specific guidance to dispatchers:

> Note: When actual/ known turbulence is reported at moderate or higher the Dispatcher shall offer an alternative route / altitude as applicable and also advise the Chief Duty Dispatcher of turbulence reported greater than moderate.[49]

Air Canada Flight Operations has issued Flight Operations Bulletin EFB 16-09R EFB DIGEST: "GETTING THE MOST OUT OF WSI OPTIMA FOR TURBULENCE MITIGATION." This 6-page bulletin provides details on how to avoid clear air turbulence. Detailed information is also provided about the tools available on the company-issued iPad to support the flight crew in avoiding turbulence.

Section 8.18.2.1 of the Air Canada *Flight Operations Manual*, "Clear Air Turbulence," has been approved for incorporation into the April 2017 amendment. The update includes information on where clear air turbulence can be found, including mountainous terrain, and avoidance techniques.

This report concludes the Transportation Safety Board's investigation into this occurrence. The Board authorized the release of this report on 04 January 2017. It was officially released on 20 February 2017.

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

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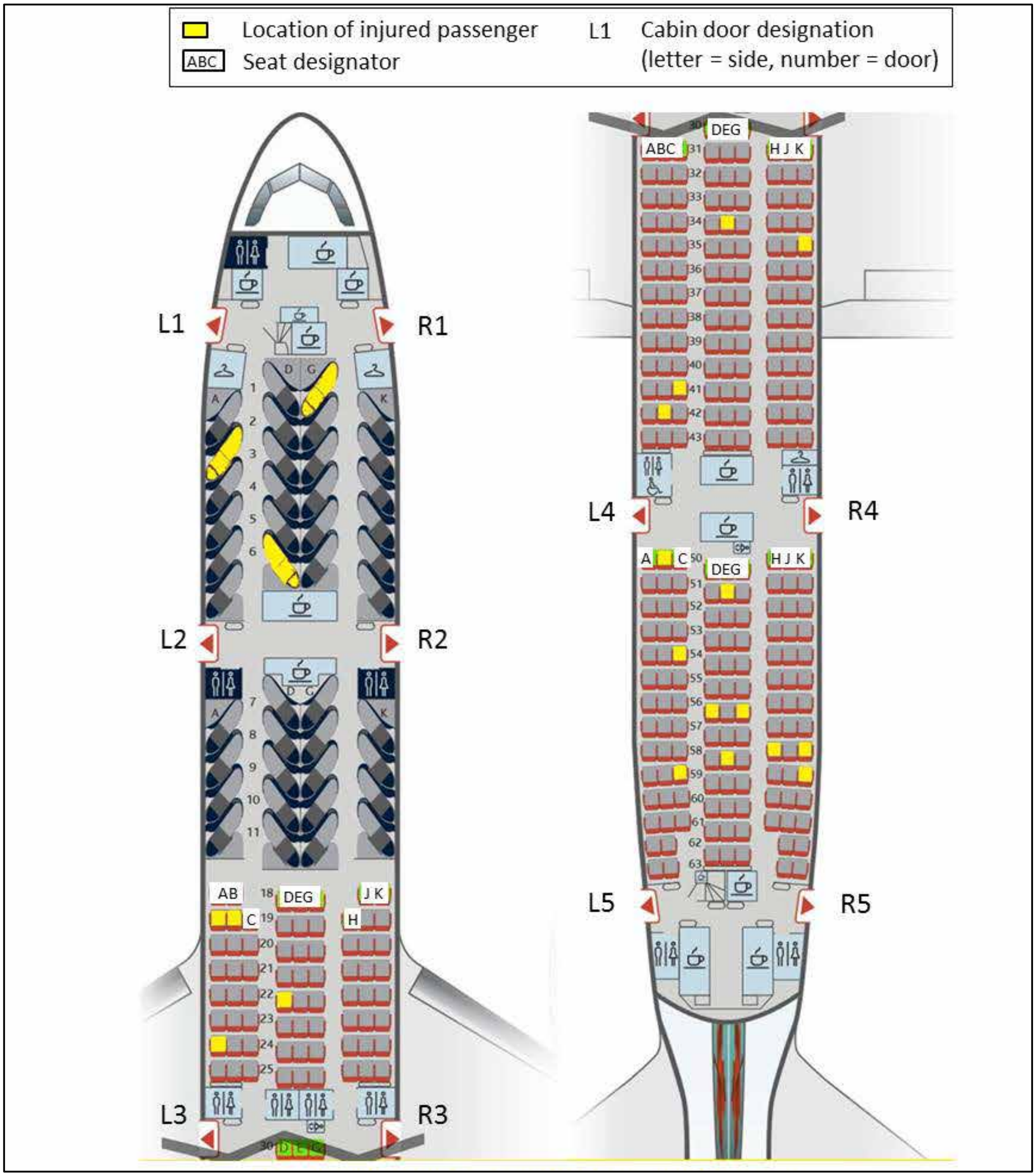
49 Air Canada, Flight Dispatch, ACA SOP Bulletin #16/16R1: SUBJECT FDM 6.3: Flight Watch Tasks and Responsibilities (19 July 2016).

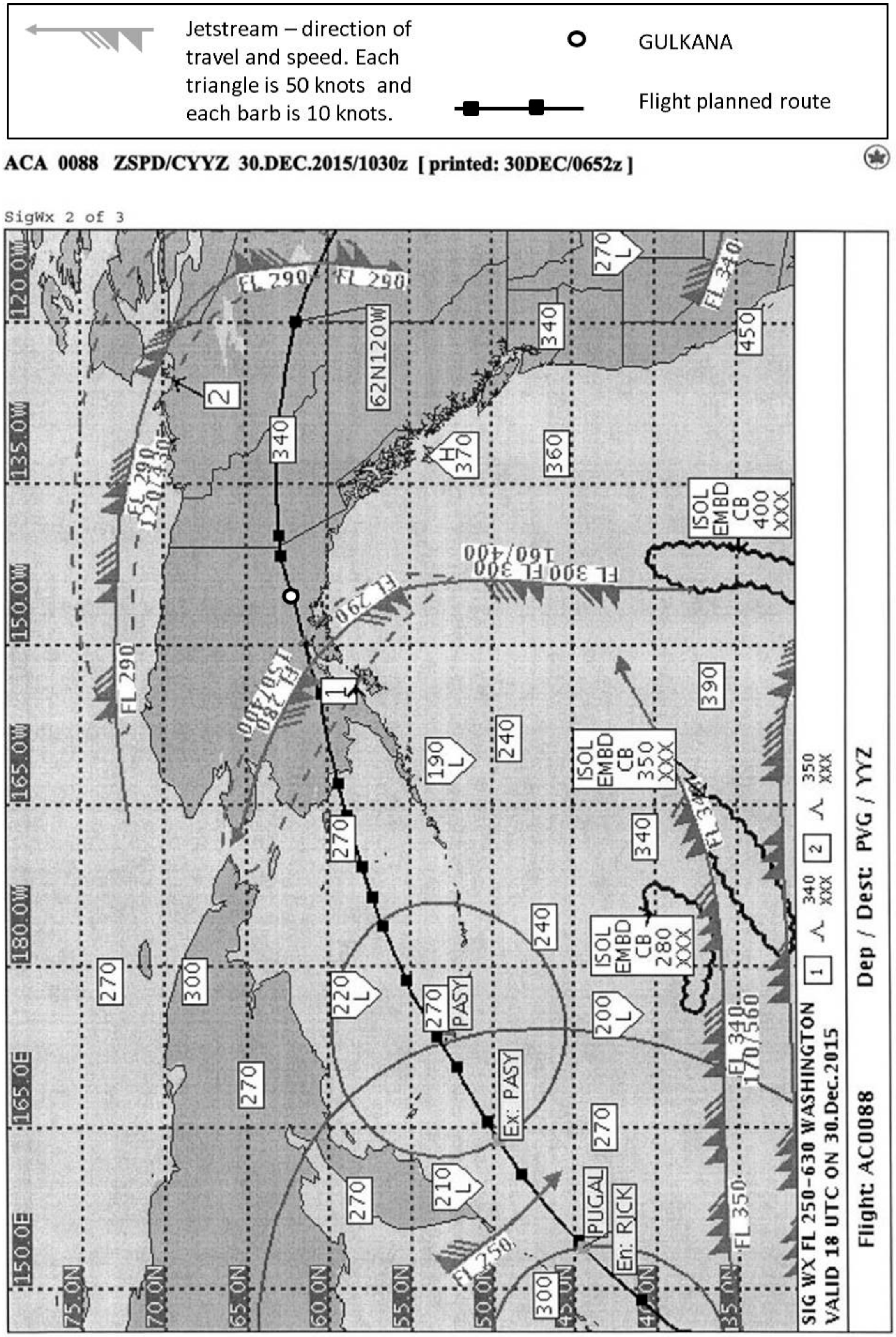
Appendices

Appendix A – Cabin layout and door location



Source: Air Canada, with TSB annotations

Appendix B – Air Canada significant weather chart



Source: Air Canada

Appendix C – Digital flight data recorder plot for Air Canada flight 088