Continental Airlines, Inc.
Submission

Aircraft Accident
Boeing B-737-524, N18611
Denver International Airport (DEN)
Denver, Colorado
December 20, 2008

NTSB ACCIDENT INVESTIGATION
DCA09MA021

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1. Executive Summary

What began as a seemingly normal takeoff quickly became an abnormal flight management challenge to the crew of Flight 1404. When the tower cleared Flight 1404 for takeoff at 1817:26 MST,[1] the crew had the following wind information:

- ATIS reported winds of 270 degrees at 11 knots with no gusts.
- Tower advised the crew of winds of 270 degrees at 27 knots at the time of the takeoff clearance.[2]
- The crew only had these two sources of wind direction and velocity and had no knowledge that any gusts were occurring. As a result, the crew reasonably believed the wind was well below Continental's 33-knot crosswind component guideline.

At 1817:40, Flight 1404 began its takeoff roll, which proceeded normally until 1818:08 when the Captain input full right rudder (26.7 degrees) and the aircraft corrected approximately 0.6 degrees back to the right. While the rudder effectively corrected the plane's track towards the centerline the first time that the Captain used full right rudder, a few seconds later, at 1818:12, another significant right rudder input (23.4 degrees) did not stop the plane's weathervaning or yawing to the left. Instead, the plane continued to yaw rapidly to the left, and departed the left side of the runway at approximately 1818:17.[3]

Denver International Airport (DEN) has a sophisticated Low-Level Windshear Alert System (LLWAS) with 32 sensors. LLWAS sensor #2 is located east of Runway 34R near the south or approach end of the runway. LLWAS sensor #3 is located east of Runway 34R near the north or departure end of the runway.[4] The wind provided by the tower controller to Flight 1404 was obtained from LLWAS sensor #3.[5] However, the tower controller did not provide the crew with available wind information from LLWAS sensor #2, the sensor closest to the aircraft that displayed winds of significantly higher velocity.[6] In addition, LLWAS sensor #2 recorded gusts averaging 40 knots beginning before the takeoff clearance, but no report of gusts was ever given to the crew.[7] Further, the NTSB estimated wind extraction showed a peak gust of 45 knots

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[1] All times used in this Submission are Mountain Standard Time unless otherwise stated. Further, all times are derived from the FDR, which are presumed to be correct.

[2] The crosswind component, therefore, was 25 knots. Continental Airlines 737 Flight Manual, Section 5, page 141.

[3] Airplane Performance Study, page 2, note 1.

[4] See Figure 1, page 10.

[5] Air Traffic Control Factual Report, page 8.

[6] Meteorological Factual Report; Table 4, page 9; see Table 1, page 5.

[7] Meteorological Factual Report; Table 3, page 10; see Table 2, page 11.

about the same time the second significant rudder input was returning to a near neutral position.[8] This estimated wind extraction was predicated on the rudder being effective.

Post-accident meteorological analysis shows that conditions were favorable to the formation of mountain waves and that extremely strong gusts moved over Runways 34L and 34R at the time of the accident. The behavior of the aircraft in response to large rudder inputs was consistent with the meteorological analysis. The aircraft responded as the Captain expected to the first large rudder input, but within a few seconds the aircraft encountered a very strong crosswind gust that rendered the aircraft unresponsive to significant rudder input.

Table 1 depicts the LLWAS wind sensor information for LLWAS Sensor #2 (WS2) and LLWAS Sensor #3 (WS3) that was available to the air traffic controllers immediately before the accident. The numbers appearing in red are the wind speeds from WS2 that are at or above Continental's 33-knot crosswind component guideline, while the highest wind speed from WS3 is only 28 knots.

Pre-Takeoff Clearance Winds

Time MST	WS2	WS3
1814:12	29	23
1814:22	30	23
1814:32	27	25
1814:42	29	25
1814:52	30	24
1815:02	30	26
1815:12	**34**	22
1815:22	29	24
1815:32	26	23
1815:42	30	25
1815:52	29	23
1816:02	30	24
1816:12	**36**	25
1816:22	**40**	23
1816:32	**38**	25
1816:42	**38**	26
1816:52	**35**	28
1817:02	32	27
1817:12	**35**	26
1817:23	**33**	25
1817:26	*Takeoff clearance*	

Table 1.

When two LLWAS sensors near the same runway display dramatically different wind conditions, common sense suggests that both sets of values, or at the very least, the highest values, be provided to the crew when issuing a takeoff clearance, especially when the sensor displaying the higher wind speed is closest to the plane's location. Had the crew known of the actual current wind conditions as displayed on sensor #2, which exceeded Continental's 33-knot guideline, they would have waited until wind conditions improved or requested a different runway.

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[8] Airplane Performance Study, page 5.

The Captain of Flight 1404 was confronted with an unusual and totally unexpected set of environmental circumstances that presented extraordinary flight management challenges. Even though the Captain did not receive accurate wind conditions and the plane's rudder failed to respond as expected, he was able to mitigate a potentially disastrous situation by keeping the aircraft upright after its departure from the runway.

2. Factual Information

2.1. History of Flight

Flight 1404 was scheduled to depart DEN for George Bush Intercontinental Airport (IAH) at 1800 on the evening of December 20, 2008. The flight crew arrived at the airport at approximately 1700, and met at the gate shortly after the airplane arrived. The Captain and the First Officer performed their usual preflight duties, and after the cabin crew closed the airplane's doors, the First Officer contacted ramp control and received a clearance to push back from the gate for a west taxi, and the flight pushed back at 1804.[9] Ice and snow were visible on the ramp, so the Captain started both engines and turned the engine and wing anti-ice systems on. The flight was cleared to taxi to 3W, and the Captain began to taxi the airplane. Approaching 3W, the First Officer contacted ground control and received clearance to taxi to Runway 34R, via taxiway F.

The flight crew heard ground control tell the flight in front of them that Automated Traffic Information System (ATIS) Sierra was current. The flight crew already had information Sierra, which reported winds at 270 degrees and 11 knots. They continued to taxi on taxiway F toward Runway 34R. The Captain did not notice any buffeting of the airplane from wind during the taxi.[10]

As the airplane approached Runway 34R, the flight crew performed the before takeoff checklist and contacted the tower. A Raytheon B-1900 was on the runway ahead of them, awaiting a takeoff clearance. After that aircraft departed, the tower instructed Flight 1404 to taxi into position and hold on the runway. The runway appeared to be clear of snow and ice, so the Captain deselected the engine and wing anti-ice systems but left the engine igniters on, as is standard procedure. The Captain positioned the airplane on the runway, and the flight crew waited for two or three minutes. The runway lights and all of the airplane's lights were on, and runway visibility was excellent.

The tower contacted the flight crew, informed them that winds were 270 degrees at 27 knots, and cleared them for takeoff:[11]

1817:26 TWR	Continental fourteen zero four wind two seven zero at two seven turn right heading zero two zero runway three four right cleared for takeoff.

[9] CVR Factual Report, page 12-25.

[10] Operations/Human Performance Group Chairman's Factual Report, Attachment 1, page 4.

[11] CVR Factual Report, page 12-36.

1817:34	RDO-2	Heading zero two zero cleared for takeoff runway three four right Continental fourteen zero four.
1817:37	CAM-1 (Captain)	Alright.
1817:38	CAM-1 (Captain)	Left cross wind twenty ah seven knots.

The Captain stated in his interview that this "raised their ears" because it was higher than the wind reported on the ATIS.[12] The crosswind given was still within Continental's 33-knot crosswind component guideline.

The Captain was the Pilot-Flying and began a reduced-power takeoff. He first pushed the thrust levers up to achieve 40% N1, then increased power to 70% N1. He noticed a difference in the thrust being generated by the two engines, but the two engines matched as he increased N1 to 90%. After verifying this, he pressed the TOGA button and called out, "check power." The First Officer responded that thrust was set at 90.9% N1. The Captain applied a left control wheel crosswind correction, and used variable right rudder to keep the airplane aligned with the runway centerline during the takeoff roll. He recalled that it felt at first like a "normal crosswind takeoff."

The Captain recalled that as the airplane was getting up to speed it suddenly yawed to the left, as if hit by a "massive gust of wind," or as if the tires had hit a patch of ice and lost traction. He recalled using full right rudder but seeing the airplane continue to veer left. The First Officer recalled that as airspeed was increasing from 87 to 90 knots, he looked up from the airspeed indicator he was monitoring and saw the airplane drifting left off the runway centerline. He thought the Captain was correcting back to the right, but the airplane suddenly yawed 30 to 45 degrees to the left. It appeared to the First Officer as if there was "zero directional control." He recalled feeling the rudder pedals with his feet and he believed the Captain was applying full right rudder.

The Captain further recalled facing the edge lights on the left side of the runway. He believed the airplane was going to exit the left side of the runway and, as a last resort, he reached down with his left hand and grabbed the tiller for a second or two. He attempted to steer the airplane back onto the runway using the tiller, but this did not work so he put his left hand back on the yoke.

The Captain also recalled using right control wheel to keep the wings level as the airplane departed the left side of the runway. He said that he did this because he thought the ground next to the runway sloped down and he feared that the aft end of the fuselage would slide down that incline and cause the airplane to "tumble on its side." After the airplane had completely exited the runway, the Captain said "reject" and tried to deploy the thrust reversers. He recalled, however, that he was unable to deploy the reversers because the ride was very rough.[13]

Runway 34R was inspected before and immediately after the accident.[14] The runway surface was reported as bare and dry.[15] Approximately 1-6 inches of patchy snow was on the shoulders

[12] Operations/Human Performance Group Chairman's Factual Report, Attachment 1, page 2.

[13] Operations/Human Performance Group Chairman's Factual Report, Section 1.1, page 4.

[14] According to the Survival Factors Factual Report, Section 5.0, page 29, ARFF conducted the inspection immediately after the accident at 1821.

[15] Survival Factors Factual Report, Section 5.0, page 29.

of the runway and in the safety areas. Airport operations conducted a runway friction test soon after the accident;[16] the recorded test results showed *mu* values exceeding 1.0, indicating a normal/good surface condition.

2.2. Crew Qualification Information

2.2.1. The Captain[17]

The Captain had accumulated 13,100 hours flying time, 6,300 in the B-737 aircraft including 1,015 as Pilot-In-Command in the B-737. He was certificated in accordance with applicable regulatory requirements.

FAA certification records revealed no history of failures or re-tests for FAA airman certificates and ratings. A search of FAA records revealed no FAA enforcement actions, incidents, or previous accidents.

The Captain began his flight career with the United States Navy in 1979, until the end of 1993, when he left the Navy with an honorable discharge and the rank of Lieutenant Commander. During that time, he flew several different types of aircraft, and had five deployments with nearly 600 carrier landings. He spent 3.5 years on aircraft carriers and logged 200 carrier landings at night. He logged about 3,200 hours while in the Navy and received several awards during his service.

The Captain has been with Continental since 1997 and has consistently received positive performance reviews. During this time, he has logged approximately 60 to 80 flights into and out of DEN.

2.2.2. The First Officer[18]

The First Officer had accumulated 7,500 hours flying time, 1,500 as Second-In-Command in the B-737 aircraft. He was certificated in accordance with applicable regulatory requirements.

FAA records revealed no history of any failures or re-tests for FAA airman certificates and ratings, and no evidence of enforcement actions, incidents, or previous accidents.

The First Officer has also consistently received positive performance reviews during his career with Continental.

[16] Survival Factors Factual Report Addenda/Errata 1.

[17] Operations/Human Performance Group Chairman's Factual Report, Section 1.5.1, pages 5-8.

[18] Operations/Human Performance Group Chairman's Factual Report, Section 1.5.1, pages 8-11.

2.3. Summary of the Weather

2.3.1. Synoptic Overview

The synoptic surface map showed a front just east of DEN demarking a boundary between a cold arctic air mass over the Great Plains and air warmed by subsidence compression and vertical mixing in the lee of the Rocky Mountains along the Front Range. East of the front surface winds were light and easterly, while winds west of the front, including over the airfield, were westerly.

Winds aloft were westerly to northwesterly as a broad synoptic-scale trough was centered over the northern Great Plains. Wind speeds increased with height, as the core of the jet stream around the trough passed over northeast Colorado, though the strongest winds of the jet stream, exceeding 150 knots, were on the east side of the upper-level trough, over Ohio.

The 1700 sounding from Denver showed a deep layer of near dry-adiabatic temperature near the ground. The winds were nearly unidirectional from the northwest, after an initial veering above the surface. The maximum wind was 115 knots near the tropopause height, at 33,368 feet.[19]

Evidence from vertical cross-sections of the operational 12-kilometer RUC model, the sounding data and surface data are consistent with mountain waves.[20] Evidence from a numerical model run at high-resolution (250 meters) was also consistent with mountain wave activity and supported the thesis that gustiness at a fixed location was due to mountain waves passing from west to east across the airfield. Mountain wave activity of this type is able to create strong small-scale horizontal surface wind gradients of the type indicated by the LLWAS winds on the evening of December 20.

Addendum 1 to the Meteorological Factual Report demonstrates that there were extremely high wind gusts occurring at DEN around the time of this accident, and that these gusts were caused by mountain rotor wave activity coming off the Rocky Mountains. The report describes the results of a high resolution simulation of the events of that evening:

> Embedded in the overall flow structure are many gusts which move from west to east across the domain. For example, a particularly strong gust with east-west speeds reaching more than 35 m/s (68 kts) can be seen propagating across the southern end of the airport during the 10 minute time period from 1808 to 1818 MST. As it moves across the airport it tracks just south of runway 7/25, then over the approach end of runways 35L and 35R. It should be noted that there had been wind shear alerts for runway 7 within minutes of the accident.
>
> Another gust with east-west wind speeds over 20 m/s (40 kts) moves over runways 34L and 34R, directly crossing the accident site, between 1814 and 1816 MST. This represents a 40 knot cross-wind gust.
>
> In summary, the NCAR model shows a large amplitude lee wave extending downstream of the mountains over KDEN. Regions of high velocity extend

[19] Meteorological Factual Report, Addendum 1, page 17.

[20] Meteorological Factual Report, Addendum 1, page 17.

downward from this wave. Pulsations in the lee wave amplitude are manifested at the surface as intermittent gustiness.[21]

While the report is of high quality and technically sound, the analysis does not take into account the variable physiography of the airport grounds in the vicinity and particularly to the west of the accident site, which might have produced highly localized features in the wind field. Continental has suggested that wind sensors be placed along the west side of Runway 34R to study the possibility of varying wind direction, velocities, and localized features along the 12,000 feet runway. Also, Continental has suggested that a very fine-scale simulation of wind in the presence of this physiography should be conducted. To date, neither of these has been done.

2.3.2. Wind Information

The crosswind of 270 degrees at 27 knots that the tower reported when giving the takeoff clearance at 1817:26[22] corresponds to the 10-second wind from LLWAS sensor #3, which is located east of the departure (north) end of Runway 34R[23] on a 100-foot tower.[24]

LLWAS sensor #2 is located near the approach (south) end of Runway 34R on a 40-foot tower. LLWAS sensor #29 is located just west of Runway 34L, near the mid-point of Runway 34R, on a 40-foot tower. The locations are shown in Figure 1:[25]

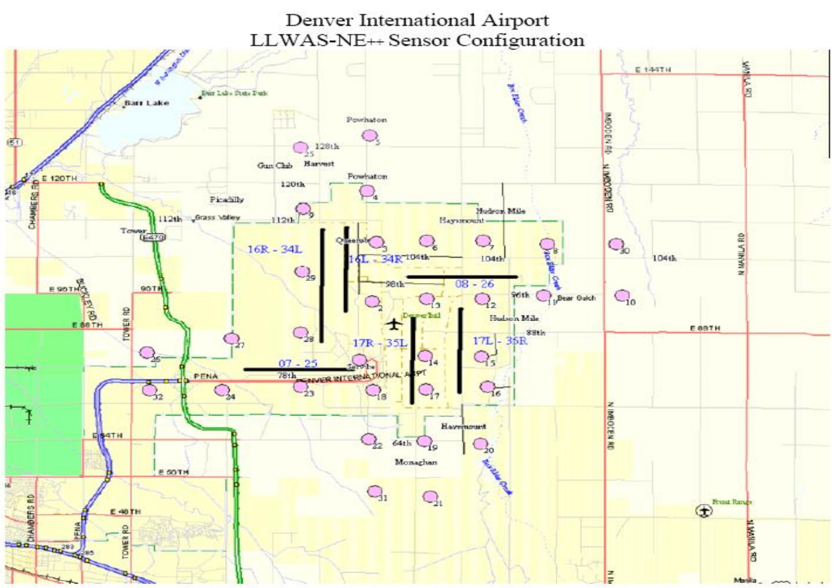

Figure 1 – Locations of DEN LLWAS sensors.

[21] Meteorological Factual Report, Addendum 1, page 39.

[22] FAA Transcript of Denver Tower communication with CAL-1404, dated Feb. 11, 2010.

[23] Weather Factual Addendum 1, dated Nov. 2, 2009.

[24] Airplane Performance Study, pages 5 & 26.

[25] Meteorological Factual Report, Figure 9, page 20.

The observations from LLWAS sensors #2, #3, and #29 near the time of departure are shown in Table 2.[26] Note that this table does not show wind gusts from these three sensors.

Time MST	WD2	WS2	WD3	WS3	WD29	WS29
1814:12	276	29	274	23	273	23
1814:22	276	30	273	23	277	22
1814:32	276	27	269	25	277	22
1814:42	273	29	272	25	272	22
1814:52	272	30	274	24	274	25
1815:02	276	30	276	26	264	21
1815:12	277	34	273	22	270	19
1815:22	278	29	268	24	275	19
1815:32	281	26	267	23	274	19
1815:42	281	30	273	25	278	23
1815:52	280	29	269	23	275	23
1816:02	280	30	266	24	276	28
1816:12	286	36	268	25	278	29
1816:22	282	40	268	23	273	30
1816:32	280	38	269	25	273	27
1816:42	278	38	268	26	272	26
1816:52	278	35	267	28	272	24
1817:02	273	32	265	27	272	23
1817:12	276	35	268	26	276	25
1817:23	270	33	270	25	278	24
1817:26	*Takeoff clearance*					
1817:32	272	33	268	27	275	23
1817:42	281	32	270	28	273	23
1817:52	273	32	265	27	273	24
1818:02	269	37	266	26	270	24
1818:12	270	34	264	24	270	23
1818:17	*Flight 1404 departs runway*					

WD2: LLWAS Wind Sensor #2 wind direction in degrees magnetic.
WS2: LLWAS Wind Sensor #2 wind speed in knots.
WD3: LLWAS Wind Sensor #3 wind direction in degrees magnetic.
WS3: LLWAS Wind Sensor #3 wind speed in knots.
WD29: LLWAS Wind Sensor #29 wind direction in degrees magnetic.
WS29: LLWAS Wind Sensor #29 wind speed in knots.

Table 2 – Observations from LLWAS sensors #2, #3, #29 near time of departure.

[26] Meteorological Factual Report, Table 3: DEN LLWAS Wind Sensor Data (reproduced in part; times shown in MST; times of takeoff clearance and runway departure added).

Table 3[27] is also important. This table displays the two-minute average airport wind speed and direction and airport wind gusts from LLWAS sensor #2.

Time MST	DEN WD	DEN WS	DEN Gust
1814:12	280	28	G00
1814:22	280	28	G00
1814:32	280	28	G00
1814:42	280	28	G00
1814:52	280	29	G00
1815:02	280	29	G00
1815:12	280	30	G35
1815:22	280	30	G35
1815:32	280	30	G35
1815:42	280	30	G35
1815:52	280	30	G35
1816:02	280	30	G35
1816:12	280	30	G37
1816:22	280	31	G40
1816:32	280	32	G40
1816:42	280	33	G40
1816:52	280	33	G40
1817:02	280	33	G40
1817:12	280	34	G40
1817:23	280	34	G40
1817:26	*Takeoff clearance*		
1817:32	280	34	G40
1817:42	280	34	G40
1817:52	280	34	G40
1818:02	280	35	G40
1818:12	280	35	G40
1818:17	*Flight 1404 departs runway*		

DEN WD: DEN Airport 2 Minute Wind Direction in Degrees Magnetic.
DEN WS: DEN Airport 2 Minute Wind Speed in Knots.
DEN Gust: DEN Airport Wind Gust in Knots.

Table 3 – Two Minute Average Airport Wind Speed and Direction and Airport Wind Gusts from LLWAS Wind Sensor #2.

The Meteorological Factual Report states:

> According to the FAA, the airport 2 minute wind direction and speed is a running 2 minute average updated every 10 seconds. For the airport gusts the last 1-minute airport wind remote sensor poll response data is compared to the current airport wind to determine if a peak wind speed condition exists (a peak wind

[27] Meteorological Factual Report, Table 4: Two Minute Average Airport Wind Speed and Direction and Airport Wind - Gusts from LLWAS Wind Sensor #2 (Airport Wind Sensor) (reproduced in part; times of takeoff clearance and runway departure added).

> speed is at least 5 knots greater than the airport wind which must be at least 9 knots). If the maximum peak wind speed of all peak wind speeds in the last 10 minutes is greater than the current airport wind by 3 knots, and the current airport wind is at least 3 knots, the maximum peak wind speed is displayed as the gust speed value. The gust speed can persist up to 10 minutes unless the maximum peak wind speed falls within 3 knots of the current airport wind.[28]

These data demonstrate that there was considerable variation in wind speed across the airfield, with the strongest winds at the time of Flight 1404's takeoff roll located along an east-west corridor, encompassing the south end of Runway 34R and including LLWAS sensor #2.

Figure 2 shows the time series of the 10-second average crosswind speed from the three LLWAS sites closest to Runway 34R.[29] As noted in the previous Tables 1 and 2, the crosswind speed was much stronger at LLWAS sensor #2. The pilots had been provided the 27 knot crosswind speed, and specifically mentioned it in the cockpit at 1817:38,[30] but the crosswind speed measured by LLWAS sensor #2 was as high as **40 knots** before the takeoff clearance, and the crew was not given this information.

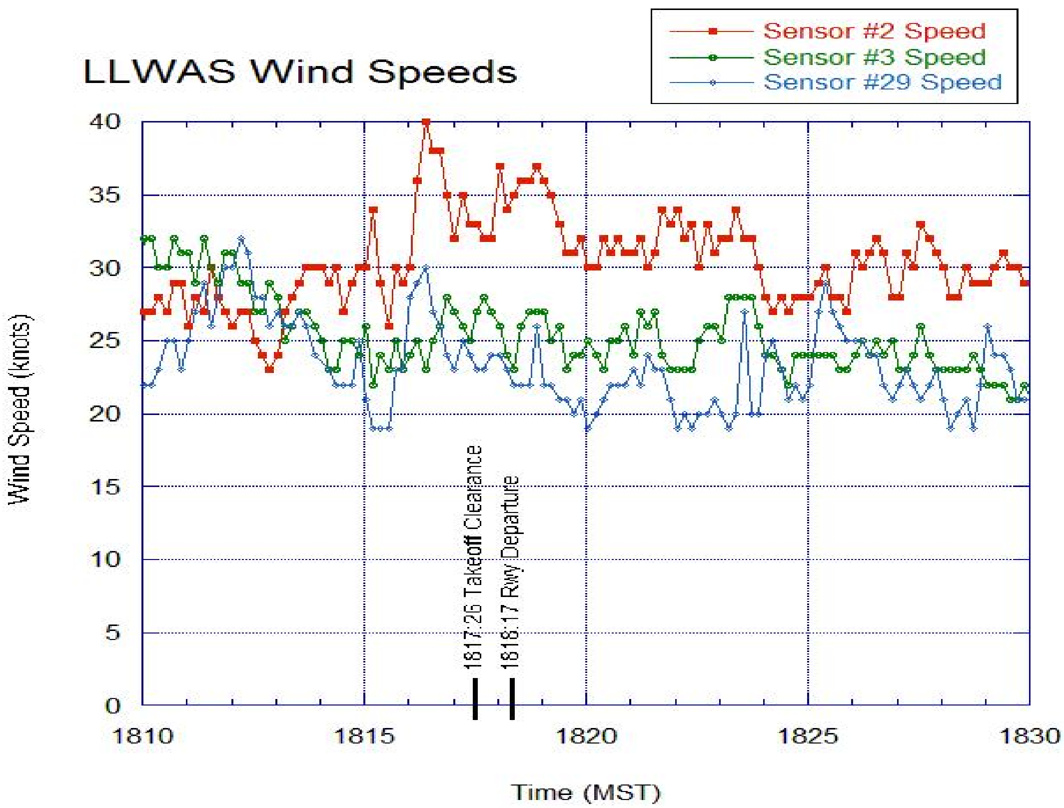

Figure 2 – Wind speed (knot) time-series for the three LLWAS sensors closest to Runway 34R.

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[28] Meteorological Factual Report, page 10.

[29] Figure created from data contained in the Meteorology Factual Report, Attachment 5.

[30] CVR Factual Report, page 12-36.

The character of the surface wind around the time of the accident was gusty. This is suggested by the 10-second data and confirmed by the DEN ASOS gust measurements[31] on a 30-foot (10 meters) tower shown in Figure 3.[32]

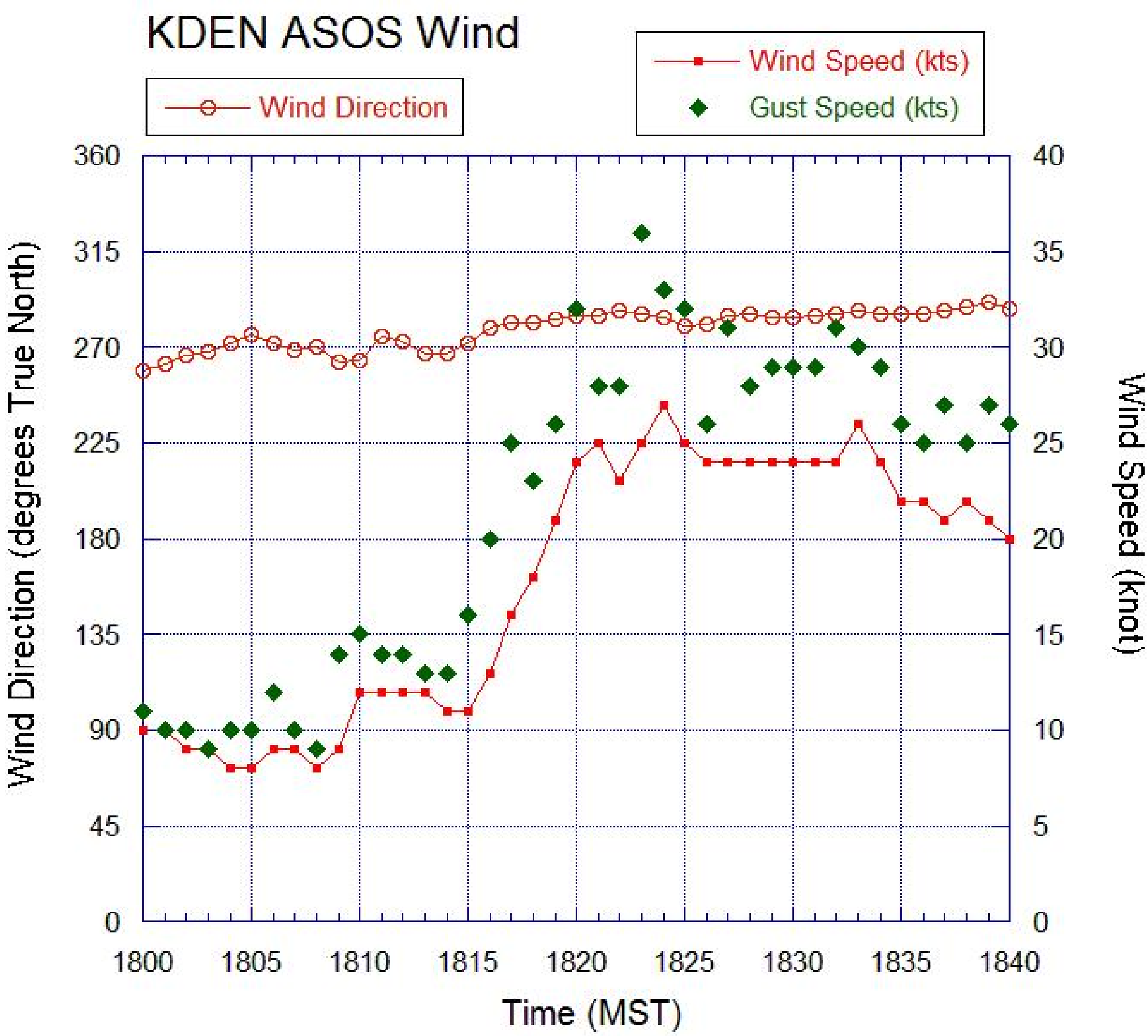

Figure 3 – 2-minute average wind speed and 5-second max wind time-series from the ASOS station at DEN.

The time of the maximum gusts recorded by ASOS likely lags those measured at LLWAS sensor #2 because the ASOS site is 14,600 feet (2.4 nautical miles) southeast of the accident site and downstream from any waves propagating from west to east. The METAR report generated by this ASOS site and available to ATC[33] at 1753 indicated a peak wind of 27 knots, but the Special Observation after the accident, at 1834 showed gusts to 32 knots and a peak wind of 36 knots, from 280 degrees true, at 1823.

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[31] DEN 1-minute ASOS observations obtained from the National Climatic Data Center.

[32] Figure created from data obtained from the National Climatic Data Center, one minute ASOS.

[33] ATC Factual Report, Section 14, Weather Products, dated Jan. 23, 2009.

2.3.3. Witness Statements Pertaining to the Wind

An employee of DEN and his wife were traveling northbound on E-470 just north of Pena and arrived at the E-470 toll plaza at 1818. According to the witness, the toll plaza is located almost exactly due west of the threshold of Runway 34R. See Figure 4. The witness has a very specific recollection of looking at the clock in his car. As he arrived at the toll plaza, he noticed the wind, because it was blowing Christmas decorations around, and he even commented to his wife about it. As he pulled out of the toll plaza and accelerated to highway speed, an extremely large gust of wind came out of the northeast. He was concerned that the gust was going to blow his F-250 4X4 crew cab pickup truck off the road, and had to steer his truck into the wind to counter the direction it was trying to push his vehicle. The side window deflectors on the windows were bending, and he had never seen that before. The wind gust lasted for 2-3 minutes and ended abruptly. He estimates the wind speed to be in excess of 50 miles per hour.[34]

Figure 4.

The Captain of US Airways Flight 94, a Boeing 737-300, en route from DEN to PHX, was interviewed by phone on January 30, 2009. He stated that while at Gate C-31 about the time of the Flight 1404 accident, he experienced a rumbling or shaking of his airplane. See Figure 4. He looked outside and saw material blowing on the ramp, and people on the ramp having "trouble standing." He estimated the wind at 50+ miles per hour with gusts from the west that lasted

[34] Meteorological Factual Report, page 34; Meteorology Factual Report, Attachment 9.

about 45-60 seconds. Gate C-31 is located about 2,960 feet east-southeast of the threshold of Runway 34R and about 1,650 feet south of LLWAS sensor #2.[35]

3. Analysis of Aircraft Controllability and Pilot Performance

3.1. Aircraft Controllability

During the initial part of the takeoff roll, the Captain used variable right rudder to keep the airplane aligned with the runway centerline. He recalled that it felt at first like a "normal crosswind takeoff."[36] As the aircraft continued down the runway, the Captain made two applications of aggressive right rudder. Figure 5 demonstrates that the Captain's first aggressive application of right rudder at 1818:08 resulted in a heading movement to the right of 0.6 degrees. However, the second rudder application failed to control the aircraft's heading when it was struck by a strong, gusty, localized crosswind from the left. Figure 5 demonstrates that the aircraft weathervaned or yawed 3.4 degrees to the left despite the Captain's proper use of right rudder.

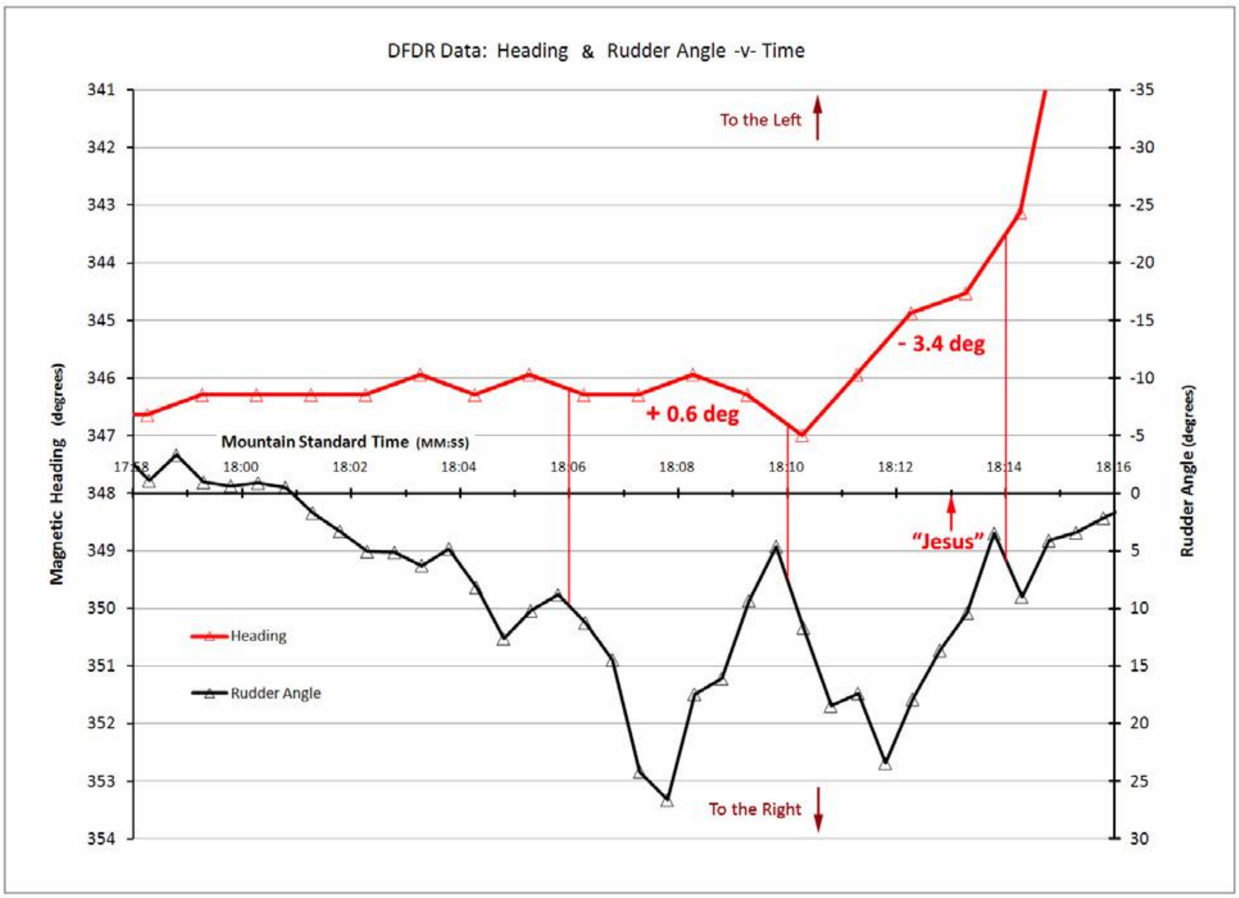


Figure 5.

[35] Meteorology Factual Report, pages 33-34.

[36] Operations/Human Performance Group Chairman's Factual Report, Attachment 1, page 4.

Lateral acceleration is also important in studying aircraft controllability. The FDR data for lateral acceleration has a higher resolution than the data for heading. Lateral acceleration is sampled four times per second, compared to heading, which is sampled one time per second. A study of other high crosswind takeoffs indicates that lateral acceleration, or rate of heading change, is the first cue to which a pilot responds for increasing and decreasing rudder inputs during a crosswind takeoff.[37] A pilot will feel the change in lateral acceleration "in the seat of the pants" (kinesthetic sensations), and then make the appropriate rudder input, after which the heading change normally follows. This explains why pilots reduce rudder input before the heading shifts, rather than leaving the rudder input in until after the heading shifts.

The Captain of Flight 1404 cued off the lateral acceleration shift as feedback for his rudder inputs, and the lateral acceleration shifts preceded the aircraft heading reaction. Moreover, high crosswind takeoffs show an increasing magnitude of lateral acceleration shifts in response to rudder inputs at higher airspeeds, especially those exceeding 80 knots. Figure 6 demonstrates that right lateral acceleration feedback was present during the Captain's first large rudder input, but the expected right lateral acceleration shift did not occur during the second large rudder input. The plane continued to yaw left despite significant right rudder input. The absence of the expected right lateral acceleration, followed by the continued movement of the nose to the left, clearly signified loss of rudder control to the Captain. This resulted in the Captain losing confidence in the plane's rudder.

Figure 7 plots historical data from a typical high crosswind takeoff. The lateral acceleration experienced by Flight 1404, as depicted in Figure 6, differs dramatically from the normal lateral acceleration during other high crosswind takeoffs. Compare Figure 6 with Figure 7.

[37] The data relied on to create Figure 7 demonstrates that lateral acceleration is the first cue to which a pilot responds for changing rudder inputs during a crosswind takeoff.

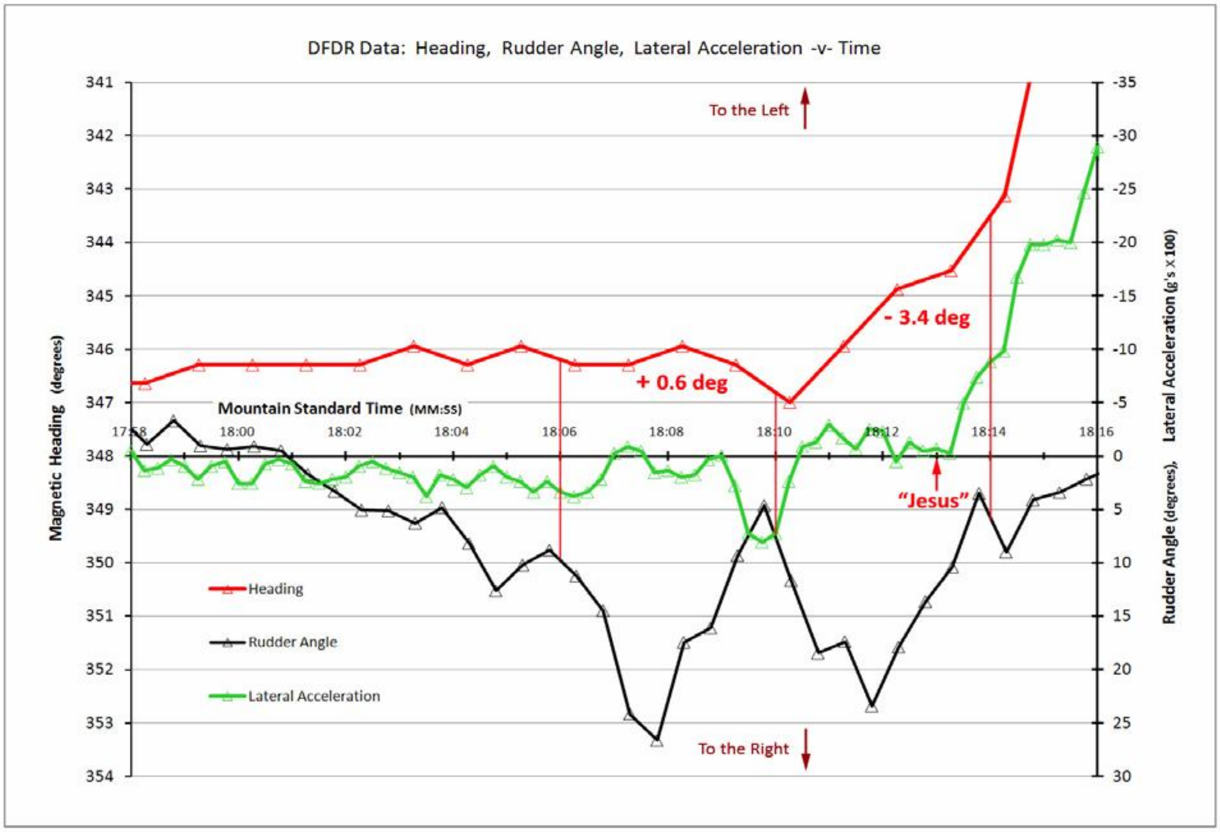


Figure 6.

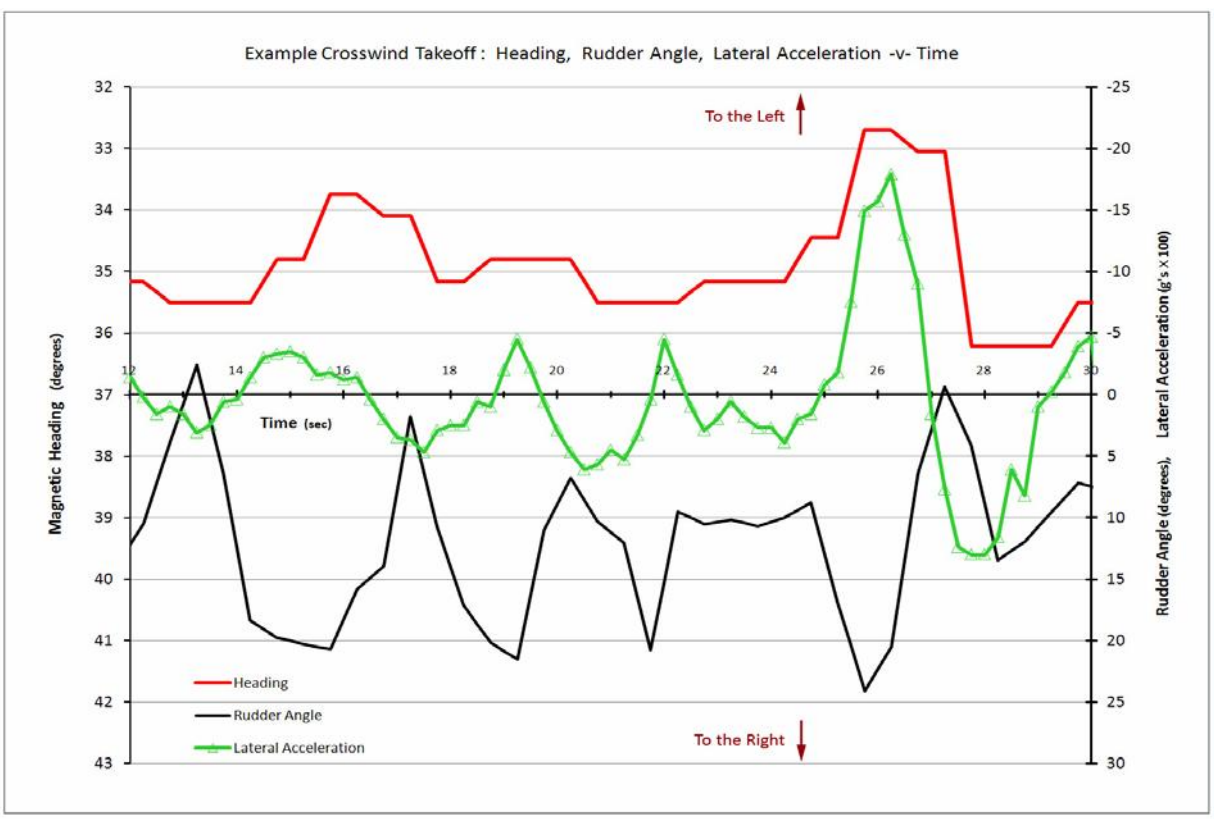


Figure 7.

3.2. Calculation of Effective Wind on the Rudder during Second Rudder Application

The following discussion illustrates the aerodynamic effects on the Boeing 737 during takeoff at the time of the gust event and shows that the unexpected very strong wind gust caused a sideslip angle that was larger than what maximum rudder deflection could counter. At the time of the event,[38] the aircraft was traveling down the runway on a magnetic heading of 350.9 degrees with a ground speed of 91 knots. The assumed gust that was experienced by the aircraft was from 257 degrees at 43 knots; therefore, the angle between the wind direction and aircraft magnetic heading is 93.9 degrees.[39] The NTSB actually extracted wind speeds up to 45 knots from their analysis, so the assumed gust of 43 knots is conservative. The first calculation is to determine the component of the gust that acted as a direct crosswind (i.e., from 260.9 degrees) to the aircraft rolling down the runway. This result is shown in Figure 8.

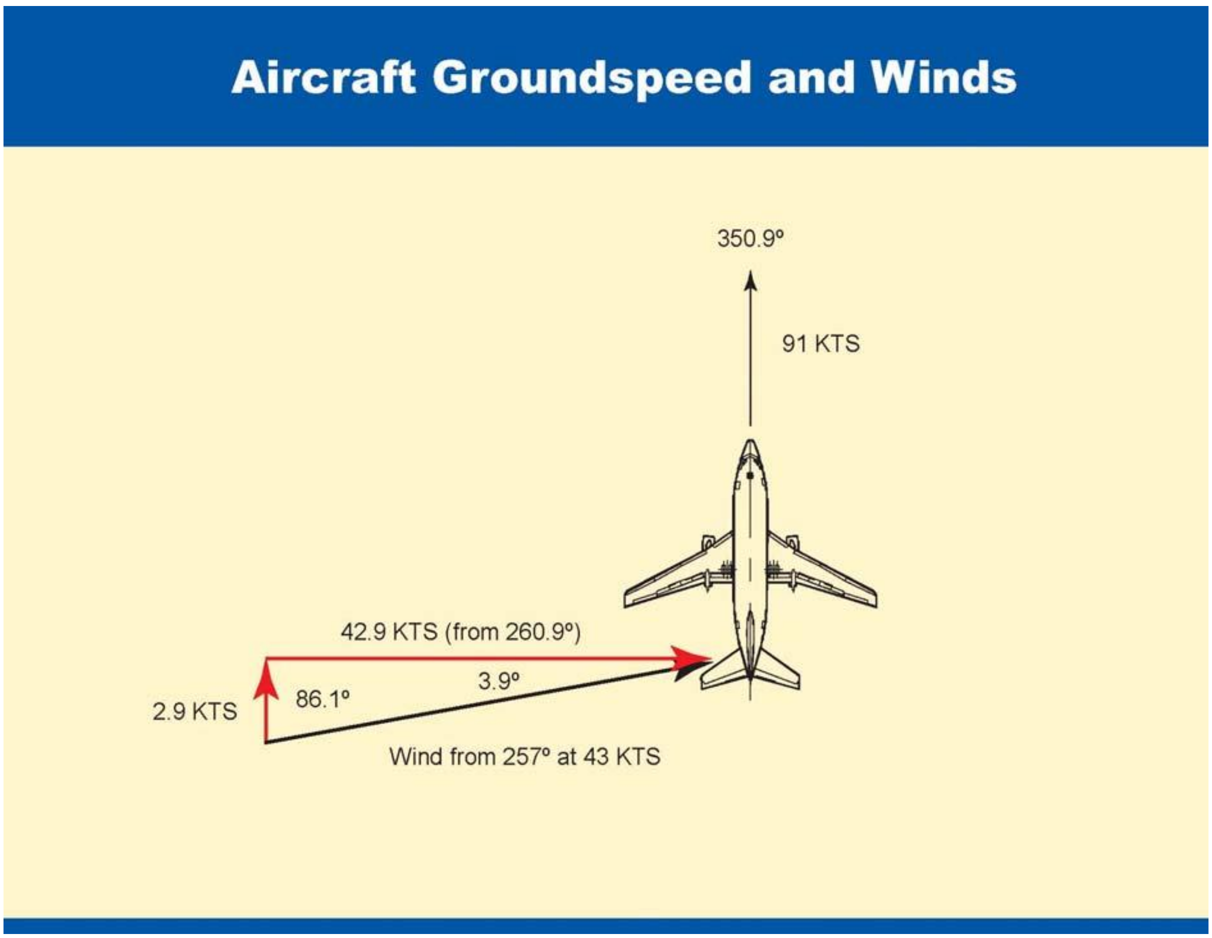


Figure 8 –Aircraft Groundspeed and Winds.

[38] This calculation was based on the event occurring at 1818:13, when the CVR recorded "Jesus."

[39] Airplane Performance Study, page 5 & Figure 18.

When the wind is resolved into a direct crosswind component from 260.9 degrees, the magnitude is approximately 42.9 knots. There is also a component of the wind that acted as a tailwind of approximately 2.9 knots, as shown above in Figure 8. These calculations are shown in Equation 1:

$$V_{crosswind} = 43 \cos(3.9°) = 42.9 \text{ knots}$$

$$V_{tailwind} = 43 \sin(3.9°) = 2.9 \text{ knots}$$

Equation 1.

As a result, the airspeed of the aircraft in the x-direction (heading of 350.9 degrees) is 88.1 knots with a direct crosswind component of 42.9 knots. This is shown in Figure 9:

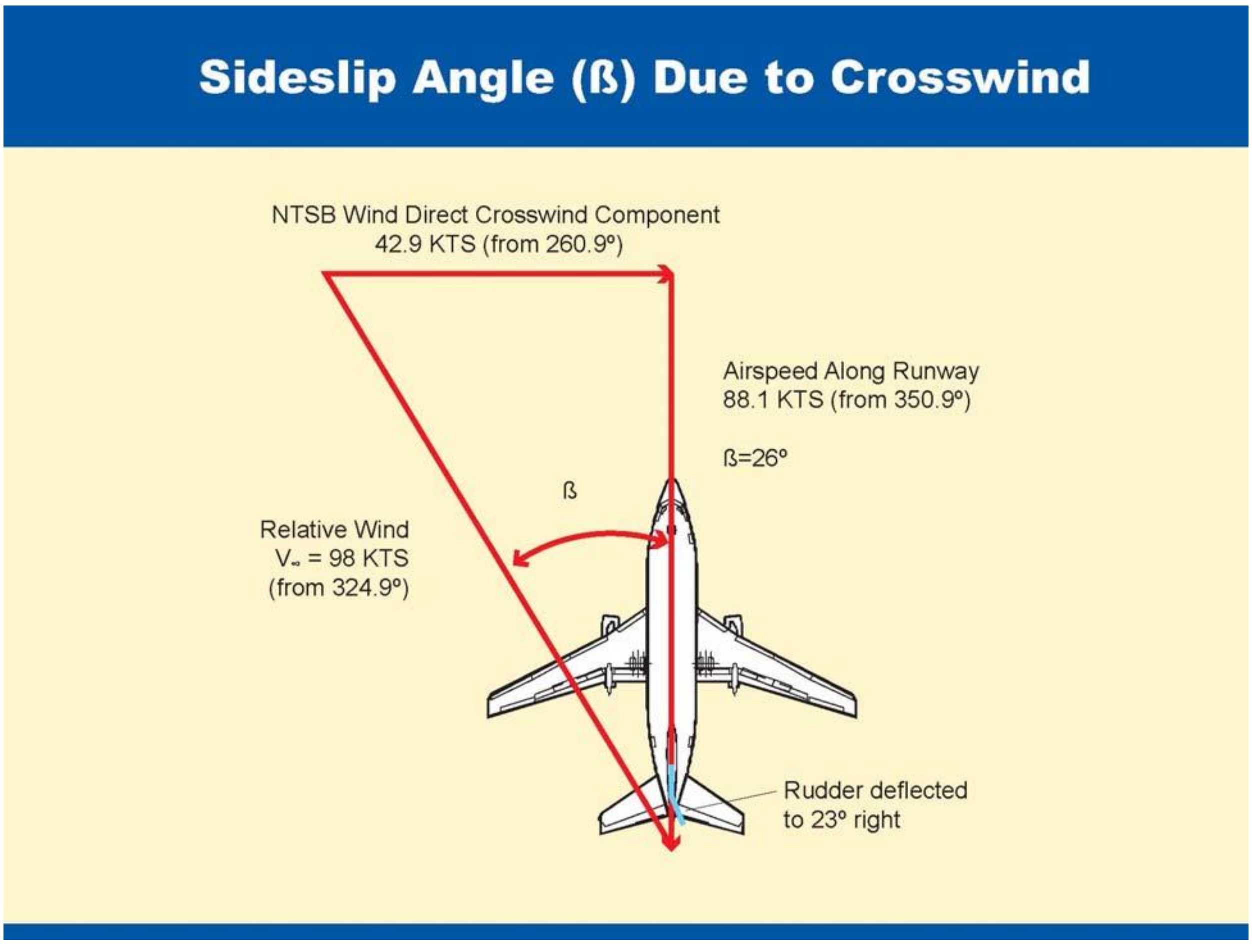


Figure 9 – Sideslip Angle (β) Due to Crosswind.

Based on the airspeed along the runway and the crosswind acting on the aircraft, the sideslip angle, β, and true airspeed, V_∞, can be calculated. The true airspeed for these conditions is 98 knots and the magnitude of the sideslip angle is found by the trigonometry in Equation 2 to be 26 degrees:

$$\beta = \tan^{-1}(42.9/88.1) = 25.96° \cong 26°$$

Equation 2.

Since the relative wind is coming from the left of the aircraft it is a negative sideslip (i.e., $\beta = -26$ degrees) by the standard sign convention.

Therefore, for the aircraft to remain straight down the runway the rudder must be capable of overcoming this sideslip angle of 26 degrees or it will weathervane to the left into the relative wind. Therefore, the rudder displacement must be capable of producing an effective angle of attack on the vertical tail of 26 degrees or the pilot cannot keep the nose aligned with the runway. The rudder on the Boeing 737-500 has a chord that is approximately 0.25 of the chord of the vertical tail. From results presented in Figure 2.23 of the book Airplane Flight Dynamics and Automatic Flight Controls by Jan Roskam,[40] for a chord ratio of 0.25, the effectiveness of the control surface is less than 0.5. This means that a rudder deflection of 25 degrees would result in an effective angle of attack produced by the vertical tail of less than 12.5 degrees, far less than needed to counteract the sideslip angle of 26 degrees.

If the above analysis was performed at an earlier time, such as the second peak rudder deflection of 23 degrees, the aircraft's approximate ground speed was 84 knots and the NTSB extracted wind was from 257 degrees at 45 knots. Based on these conditions, the calculated sideslip angle would have been approximately 29 degrees, making the rudder even less capable of counteracting it.

Such an analysis could be refined using the stability and control derivatives for the Boeing 737-500. Continental has not had time to complete its study of this issue. Specifically, the change in yawing moment due to sideslip angle, Cn_β, the change in yawing moment due to rudder deflection, $Cn_{\delta r}$, the change in side force due to sideslip angle, Cy_β, and the change in side force due to rudder deflection, $Cy_{\delta r}$, would be useful in such an analysis. It is important that these values are provided for the flight conditions that exist at the time of the takeoff since they vary depending on the conditions (i.e., they are nonlinear). For a simple analysis, the magnitude of the rudder deflection required to balance the yawing moment caused by the sideslip angle could be estimated using the equations:

$$Cn_\beta \beta + Cn_{\delta r} \delta r = 0$$ **Equation 3.**

or

$$\delta r = (Cn_\beta \beta)/ Cn_{\delta r}$$ **Equation 4.**

In general, the magnitude of the Cn_β is larger than the magnitude of $Cn_{\delta r}$ so the rudder deflection, δr, required will be larger than the sideslip angle. For example, typical data for a Boeing 747 presented in Roskam's book for one low speed flight condition gives a Cn_β of 0.184 /radian and a $Cn_{\delta r}$ of -0.133 /radian. With this 747 example, it would take approximately 36 degrees of rudder deflection to counteract a 26 degrees yaw angle. Therefore, the capability of the rudder is likely not sufficient to overcome the nose left yawing moment for the large sideslip angle that existed in this takeoff.

One must recognize that the landing gear tires provide some stabilizing moment in yaw. However, that moment is greatly reduced once the tires begin skidding, which occurred in this case.

[40] Roskam, J., Airplane Flight Dynamics and Automatic Flight Controls, Part I, Design, Analysis and Research Corporation, 1995.

This explains why the Captain correctly believed the rudder was not producing the desired effect, and is consistent with his interview summary:[41]

> "All of a sudden, he felt like something … either one of two things happened. It was like someone had put their hand on the tail of the airplane and weathervaned it to the left, or they might have hit some ice with the rudder in and the tires might not have held with as much rudder as he had in."
>
> "The rudder was pretty much at its stop, and the airplane was heading toward the left edge of the runway."

The complete absence of expected lateral acceleration, followed by the continued movement of the nose to the left, clearly signified to the Captain loss of rudder control. The Cockpit Voice Recorder (CVR) recorded the sound of two "snaps," which may have also led the Captain to suspect a rudder failure.

3.3. Drift (Skid) Angle As Discerned By Tire Skid Mark Configuration

The skid marks left by the nose wheels as they converged with the set of left main landing gear skid marks suggest that the aircraft entered a period of skidding sideways, producing a right drift angle with respect to the aircraft heading.

Figure 10 suggests an approximate drift angle of 15 degrees at the point that the left main landing gear and nose gear skid marks converged. This occurred while the aircraft was still on the paved surface as the aircraft approached the west side of the runway.

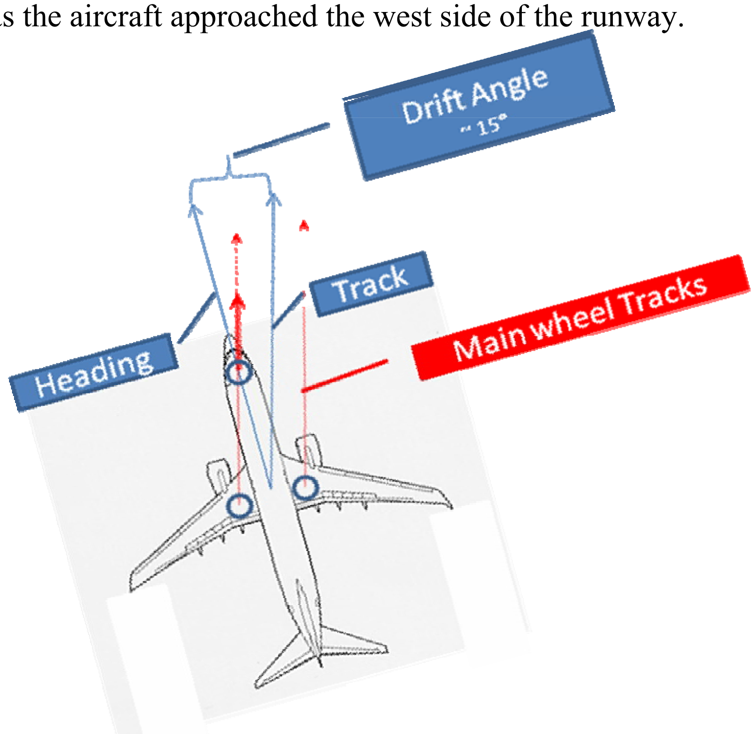


Figure 10.

[41] Operations/Human Performance Group Chairman's Factual Report, Attachment 1, page 2.

Figure 11.

Figure 11[42] shows the tracks of the aircraft main wheels were parallel and uniform in separation from the edge of the paved surface of runway 34R to the end of the ground run. The airplane rests in alignment with the ground scar witness marks.

The Structures Factual Report states that the distance between the main wheel scars remained between 14 feet and 16.7 feet apart. The structural distance between the main gears is 17.2 feet, taken at the struts. The consistency of spacing suggests the aircraft was continually aligned with its direction of travel, displaying a negligible drift or skid angle.

The Captain recalled using right control wheel to keep the wings level just before and while the airplane departed the left side of the runway. The Captain stated he did this because he thought the ground next to the runway sloped down and he feared that the aft end of the fuselage would slide down that incline and cause the airplane to "tumble on its side."

The Captain's use of the flight controls served to maintain the alignment of the aircraft fuselage along the ground path traveled and possibly prevented wingtip contact. His actions stabilized the aircraft, preventing a more serious accident.

3.4. Denver International Airport Winds

The crew of Flight 1404 experienced a very rare and unusual crosswind scenario, estimated by the NTSB at 45 knots, well over Continental's 33-knot guideline.[43]

Out of 940,000 takeoffs in all Continental airplane types (except the B-737-300), when crosswind component was measured 7 seconds after takeoff,

- Only 0.0266% of flights encountered a crosswind of 25 knots or greater,
    - 0.0130% encountered a crosswind of 27 knots or greater, and
    - 0.0066% encountered a crosswind of 30 knots or greater.

[42] Structures Group Factual Report, Figure 4 – Aerial View of Ground Scars and Wreckage, page 9.

[43] Airplane Performance Study, Table 11.

- Out of 250,327 takeoffs in the B-737-500, when crosswind component was measured 7 seconds after takeoff:
  - 0.00030% encountered a crosswind of 25 knots or greater,
  - 0.00010% encountered a crosswind of 27 knots or greater, and
  - 0.00002% encountered a crosswind of 30 knots or greater.

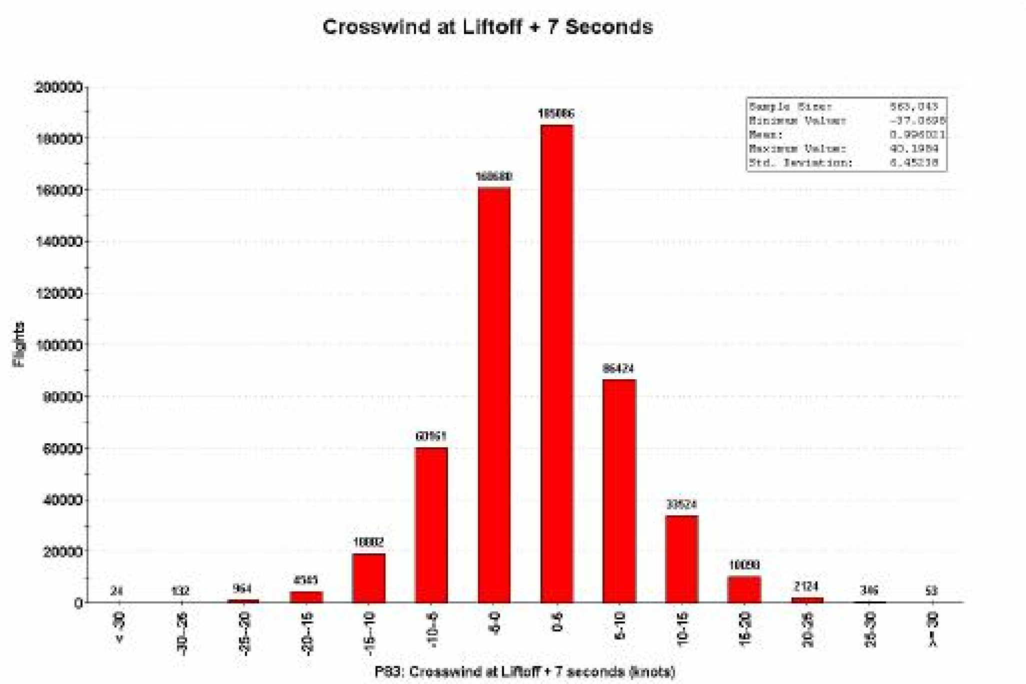
United Airlines provided operational analysis data[44] showing that 40% of their crosswind takeoffs from 25-30 knots occurred at DEN.

Furthermore, 57% of their crosswind takeoffs in excess of 30 knots occurred at DEN. See Figure 12.[45]

[44] Operations/Human Performance Group Chairman's Factual Report, Attachment 6, page 3.

[45] Operations/Human Performance Group Chairman's Factual Report, Attachment 6, page 3.

Operational Information Provided by United Airlines.



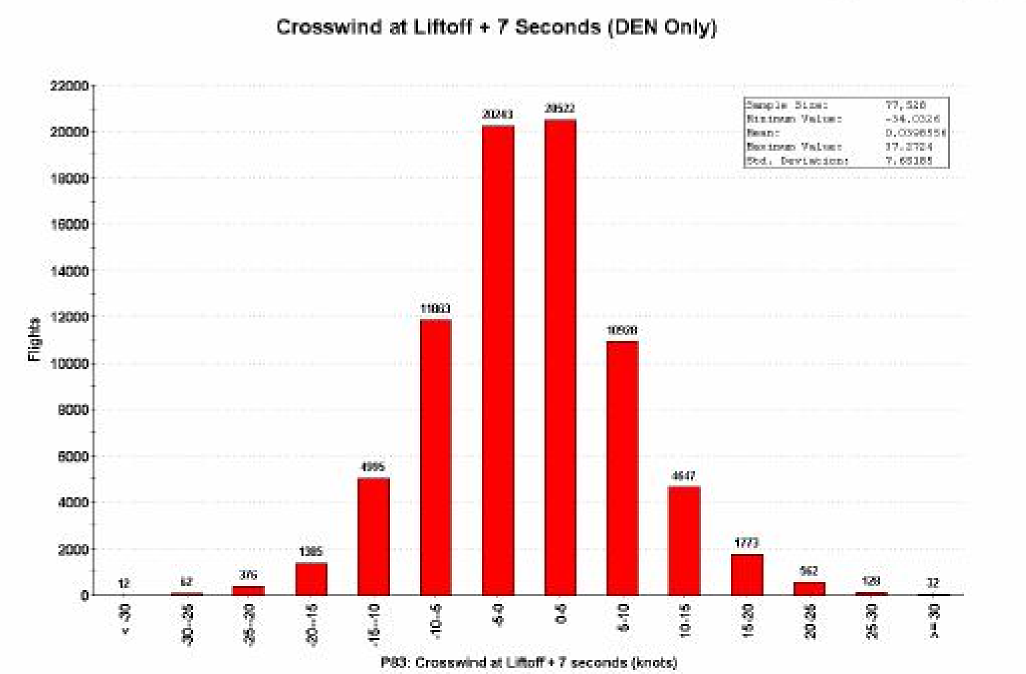


Figure 12.

3.5. Pilot Performance

Sections 3.1 and 3.2 demonstrate that the pilot believed the rudder was not effectively controlling the aircraft, and these sections also confirm that his belief was correct.

Footnote 3 in the Airplane Performance Study states:

> The Pilot reported after the accident that he was concerned about the airplane rolling over the embankment adjacent the runway and that he added RWD aileron to help prevent this from happening. However, the AMASS data and FDR integration in Figure 1 show that the airplane was still close to the runway centerline when the RWD wheel was introduced by the pilot at about 18:18:13.

This comment incorrectly implies that the Captain was mistaken or untruthful when he said he was concerned about the airplane rolling over the embankment adjacent to the runway.

However, the statement that the AMASS data and FDR integration show that the airplane "… was still close to the runway centerline when the RWD wheel was introduced by the pilot at about 18:18:13" is highly misleading. The footnote and other parts of the study mistakenly focus on the importance of some unspecified part of the airplane being close to the centerline.

Runway 34R is 150 feet wide.[46] The airplane was 97 feet, 9 inches long, and had a wingspan of 94 feet, 9 inches.[47] The distance from the main gear to the nose wheel is 36 feet, 4 inches, and the distance from the main gear to the nose is 49 feet, 6 inches. This configuration places the cockpit about 42 feet forward of the main gear. Once the plane yawed to the left, the main gear may still have been near the centerline, but the Captain and First Officer most certainly were not on the centerline.

The second aggressive right rudder input did not arrest the yaw rate. It slowed it down slightly, but the nose of the plane was still yawing to the left, even when significant rudder was applied. A crew member's exclamation of "Jesus" coincided with the Captain's awareness that the right rudder did not stop the yaw to the left.

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[46] Aircraft Performance Report, Attachment 1.

[47] Structures Group Factual Report, Section 1.0.

Figure 13 depicts an exemplar 737-500 superimposed on an aerial photograph of the runway. The aircraft's right main gear was still touching the centerline, but the plane had yawed far to the left and was skidding sideways. The Captain undoubtedly quickly realized that the plane was going off the runway even though the main gear was still near the centerline.

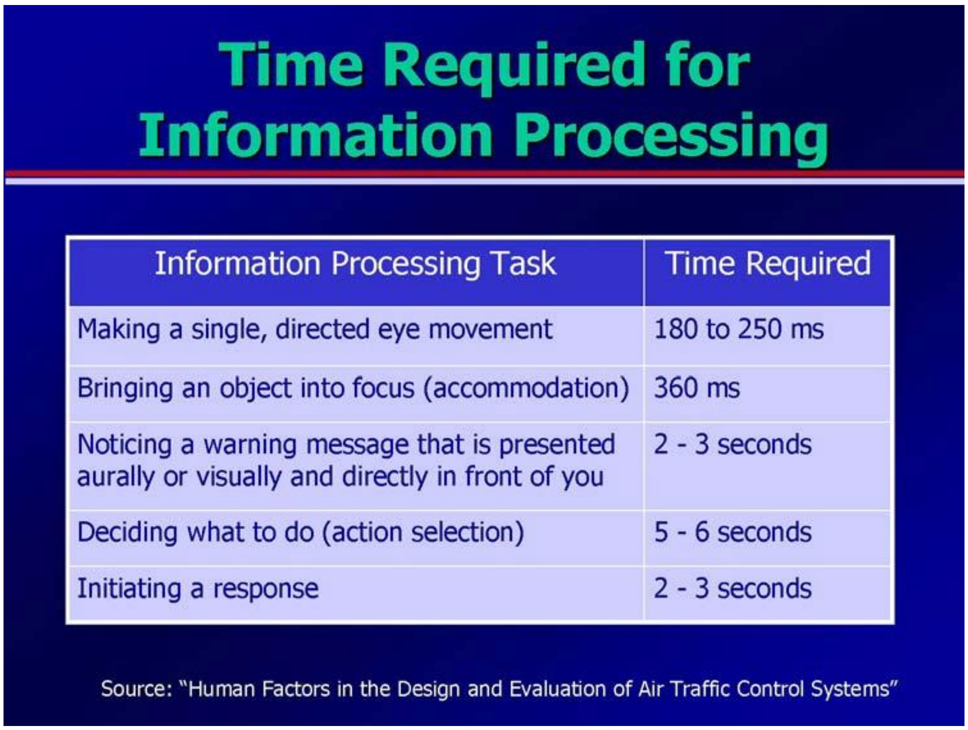
Figure 13.

Regardless of the proximity of the aircraft's main landing gear to the runway centerline, the pilot's sight picture at night where he could only see the runway edge lights, coupled with the plane's skidding and the failure of the rudder to control the yawing motion, changed his plan of action in an instant. He had no way of knowing why his hard rudder input did not work. He had no way of knowing whether he had encountered an extreme weather condition, hit a patch of ice on the runway, or his rudder was ineffective or even inoperative. The sound of two "snaps" recorded by the CVR may have reinforced the Captain's belief that something was wrong with the rudder. He knew his airplane was not responding as expected and he had to take immediate emergency action. Given the heading of the airplane, a rejected takeoff could not have kept the airplane on the runway at that point.

Even though he only had seconds to respond, he quickly:

- Recognized the loss of yaw control;
- Assessed his options; and
- Took action to stabilize the track of the aircraft as he executed a rejected takeoff after departing the runway.

It is important to recognize how little time the Captain had to process the information confronting him and react. Figure 14[48] shows the time required to process information, accommodate it, select the appropriate action, and respond. This is sometimes known as the "startle effect."


Time Required for Information Processing

Information Processing Task	Time Required
Making a single, directed eye movement	180 to 250 ms
Bringing an object into focus (accommodation)	360 ms
Noticing a warning message that is presented aurally or visually and directly in front of you	2 - 3 seconds
Deciding what to do (action selection)	5 - 6 seconds
Initiating a response	2 - 3 seconds

Source: "Human Factors in the Design and Evaluation of Air Traffic Control Systems"

Figure 14.

Figure 14 demonstrates that the time required from noticing a warning until initiation of a response ranges from 9 to 12 seconds. The plane began to yaw to the left at 1818:10.3, and departed the runway less than 7 seconds later at 1818:17. It is not realistic to expect the Captain to have responded any more rapidly than he did.

The straight track the aircraft took as it exited the runway and traversed the sloping ground to the left of the runway's paved surface was the result of the pilot successfully controlling the aircraft. This action was responsible for the aircraft remaining upright, and not tumbling on its side as the Captain believed would have happened.

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[48] Kim M. Cardosi & Elizabeth D. Murphy, Human Factors in the Design and Evaluation of Air Traffic Control Systems, John A. Volpe National Transportation Systems Center, Cambridge, Mass., Apr. 1995, page 145.

4. Comments on Select NTSB Factual Reports

4.1. Airplane Performance Study

4.1.1. Aircraft Performance Data

Continental questions the accuracy of the ground path of the aircraft shown in Figure 1 of the Airplane Performance Study. That figure shows in blue the data points for the AMASS data, but that ground path is not consistent with the main landing gear skid marks documented in the Structures Group Factual Report, paragraph D. 2.0.[49] The AMASS data show the ground path to the right of the centerline, but the skid marks show that the right and left main landing gear bracketed the runway centerline for approximately 60 feet, slightly left of center but on the centerline, before beginning the arc to the left.

Continental has other concerns about the Airplane Performance Study.

The first sentence in the first full paragraph on page 3 states:

> Irrespective of the winds that were present during Continental flight 1404's take-off attempt, select FDR data shown [sic] that the airplane was capable of tracking the runway centerline.

That statement is not correct. The FDR data only shows that the airplane was capable of tracking the runway centerline until it stopped tracking the centerline due to an uncontrollable left yaw at 1818:14 when the aircraft failed to respond to the second aggressive application of right rudder. There is no FDR data that shows the plane was capable of tracking the runway centerline once it was hit by the strong crosswind gust.

The next sentence states:

> The airplane largely tracked the centerline until approximately 18:18:13 when the FDR rudder deflection went from 24° ANR to a near neutral position and the wheel transitioned from 20° LWD to over 80° of right-wing-down wheel (RWD).

There are at least three inaccurate or misleading statements in that sentence:

- First, the center of the plane may have still been near the centerline, but the plane yawed sharply to the left while the Captain was using significant right rudder. The crew members were not on the runway centerline, but were heading towards the runway edge lights at 107 knots (180 feet per second).

- Second, the sentence improperly suggests that the airplane departed the centerline because the pilot relaxed the rudder pedal, but the Captain relaxed the rudder pedal only after failing to experience the expected lateral acceleration forces and after the plane failed to respond properly when he applied significant right rudder. The Captain

[49] Structures Group Factual Report; D. 2.0, Debris Path, page 2.

then momentarily attempted to use nose wheel steering in a desperate effort to overcome the failure of the rudder to control the plane.

- Third, the comment about RWD is irrelevant. The Captain's desperate use of right aileron had zero effect on the plane's track. Figure 1 shows the plane's track on centerline when a crewmember exclaimed "Jesus." He made that exclamation because the plane had yawed quickly to the left and did not respond to his use of right rudder.

Additionally, the wheel transitioning from 20 degrees LWD to over 80 degrees RWD was a desperate move, made when it was apparent the aircraft was about to depart the runway and the Captain feared the aircraft would tumble down the slope from the runway.

4.1.2. NTSB and Boeing Wind Estimation

The NTSB estimated that winds near the time of the accident varied between 30 and 45 knots out of the west, almost a straight crosswind for Denver's Runway 34R with a peak gust of 45 knots,[50] far in excess of the 270 degrees at 27 knots the tower controller gave to the crew.

It is notable that the NTSB graphic[51] of crosswind shows multiple velocity spikes of nearly 40 knots and one extremely strong wind gust of 45 knots at 1818:12. This far exceeds any demonstrated crosswind performance ever documented by Boeing.

According to the Airplane Performance Study:

> The average peak wind speed from the two methods used by Boeing was about 45 kt, the same peak wind extracted by the NTSB. However, after considering the reported LLWAS winds, Boeing modified their wind solution and a peak of 40 kt resulted. [52]

While the NTSB used empirical data, Boeing reports that rather than using direct calculations from available DFDR data they have "… modified their wind solution and a peak of 40 kt resulted." Boeing states that this "[o]ne refinement was to reduce the peak winds slightly which produced a slightly better simulation match and brought peak winds within the bounds of the LLWAS winds."[53] Boeing's report refers to an "… apparent spike in the crosswind component …" that they discount in the next sentence, "[t]his spike is not a wind gust …."

Boeing's estimation of the crosswind component equals the value Boeing has given to operators of the B-737-500 as its crosswind controllability maximum value.

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[50] Airplane Performance Study, NTSB Wind Estimates, page 5.

[51] Airplane Performance Study, Figure 10.

[52] Airplane Performance Study, page 7, note 8.

[53] Supplement to Boeing Wind Analysis November 2009 CAL 737-500 (PT811) Runway Excursion Accident at Denver (DEN), page 5.

4.1.3. Continental Airlines Boeing 737-500 FFS Models for Crosswind Training

The paragraph at the top of page 8 of the Airplane Performance Study discusses the Boeing 737-500 full flight simulator (FFS) and states:[54]

> While no problems were identified with Continental's FFS airplane performance models, a problem with the simulator atmospheric model was found: no gusts are included below a 50 ft altitude (above ground level). See Attachment 3[10] for details. This means that flight crews training in the Continental FFS will only be exposed to a steady-state wind and no gusts during take-off and landing. This is a problem if the FFS is the sole means for training crosswinds to Continental flight crews; the first time that crews will be exposed to gusty winds in the 737-500 will be in the actual airplane.

The above statement provides an incomplete and misleading picture of Continental's flight crew training for gusty crosswind takeoffs and landings. It incorrectly suggests that Continental flight crews do not receive crosswind training in gusty conditions. To the contrary, Continental does provide gusty crosswind training, including the following:

1. The 737-500 FFS does provide gusts above 50 feet. Therefore, flight crews are exposed to flight control inputs required during takeoff and landing in gusty conditions. These procedures reinforce appropriate flight control inputs in gusty crosswinds during takeoff.
2. Continental has four Boeing 737-800 FFS training devices that have atmospheric models that provide crosswind training in gusty winds during takeoff. Because all Continental 737 pilots operate all of the 737 models Continental has in line operations, each pilot receives training in all available 737 fleet variant training devices. Thus, the pilots are exposed to crosswind training in gusty winds during takeoff on the 737-800 FFS and therefore, the 737-500 FFS is not the sole means for crosswind training.
3. Flight control inputs for steady-state crosswind takeoffs versus gusty conditions only differ in amplitude and frequency. The training pilots receive focuses on procedures, which are the same regardless of the specific crosswind conditions pilots may encounter.
4. Under the Advanced Qualification Program (AQP) training program training tasks are accomplished in various levels of training to include, written documentation, flight crew briefings, Flight Simulation devices, and operating experience in the aircraft with an FAA approved check airmen. Initial Operating Training (IOE) training in the 737-500 aircraft with a qualified check airman is also considered a part of training. Pilots are not considered qualified until training standards have been met or exceeded in all phases of the training program.

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[54] Airplane Performance Study, page 8.

4.2. Back-Drive Simulation Study[55]

Operations/Human Performance Group Members and others observed a back-drive simulation of the accident sequence derived from FDR data. A stated purpose of the simulation was to better understand what the flight crew experienced.

The back-drive re-created the visual scene from the cockpit, flight control inputs, and aircraft accelerations based on FDR parameters. Boeing provided information describing the characteristics of the back-drive simulation. These are all **subjective** comments by pilots who knew in advance what was about to happen and should be ignored.

Nevertheless, several excerpted comments from participants in the simulation demonstrate the Captain's predicament:

- I believe there was a disconnect between what he's doing and airplane's response. Probably a distraction around 100 knots when he took the rudder out. We did a run where we closed our eyes and I opened them when I felt the airplane was sliding sideways. When I opened my eyes, the airplane was already headed 3 or 4 degrees off centerline. His impression may have been that something happened to the airplane. If he was distracted, he would have had only seconds to reconstruct his mental model of the situation and he may have run out of time.[56]

- The use of full rudder and hitting the stop with only a little right heading change might have shaken his confidence at that point.

- I can't explain what occurred afterwards. I think there was a distraction of some sort right about a hundred knots give or take, where his concentration on the outside diverted momentarily .… He was controlling the aircraft and then suddenly headed to the left side of the runway.

- Rudder input almost full extension of my right leg.

- Felt like he had rudder in the whole time after the first input. [Right seater: You would feel it if in your leg muscles you were maintaining right rudder.]

- [Simulated grabbing the tiller at the end.] Feels like he does have rudder in as the airplane is veering left. Do not think he felt more right rudder would help.

- I can't explain that. I don't know what would have caused the lack of rudder. The second rudder input didn't feel like it was that much. The first one felt like a pretty good right rudder input. [Observer question – when would you have rejected? Answer: If I had full right rudder in and it was still heading off the runway.]

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[55] Operations/Human Performance Group Chairman's Factual Report, Back-Drive Simulation Study, dated Aug. 27, 2004.

[56] Continental does not believe the Captain was distracted, and the Captain insists that he was not.

- Seems like there is a gust acceleration during the big yaw unrelated to pedal.
- Feels like gusts hitting as rudder coming out the last time, as if the gusts hit him at a bad time.
- In my opinion, the airplane was veering left while he had right rudder … Even with full right rudder at 80 knots, I would think that you would be overdoing it, but that wasn't the case. The best he could do was barely keep the nose tracking the way it needed to be tracking. The nose never went too much to the right, and he had to make a full right rudder input to get the right movement at 80 knots.

Even some of the pilots sitting in the simulator without the pressure of an emergency situation clearly recognize the Captain's desperate circumstances.

4.3. Boeing's Crosswind Guidelines

The NTSB asked Boeing to explain the operational meaning of a Boeing crosswind "guideline," the methods Boeing used to develop the 737-500 dry runway crosswind guideline, and whether Boeing thinks crosswind guidelines for the 737-500 should be revisited.[57] Boeing responded, in part:

> Under federal aviation regulations, aircraft manufacturers are not required to establish crosswind guidelines. However, Boeing has provided additional manufacturer guidance for both dry and contaminated runways.
>
> It is assumed that a pilot will use basic airman skills, including normal crosswind techniques. There is also an expectation that a pilot will utilize the control capabilities provided to him/her.
>
> As discussed during our meeting in Seattle last month, Boeing does not believe it is necessary to revisit its crosswind guidelines. Millions of hours of service suggest that the current guidelines are sufficient. The lack of rudder pedal input as Flight 1404 departed the runway makes this an inappropriate case to base changes to the crosswind guidelines, as there is no data suggesting that the crosswinds experienced during this event exceeded the capability of the airplane.

Instead of simply answering the questions, Boeing provided analysis, but no support, especially for the statement that the lack of rudder pedal input "makes this an inappropriate case to base changes to the crosswind guidelines, as there is no data suggesting that the crosswinds experienced during this event exceeded the capability of the airplane." Boeing made this incorrect statement in Addendum 5, dated October 14, 2009, to the Operations/Human Performance Factual Report before the release of the Airplane Performance Study, on December 8, 2009, which describes the strong, gusty, localized crosswind experienced by Flight 1404. The absence of expected right yaw response and lateral acceleration to the second aggressive right rudder input in the face of a wind gust of 45 knots, demonstrates that the strong, gusty, localized

[57] Operations/Human Performance Group Chairman's Factual Report – Addendum 5, Boeing's responses to questions about crosswind guidelines.

crosswind experienced during this event resulted in the lack of control of the airplane. See Section 3.2

The Continental Boeing 737 Flight Manual contains a 33-knot crosswind component guideline for a dry runway. The manual contains a note that states, "The crosswind guidelines presented below were derived through flight test data, engineering analysis, and piloted simulation evaluations. Therefore, the use of these guidelines should be based on the current weather conditions and the pilot's ability and experience level."[58] According to Boeing, the maximum demonstrated crosswind component for takeoff and landing in the B-737-500 was 35 knots. This figure was demonstrated during the certification, and was not considered limiting on a dry runway with all engines operating.[59] In a supplemental type certificate report, Aero Tec (on behalf of Aviation Partners Boeing, the manufacturer and installer of winglets installed on the accident airplane) subsequently published a maximum demonstrated crosswind component of 22 knots for a winglet-equipped B-737-500.[60]

Boeing's most recent crosswind guideline for the B-737, published in 1996, is for a dry runway for the B-737-500 at 40 knots.[61]

Continental Airlines established a dry runway crosswind takeoff guideline of 33 knots for its B-737 fleet based on the maximum demonstrated crosswind of 33 knots listed in the Aviation Partners Boeing publication, Airplane Flight Manual Supplement for the Boeing 737-800-3 with Aviation Partners Boeing Blended Winglets.[62]

Continental's selection of a 33-knot crosswind component guideline for its B-737 fleet was conservative, compared to Boeing's recommendation of 40 knots. The 22 knot demonstrated crosswind component is not relevant, because that simply happened to be the wind that was present on the date the flight test was conducted.

4.4. Air Traffic Control Factual Report

The Air Traffic Control Factual Report demonstrates operations were proceeding normally during the minutes before Flight 1404 began its takeoff roll.

- 1816:30 a Skywest regional jet, call sign Skywest 5973, departed Runway 34L with surface wind of 270 degrees at 22 knots on a 345-degree departure heading.

- 1816:34, a Frontier Airlines Airbus A319, call sign Frontier Flight 811, was put into position and hold on Runway 34L.

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[58] Operations/Human Performance Group Chairman's Factual Report, Section 1.6.3.1, page 20.

[59] Operations/Human Performance Group Chairman's Factual Report, Section 1.6.3.2, page 20.

[60] Operations/Human Performance Group Chairman's Factual Report, Section 1.6.3.2, page 20.

[61] Operations/Human Performance Group Chairman's Factual Report, Section 1.6.3.2, page 20.

[62] Addendum 4 and Corrections to the Operations/Human Performance Group Chairman's Factual Report.

- 1817:27, the tower controller issued COA 1404 the wind of <u>270 at 27</u>, assigned a heading of 020 and cleared COA 1404 for takeoff on Runway 34R.

- 1817:35, COA1404 acknowledge takeoff clearance with “heading zero two zero cleared for takeoff runway three four right continental fourteen zero four.”

- After COA1404 started its takeoff roll, a Learjet, call sign Solutions 623, was put into position and hold on Runway 34R at 1817:43. Solutions 623 acknowledged and accepted this position and hold instruction.

According to the Local Controller in charge of the west-side runway complex (LC3/4), traffic was “… heavier than normal for a Saturday ….”[63] This same Local Controller was also responsible for Runway 25.[64] Despite the higher traffic volume, air traffic control tower management combined the LC3/4 position, which usually has two controllers on duty.[65]

Frontier 811 was one of three additional aircraft that accepted a north-bound runway around the time that Flight 1404 accepted Runway 34R for departure. At 1817:50, Frontier 811 was in position and holding on Runway 34L, and questioned the Local Control 3/4 controller, “[w]ind shear alerts for runway three four left for eight eleven?” The tower controller responded with: “Frontier eight eleven I’ve not had any for three four left at all, the only thing I’ve had for this side of the airport [west side] was momentarily down on [Runway] two five.” At 1818:13, Frontier 811 was issued the wind of 270 [degrees] at 24 [knots], fly heading 345, Runway 34L, cleared for takeoff. Frontier 811 acknowledged and accepted the takeoff clearance.

The CVR transcript reveals that the tower reported to Flight 1404 at 1817:26 when issuing the takeoff clearance: “Continental fourteen zero four **wind two seven zero at two seven** turn right heading zero two zero runway three four right cleared for takeoff.” There was no mention of a gust or windshear.

As stated in Section 2.3, the tower local controller who issued the takeoff clearance had wind information on his display for both the approach and departure ends of Runway 34R. The wind issued to Flight 1404 was provided by LLWAS sensor #3 located closest to the departure end of Runway 34R.[66] However, LLWAS sensor #2 located closest to the plane’s ground path displayed crosswinds ranging from 30 to 40 knots during the period before the controller issued the takeoff clearance. Moreover, the two-minute average airport wind speed and direction and airport wind gusts from LLWAS Wind Sensor #2 (Airport Wind Sensor) at 1817:23 was 280 degrees at 34 knots with gusts to 40 knots, and showed average gusts from 35 to 40 knots beginning at 1815:12 until after the accident. No weather source ever reported any gusts to the crew.

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[63] ATC Factual Report – Interview Summary of the Local Controller, page 27.

[64] ATC Factual Report, pages 8, 21, & 25.

[65] ATC Factual Report – Interview Summary of the Local Controller, page 27.

[66] This is confirmed by the ATC Factual Report, page 8: “The RBDT displayed wind from the LLWAS sensor closest to the approach and departure end of the runway(s) for which the controller was responsible. For example, the LC4 had wind information available to him for the approach and departure end of runways 34L/R and the departure end of runways [sic] 25.”

Figure 15[67] depicts the DEN ATCT ribbon display terminal wind display. The wind direction and velocity on this figure were not the ones pertinent to this accident, but those are listed in Table 1 on page 5. The controller's display would have shown the dramatic difference between the wind velocity, at the north and south ends of Runway 34R.

AW – airport wind, a 2 minute overall airport average wind speed and velocity, currently displaying the wind at 100 degrees at 4 knots.

The runway wind sensors display a 30 second wind average for
34RD - runway 34R departure winds – 090 degrees at 5 knots
34LD – runway 34L departure winds – 140 degrees at 3 knots
34RA – runway 34R arrival winds – 100 degrees at 4 knots
34LA – runway 34L arrival winds – 120 degrees at 5 knots
07A – runway 7 arrival winds – 120 degrees at 4 knots
25D – runway 25 departure winds – 120 degrees at 4 knots

Figure 15 – DEN ATC ribbon display terminal (RBDT) wind display.

[67] ATC Factual Report, page 12, Figure 3. The AW should be wind direction and velocity.

5. Proposed Conclusions

5.1. Proposed Findings

1. During the period preceding the accident, there was a rapid increase in both wind speed and gustiness in the vicinity of DEN, notably on the south half of Runway 34R.

2. If the flight crew had been advised of actual current wind conditions, they would have recognized immediately that the crosswind exceeded Continental's 33-knot guideline and delayed their departure or requested another runway.

3. The winds displayed by LLWAS sensor #2 should have been communicated to the crew. Even assuming air traffic control tower personnel were following FAA procedures, it makes no sense to provide the lower wind velocity when a higher wind velocity is displayed for that same runway, especially in a crosswind or tailwind situation.

4. Air Traffic Control personnel inappropriately maintained a north takeoff flow in the face of very strong and gusting westerly winds.

5. The Flight 1404 crew unexpectedly encountered strong, gusty, localized crosswind conditions that suddenly presented them with an extraordinary set of management challenges. The Captain properly used right rudder, and his first large input succeeded in bringing the nose of the aircraft to the right. However, the second large rudder input did not stop the plane's yawing or weathervaning motion to the left. If the airplane had responded to the Captain's rudder input in the manner he expected, the aircraft would have stayed on the runway. Instead, the Captain was immediately faced with a desperate situation to which he responded appropriately under the circumstances.

6. Boeing's crosswind guidelines do not take into consideration the significant differences between the classic and new generation 737 aircraft. Airlines do not have access to all the data needed to properly establish guidelines for all models/variants.

7. The strong, gusty, localized crosswind exceeded the capability of the aircraft. As explained in Section 3.2, the sideslip angle was larger than what could be corrected with maximum rudder deflection, and the rudder was incapable of overcoming the left yawing moment. The vertical stabilizer with the rudder deflected could not generate enough lift to compensate for the sideslip resulting in the failure of the rudder to maintain directional control of the aircraft.

8. The nearly straight track the aircraft took as it exited the runway and traversed the sloping terrain was a result of the Captain's successful use of his piloting skills. His action was responsible for the aircraft remaining upright, and not tumbling on its side as the Captain believed would have happened.

9. The evacuation was successful in mitigating further injuries.

5.2. Proposed Probable Cause

5.2.1. Causal

A strong, gusty, localized crosswind condition unknown to the crew caused the aircraft to weathervane or yaw rapidly to the left as it accelerated during the takeoff roll despite the Captain's proper use of right rudder. The yawing moment caused by the unexpected violent wind gust exceeded the ability of the rudder to control the aircraft resulting in the aircraft departing the runway surface.

5.2.2. Contributing

The failure of ATC personnel and FAA procedures to provide safety critical wind information resulted in important wind information not getting to the crew. There was wind information available to ATC that, if known to the crew, would have prevented this accident.

6. Proposed Recommendations

1. The FAA should evaluate and change its procedures for evaluating and disseminating surface wind information to flight crews. If wind information is displayed for a runway on two different sensors, the crews should be given the wind information from the sensor displaying the highest velocity and the location of that sensor.

2. The FAA should examine the criteria for preferred runway assignment for takeoff. Safety of flight, rather than flow, should be the controlling consideration for this process.

3. The FAA should enhance training of ATC personnel to make better use of available weather reporting assets such as Terminal Doppler Weather Radar (TDWR), Next Generation Radar (NEXRAD), or other available technologies, to monitor dangerous wind patterns.

4. The FAA should provide sufficient staff, commensurate with traffic volume, so that controllers can maintain critical situational awareness and fully assess risks associated with their traffic load.

5. Additional wind sensors designed to provide accurate wind information for aircraft landing and taking off should be installed adjacent to runways at airports subject to strong, gusty, localized crosswind conditions, like DEN.

6. The FAA should consider mandating crosswind guidance for aircraft certification to include strong gusts.

7. The FAA should require Boeing and other manufacturers to develop and recommend to operators suggested guidelines for operations in crosswinds for each aircraft variant.

8. The FAA should ensure that all flight simulators are capable of simulating strong, gusty conditions on the surface.

9. There have been thorough studies and training aids developed based on windshear and microburst accidents. This accident highlights the need for a similar study of the effects of strong, gusty, localized crosswinds on arriving and departing aircraft and, if appropriate, training aids should be developed.