V. Flight Crew Scenarios

The previous sections of this submission considered and reviewed theoretical airplane rudder system failures that could have contributed to the Flight 427 accident. In a similar manner, the possibility of a flight-crew-related event must be examined. Therefore, this section thoroughly reviews various aspects of the crew's performance and actions before, during, and after the encounter with wake turbulence.

Analysis of flight crew performance forms an integral part of any accident investigation. Such analysis is usually facilitated by a thorough examination of the DFDR and CVR records. While the CVR record for this accident is remarkably clear, the DFDR lacks sufficient parameters to fully describe the crew's control inputs. Consequently, this discussion of possible flight crew performance scenarios also includes the results of the kinematic analyses, as well as known facts about other crews' performances following unexpected flight-path upsets. Scientific studies are referenced that offer further insights as to why a professional flight crew, experienced in line operation, could respond in the manner described below.

In reviewing this section, it must be realized that the critical stimuli, reactions, and any crew decisions occurred within about six seconds after the wake turbulence encounter. The impact on the crew of such a short, compressed, and dynamic series of events is difficult to appreciate in the context of a detailed and thorough investigative analysis, yet it is the key to understanding what follows in this section.

A. Operational Evidence

Before examining the details of any flight crew scenario, it is important to first understand that experienced crews do not always respond to flight path upsets in a predictable or routine manner, particularly when they are suddenly surprised. While today's commercial flight crews are well-trained professionals, they spend most of their time flying in the rather benign environment of typical passenger-carrying operations. This environment is often characterized as boring and uneventful. Hence, the onset of sudden, unexpected events can startle a pilot. Moreover, such events tend to exaggerate human perceptions of the airplane's response, and perhaps evoke human reactions that may seem contrary to what one might expect.

Operational reports—such as those listed in Appendix D, and described in the document[23]—offer insight into such reactions. A review of these reports reveals several important facts about how some flight crews perceive and react to unexpected encounters with turbulence. The examples provided below are in some cases repeated to illustrate more than one of the points made in bold text. The numbers in parentheses at the conclusion of each example list the divider tab numbers of the submissions supplement for reference purposes.

1. **Encounters with wake turbulence can surprise or startle experienced flight crews.**
   - ASRS 293944 (Jan. 1995). A 737-200 encountered wake turbulence from another 737 at 4,000 ft AGL. The pilot flying reported that upon encountering the turbulence, "the nose abruptly pitched up 5 – 10 degrees and the aircraft rolled 40 degrees to the left." The pilot disconnected the autopilot. "The severity of this encounter surprised me.... Had I been distracted by looking at a chart or checking engine instruments, etc., I could have very easily ended up on my back, and this was from another 737!" (60)
   - 737 event (June 1995). Crew reported uncommanded upset that produced aircraft roll of "at least 45" degrees. Upon landing, the crew was observed to be "visibly shaken." According to the crew, "AC felt out of control, very mushy," and, "She didn't think she could control the AC." FDR showed actual roll to be 18 degrees. (5), (55), (56), and (57).

[23] *USAir 427 Submissions Supplement: Human Factors,* Boeing, Sep. 25, 1997.

- ASRS 286702 (Oct. 1994). A 737-300 crew encountered wake turbulence from a 727 during approach. Crew reported that while in a 12-degree left bank, wake turbulence from the 727 "rolled the a[ircraft] to the r[ight] about 12 deg[rees], requiring 30 deg[rees] of yoke travel, and pitched and yawed the a[ircraft] an unstated amount. These perturbations lasted about 8 seconds." Crew was "surprised" by the severity of turbulence. (9)
- ASRS 188899 (Sep. 1991). Captain of medium-large transport experienced more wake turbulence from a preceding large aircraft than was usual during a visual approach with about 3.5 miles separation. He elected to fly about 1 dot high on GS to stay out of his wake. At about 50 ft AGL the "a[ircraft] rolled rapidly r[ight] then violently l[eft]." He countered with full right aileron. Aircraft continued left roll and captain initiated a go-around. Pilot stated that, "Never in 27 y[ears] have I experienced such wake turb[ulence]." (10)
- 737-300 event (Aug. 1995). Crew reported that the airplane "shuddered and shook similar to wake turbulence," and rolled left 30 degrees. FDR showed actual roll to be 19 degrees. "Both crew [were] startled by rate of roll." (91)
- ASRS 280652 (Aug. 1994). A medium-large transport encountered wake turbulence from large transport at FL330. "The possible wake was exceptionally strong, rolling our a[ircraft] into a 20 deg[ree] bank, and disengaged the autopilot. It lasted about 10 seconds at which point we returned to smooth air." Crew stated that "I have never experienced a wake this strong at such a high alt[itude]." (15)
- The NASA ASRS Multi-Engine Turbojet Uncommanded Upsets Structural Callback Summary, dated November 8, 1995, contains a compilation of loss of control factors in multi-engine turbojet upsets from January 1987 to May 1995. (93) This compilation shows that encounters with wake turbulence are far and away the leading cause of events in which pilots report loss of control. Over twice as many loss of control events are attributed to wake turbulence as to the next leading cause. (94)

2. **Crews typically over-perceive the magnitude of unexpected rolls by a factor of two or three, and may react accordingly.**
   - CAA Air Traffic Control Evaluation Unit, ATCEU Memorandum No. 197, "The Vortex Reporting Program: Analysis of Incidents Reported Between January and December 1992." Pilots in 15 of 20 reported events believed the upsets to have been more severe than the FDR showed them in fact to have been. In one case, a pilot believed he encountered a 30 degree roll, when the FDR showed the roll to have been 7 degrees. (32)
   - *Safety Issue Analysis and Report on Boeing 737 Uncommanded Rolls,* FAA Safety Analysis Branch Office of Accident Investigation (Sep. 1995). The report indicates that "pilots typically overstate the degree of roll in an event." Pilots in 7 out of 7 reported events (US domestic airlines) believed the upsets to have been more severe than the FDR showed them in fact to have been. (86)
   - 737-300 event (Aug. 1995). Crew reported that the airplane "shuddered and shook similar to wake turbulence," and rolled left 30 degrees. FDR showed actual roll to be 19 degrees. "Both crew [were] startled by rate of roll." (91)
   - 737-300 event (Nov. 1995). At 7,000 feet, crew reported that the "airplane rolled 20 degrees right ..." and "...airplane felt squirrelly, and [pilot] was afraid that if it banked more than fifteen degrees it would keep going." FDR showed the largest roll to be less than 3 degrees to the right. (95)

- 737 event (Oct. 1995). Crew reported that during approach at 4,000 feet with autopilot engaged, the airplane "starts suddenly to roll hard to the left." Crew disconnected the autopilot, then approximately 45 seconds later the airplane again rolled to the left, "exceeding 30 [degree] bank." FDR showed the largest roll to be less than 8 degrees. (24)
- 737-500 event (Feb. 1996). Crew reported an uncommanded left roll to 25 degrees which occurred while the autopilot was engaged. FDR showed the largest left roll to be about 10 degrees. (46)
- 737-300 event (Apr. 1997). Crew reported that the airplane rolled right to approximately 30 degrees in 1 to 2 seconds. FDR showed the maximum bank angle reached was approximately 15 degrees with a roll rate of 7 degrees per second. (58)

3. **Flight crews typically respond to unexpected upsets by immediately manipulating the flight controls. Both wheel and rudder inputs are often used during recovery.**
   - ASRS 251615 (Sep. 1993). A crew of a large transport reported that their aircraft at cruise altitude rolled violently to the right and then to the left. "The Capt.'s control inputs were full opposite aileron and rudder." (44)
   - ASRS 220642 (Sep. 1992). A flight crew of a medium-weight transport reported that they encountered turbulence during an autopilot climb. The crew disengaged the autopilot and commanded "considerable left rudder" and left wheel. (42)
   - ASRS 190748 (Oct. 1991). After taking off and passing 1,200 ft MSL, crew of a medium-large transport encountered severe wake turbulence from a previously departing large transport. Crew reported that "PF was struggling to retain a[ircraft] c[ontrol], using full fl[ight] c[ontrol] inputs to counteract the roll rate." (65)
   - 737 event (Sep. 1995). The F/O "experienced an abrupt left roll to about 25 degrees" during cruise with autopilot engaged. "The captain took hold of control wheel and applied immediate aileron and input right rudder." F/O reported "it felt like wake turbulence." (90)
   - 737 event (July 1995). Crew responded to a misunderstood autopilot commanded right roll of 30 degrees by using left rudder and left wheel. The left rudder was not removed for the remainder of the flight (the crew made left rudder inputs from 5.5 to 1.5 degrees for the remainder of the flight). The crew offset the left rudder inputs by cross-controlling with right wheel and right wheel trim. (6)

4. **Airlines are now teaching their pilots to use rudder to counter rolls caused by wake turbulence.**
   - In the unusual attitude training programs that have been initiated in recent years, airlines have been training pilots to use rudder to recover from roll upsets caused by wake turbulence. In the written instructional material associated with one of these programs, the airline has acknowledged that the perceived consequence of a wake turbulence encounter is a "rolling moment on the aircraft [that] can be dramatic." According to this airline's training materials, pilots are instructed that "rudder is an effective means of roll control" in responding to a wake, and pilots should "rapidly roll wings level utilizing aileron and rudder." (92)

5. **Flight crews have on occasion misapplied the rudder, used the wrong rudder altogether, or have failed to remove rudder inputs when they are no longer necessary.**
   - 737 event (June 1997). The crew of a 737 encountered wake turbulence from a 747 that was positioned approximately seven miles away, causing the 737 to roll 20 degrees to the left. The autopilot responded with a right wheel input. The crew overrode the autopilot with an additional right wheel input. The crew

also made a right rudder input. While continuing to command right rudder (at times commanding close to the maximum rudder available), the crew made several left and right wheel inputs. The airplane recovered from the left roll, rolled through wings level, and rolled to a 17 degree right wing down configuration. Still the crew commanded right rudder. The airplane was "cross-controlled" for much of the recovery. (59)

- 737 event (July 1995). Crew responded to a misunderstood autopilot commanded right roll of 30 degrees by using left rudder and left wheel. The left rudder was not removed for the remainder of the flight (the crew made left rudder inputs from 5.5 to 1.5 degrees for the remainder of the flight). The crew offset the left rudder inputs by cross-controlling with right wheel and right wheel trim. (6)
- 737-300 event (Oct. 1986). F/O encountered rapid roll oscillations on first approach. Captain took over and had no difficulty controlling aircraft. On second pass, F/O was again in command and again encountered control difficulties. The captain took over and landed uneventfully. The FDR showed that when the F/O was flying the approaches, right rudder inputs were made, which were countered on both approaches with left wheel. "On both approaches the rudder pedal increased to near full deflection." (25).
- On March 8, 1994, Sahara India Airlines conducted a 737-200 training flight in New Delhi. As the aircraft was completing a touch-and-go, the instructor pilot initiated an unscheduled engine-inoperative training exercise in which he retarded the left engine thrust lever just after takeoff rotation. The FDR and CVR indicate that the trainee initially responded to the asymmetric thrust by applying right wheel and some right rudder. Following a "rudder, rudder, rudder" comment from the instructor pilot, the trainee applied full left rudder. The instructor pilot took over the controls and removed the left rudder before the airplane crashed. The Indian Court of Inquiry and Ministry of Aviation concluded that "the accident occurred due to the application of wrong rudder by trainee pilot during engine failure exercise." (See Appendix C for more information.) (29)
- 737 event (April 1993). Crew responded to wake encounter by commanding left wheel and right rudder and then commanding left rudder. (96)
- NTSB Aircraft Accident Report, Sept. 6, 1985, Midwest Express Airlines DC-9-14 at Milwaukee, Wisconsin. During the initial climb following takeoff, there was a loud noise and loss of power from the right engine. The aircraft continued to climb, but then rolled to the right until the wings were observed to be in a near vertical, 90 degree right bank. The aircraft entered an advanced stall and crashed. The NTSB found that "the crew response to the right engine failure was not coordinated" and that "the rudder was incorrectly deflected to the right 4 to 5 seconds after the failure of the right engine." (37)

  The NTSB also noted that "[i]n the course of this investigation, the Safety Board learned of several simulated engine failure incidents in which pilots responded initially with deflection of the incorrect rudder pedal.... A Douglas test pilot, who had flight instructor experience in the DC-9, testified to a personal experience where a pilot who was receiving DC-9 instruction commanded rudder deflection in the wrong direction in response to a simulated engine failure. An FAA DC-9 instructor, with extensive training experience, testified that about 1 of every 50 of his students, each of whom held an airline transport pilot certificate, had attempted to deflect the wrong rudder pedal during simulated engine failure on takeoff." (37)
- Air National Guard C-130 accident near Evansville, Indiana, in which the flight crew was returning to its home base. The F/O applied the wrong rudder, causing the aircraft to roll excessively and crash.
- Airlines today acknowledge that wrong-rudder crew inputs occur in various circumstances. One airline has written in its instructional material that, in pilot

responses to low-airspeed, high-drag situations, "Our biggest problem has been stepping on the wrong rudder!!" (92)

6. **There are occasions when crew members have independently commanded the controls. In some instances, one crew member has been unaware of the other crew member's rudder input.**
   - 737 event (June 11, 1980). The F/O was flying a 737-200 on approach. At 800 feet, captain noted and called attention to an increase in airspeed and rate of descent. He expected the F/O to reduce power. Just as the captain touched the power levers intending to initiate a missed approach, the aircraft slued to the left in a wild descending uncoordinated turn caused by the F/O becoming incapacitated. The captain encountered 45 degrees of bank. He pushed the power levers to the forward stops and was able to roll out of the bank, but chose not to because the airplane felt "funny" and "uncoordinated." A male flight attendant then entered the cockpit and discovered that the cause of the steep turn was that the unconscious F/O's leg was holding full left rudder. In the NTSB interview, the captain said he was "startled at the beginning of the incident" and "was surprised he did not realize that the rudder was in." (97) (Witness Interview, Attach. 2, Fourth Addendum, Human Performance Factual Report, Nov. 8, 1996)
   - ASRS 72048 (July 1987). Crew of a medium-large transport encountered wake turbulence from a large transport during a visual approach at 2,000 ft. Crew reported that the "aircraft began roll to right, full opposite aileron was applied, with both p[ilots] on controls. Aircraft continued to roll to a bank angle exceeding 75 deg[rees] of bank, stick shaker and g[round] prox[imity] warning system sounded." (12)
   - ASRS 276165 (July 1994). Flight crews of a large transport encountered crosswind and possible wake turbulence, and had control difficulty during landing. Crew reported that "in the flare the a[ircraft] picked up a l[eft] to r[ight] drift. F/O tried to compensate with rudder and aileron" while captain was flying. (81)
   - 737 event (Mar. 1995). Crew encountered an upset due to a right yaw damper kick. The captain thought the roll acceleration experienced was sufficient to roll the aircraft "on its back" if left unchecked. The F/O stated that he thought he applied right rudder in response to the kick; the captain said that he applied "1/4 left rudder" with "no effect." (33)
   - 737-300 event (June 1995). Airplane encountered upset while autopilot was engaged. Crew reported that the aircraft "began an uncommanded roll of up to 30 to 45 deg[ree]s to the l[eft]. Both p[ilots] applied aileron input to correct. F/O applied R[ight] rudder...." According to the flight crew, this upset lasted as long as 8 seconds. (5)
   - ASRS 92829 (Aug. 1988). Crew of a light aircraft stated that "during the l[anding] and roll out the a[ircraft] began to veer to the right." "In an effort to assist the cap[tain] I attempted to apply full left rudder and found that the capt[ain] had already done so." (80)

In summary, there is substantial evidence that professional flight crews can be surprised by unexpected wake turbulence encounters. These events can last for more than a few seconds, and tend to be perceived as more severe than they actually are. The latter fact is not surprising, given the inner ear's primary sensitivity to roll *accelerations*. Crews subsequently respond with rapid control inputs that sometimes are, or could become, inappropriate. Although general pilot training has traditionally been expected to overcome such normal human reactions during unexpected upsets, the industry has recently recognized the need for specifically designed upset recovery training in full-flight simulators, and has implemented such training on a routine basis. The performance of the flight crew of Flight 427 must be viewed in light of these operational findings and new training insights.

B. Possible Crew Scenario

Why would the flight crew put in left rudder, and then persist with that input? Several sources of evidence help explain this apparent puzzle and show how it is consistent with known human behavioral tendencies. Some of this evidence comes directly from the accident investigation. Indirect evidence is provided by the operational data discussed above, and by findings from the scientific literature.

Explanation for Initial Left Rudder Input

Central to understanding the usage of rudder in this scenario is understanding why one crew member *initially* commanded the left rudder. The startling nature of the wake-induced upset, combined with the relaxed state of the crew beforehand, together provide a possible explanation. At the time of the wake vortex encounter, the crew was on its third flight of a three-day trip, and on approach to a very familiar home-base airport with no reason to expect any unusual event. The weather was ideal on a balmy, late-summer early evening. The F/O was flying the airplane by utilizing his autoflight systems, and had also just performed a number of tasks usually performed by the pilot not flying.

Just before the final descent, the pilots had been joking with a flight attendant in the cockpit, and had neglected to make a series of required altitude calls during the descent. The crew's attention became briefly focused on a traffic call from ATC. Because the reported traffic was positioned in the lower forward corner of the number-two window, the F/O was most likely leaning forward and looking down on the right side toward the aircraft 2,000 feet below. After a 30 second delay, he announced that he saw the traffic, doing so jokingly in an drawn-out, feigned French accent. This jocular expression illustrates the crew's relaxed state of mind.

As the F/O spoke, the aircraft suddenly encountered the wake vortex. The result was an unanticipated left roll with an unusually large left roll acceleration accompanied by vertical turbulence. Almost simultaneously, the captain exclaimed "sheeez" and the F/O abruptly ended his sentence with a "zuh." Both outside CVR experts retained by the NTSB have independently interpreted these recordings as involuntary vocal reactions to a sudden, surprising physical stimulus.

As the autopilot attempted to initiate a roll back to the right, the airplane went in and out of a wake vortex core, resulting in two loud "thumps." Immediately, the F/O manually overrode the autopilot *without* disengaging it, putting in a large right-wheel command at the rate of 150 deg/sec (see Section II, Figures 2 and 3). The airplane started rolling back to the right at an acceleration that peaked at 36 deg/sec^2. As a result, the crew experienced a dramatic change in roll acceleration of 54 deg/sec^2 within just 1.8 seconds. The captain inhaled and exhaled rapidly before exclaiming, "whoa."

At this point, the analysis shows that the rudder deflected left, with a corresponding left pedal motion, followed closely by a removal of much of the right wheel input. The timing of the left rudder input, and the subsequent removal of the right wheel command—both of which are left roll commands—suggest that both actions were conscious attempts to control the rapid right roll acceleration that resulted from the right wheel inputs. Support for the intentional character of these initial inputs is provided by Figure 3 in Section II, which depicts both FDR and kinematically derived control inputs together with the CVR data. Note that the changes in inputs are not disjointed, but rather appear to be timed in close proximity and related to one another. For the next 2.7 seconds, the F/O continued to maneuver the airplane aggressively while remaining in the autopilot's CWS mode.

Further support for crew usage of rudder to control or "slow down" the roll acceleration forces associated with the right wheel input can be found in operational data. For example, in April 1993, a 737 encountered wake turbulence that produced a left roll. The crew—like that of Flight 427—responded with a significant right wheel command. As the airplane rolled back toward wings level, the crew—again like that of Flight 427—commanded left rudder to control the recovery and reduce the rate of the right roll. (96)

It should be noted that the NTSB Human Performance Team also examined the possible contribution of vestibular disorientation in the USAir accident. They concluded that the VMC conditions made this unlikely.

Explanation of Sustained Left Rudder Input

The subsequent performance of the Flight 427 crew can be explained in accordance with either of two possible rudder scenarios defined by the kinematic analyses discussed in Section II-B:

1. In the first scenario, the F/O intentionally commanded left rudder inputs twice, the second time in a inappropriate effort to repeat the apparently "successful" solution that had initially corrected the large roll acceleration to the right.
2. In the second explanatory scenario, the F/O intentionally commanded left rudder once (see Figure 4).

In either scenario, the F/O persisted in this left pedal input when he became focused primarily on making lateral control wheel inputs to counter the roll oscillations. It should be noted that in both the above possible scenarios, there would be no reason for the F/O to have verbalized any conflict with his desired rudder control inputs, nor would he have demonstrated physical strain in his actions on the rudder pedals. The lack of such comments or evidence is consistent with the CVR record of this accident.

One major factor contributing to the F/O's persistence in putting in left rudder may have been the confusion he experienced in trying to sort out the airplane's response to his roll-control inputs. Given the rapidity of the accident event sequence and the brief time available to him, this confusion would have led to an increasing focus of attention on attempting to make correct wheel inputs. As a result, he may very well not have been aware of the position of his lower limbs or feet. This explanation is supported by the following facts:

First, the crew kept the autopilot engaged during the initial portion of the attempted recovery. Here, the autopilot remained in the CWS mode when the crew overrode the autopilot by making rapid and extreme inputs. The higher than normal forces required to move the wheel in these circumstances (approximately 40 pounds) could distort the normal flight control feel and the pilot's perception of how the airplane is responding to individual flight control inputs.

Second, during the first five seconds after the upset, the airplane's feedback to control inputs was modified by the wake vortex as it affected the airplane's flight path (roll rate and angle). For example, at time 137.0, as the wheel is being returned to neutral from 80 degrees right, the airplane (unbeknownst to the crew) is still under the influence of the right core of the vortex. As a result, it rolls rapidly to the left at a peak acceleration of 38 deg/sec^2, a change of nearly 74 deg/sec^2 in a period of just one second. In the short time available for evaluating the critical situation, the flying pilot's overall impression would likely have been that the airplane was not responding correctly or consistently to his control inputs.

Third, and potentially most significant, fear plays a strong role in narrowing and focusing human attention in life-threatening situations. With this fact in mind, it is important to realize that the most compelling external visual stimulus during the event was the increasing amount of ground seen through the cockpit windows. It is highly unlikely that either pilot had ever before experienced such a life-threatening view while flying a transport-category aircraft. This supposition is supported by their exercising the tendency to pull back on the control column.

The innate reaction tendency when facing such an overwhelming visual stimulus is to quickly attempt to use upper body control movements to escape. Such a situation would reasonably be expected to heighten the F/O's anxiety and concern, while substantially diminishing attention to, and awareness of, his lower-limb control inputs. As a result, his left foot would have remained in the position he last placed it before the attentional shift. Operational and scientific evidence both support this conclusion.

The operational evidence is highlighted by two 737 incidents described in Section V-A. In June 1997 and July 1995, two different 737 flight crews responded to unexpected upsets with both wheel and rudder inputs, then persevered with the *initial* rudder input while commanding multiple wheel reversals, resulting in a cross-controlled condition.

The scientific evidence supporting this conclusion comes primarily from accident analyses and operator studies in other modes of transportation. A series of studies conducted in the attempt to *understand unintended accelerations* in automobile accidents provides some key insights into how experienced vehicle operators, when startled, may misapply pedals, and then persist in those inputs, resulting in fatal accidents. Explanations for sustaining an inappropriate pedal input have evolved from this research, which is based on well-established principles of neurophysiology and can be traced back to 1935. Whatever the cause of the startle, these types of accidents reveal that people can and do make pedal errors, that these errors are more frequent than we had realized before, and that it is reasonable to think that pedal errors are involved in other modes of transportation as well.

The findings are particularly relevant to the portion of this accident occurring after the Flight 427 F/O has put in left rudder pedal and begins to aggressively manipulate the wheel and column in an attempt to improve the rapidly deteriorating situation. This aviation accident, and automobile pedal misapplication accidents, share several key behavioral events:

1. **Some level of startle is present**

   There is considerable evidence that human operators—i.e., automobile drivers or flight crews—can and do become startled. Startle may occur due to sudden changes in equilibrium, acceleration, or an unexpected change in the visual scene, etc.

2. **Activation of wrong pedal**

   Studies show that such immediate arousal causes individuals to consistently respond with faster and more forceful movements relative to comparatively less startling environmental events. In the case of unintended acceleration accidents, the driver behavior is "automatic" in that the human motor system is inherently variable in its output and can produce actions without much need for conscious attention.

3. **Lack of awareness of action/absence of feedback**

   Under the "automatic" action, the wrong pedal is pressed but the feedback from the foot is not processed by higher centers that lead to conscious perception of the foot's position. Rather, attention is devoted to the environment outside the vehicle, particularly what objects are to be avoided.

4. **Perseverance/failure to correct**

   To explain the persistence of the pedal error, the decrement in the operator's information processing due to hypervigilance or "panic" must be taken into account. This can occur when one has to respond to a life-threatening situation and there appears to be little time to reach a solution resolving the event. The way the human brain in a hypervigilant state processes information may hold clues to the Flight 427 accident. Specifically, information processing has been found to be severely disrupted in several ways, most notably:

   - **Narrowed focus of attention:** Sometimes referred to as "tunnel vision," the scope of the information transmitted to the brain is reduced under hypervigilance.
   - **Perseverance:** A hypervigilant driver will persevere with the same "dominant" response, repeatedly making that response even when it does not solve the problem. Responses further down the driver's hierarchy of possible reactions tend to be ignored.
   - **Visual capture and dominance:** Visual information tends to attract (or capture) attention and to dominate other sensory stimuli (e.g., kinesthetic). In other words, what is seen through the windshield during an unintended acceleration event dominates the driver's thought processing. Perhaps because hand movements are more closely tied to vision than are foot movements, researchers have observed an increase in steering behavior during sudden acceleration events. Other critical information that could prompt appropriate behavior—for example, removing the foot from the accelerator—is often simply not processed during hypervigilance.

As with unintended automobile acceleration events, there is no physical evidence of a malfunction from the Flight 427 rudder system that supports a theory of a mechanical failure causing the event. As explained previously, the initial left rudder input on Flight 427 can be viewed as an understandable response by the F/O to control the abrupt right roll acceleration. The most logical explanation for why this left rudder input was sustained is that the F/O, faced with a rapidly deteriorating situation in the continuing and potentially confusing effects of the wake, narrowed the focus of his attention to his upper body movements. The captain only reinforced this response by his instructions, captured on the CVR, to "hang on," "hang on," "hang on," and later "pull," "pull," "pull."

Left Rudder Input Not Corrected

The question remains, why did the captain not intervene and correct the prolonged inappropriate pedal input? Here again, the operational data show that one pilot is not always aware of rudder pedal inputs made by the other pilot, especially in times of stress.

For example, the Human Performance Group has studied a 737 event in which the F/O, who was the pilot flying, became subtly incapacitated during an approach. Noticing an increase in speed and rate of descent, the captain was about to assume command and initiate a missed approach, when the airplane slued to the left in a wild, descending, uncoordinated turn. Encountering a 45-degree bank, the captain pushed the thrust levers to the forward stops. He was able to roll out of the bank, but chose not to because the airplane felt "funny" and "uncoordinated." A flight attendant then entered the flight deck and discovered the cause of this turn: the leg of the unconscious F/O was holding a full left rudder pedal input! In the Human Performance Group interview, the captain said that he was "startled at the beginning of the incident," and "was surprised he did not realize the rudder was in." [24]

Moreover, in the June 1997 and July 1995 events discussed previously (see page 46), inappropriate rudder inputs remained uncorrected for many seconds or—in one case—for the remainder of the flight.

Given that there is general consensus that the captain of Flight 427 was not controlling the airplane through the wheel and column until after the stall, it is possible that he did not have his feet actively on the rudder pedals. It could thus be concluded that the captain was unaware of the position of the rudder pedals. This conclusion is further supported by the lack of any CVR comment by the captain regarding rudder pedal position.

Recoverability

The DFDR shows that the flight crew essentially applied full aft control column as the airplane passed through seventy degrees of left bank, and fifteen degrees of nose-down attitude. The crew continued to command essentially full aft control column as the left bank and nose-low maneuver progressed. The column reached its full aft limit at DFDR time 143.8. The stick shaker warning activated at FDR time 145, following which the airplane entered an accelerated stall. From DFDR time 146 until ground impact, the controls remained at full right wheel, full left rudder, and full aft column.

On June 4, 1997, Boeing conducted full rudder input flight tests on a 737-300. These tests verified that when a full left rudder input is introduced to a 737-300 in a flaps 1 configuration traveling at approximately 190 knots, *the airplane is recoverable.* The recovery is dependent upon the crew making correct, timely control inputs, namely applying right wheel without commanding excessive back pressure on the column. The flight test verified that the 737-300 simulation provides a reasonable match of the airplane characteristics, and therefore the recovery characteristics demonstrated in the simulator in the presence of the 727 wake are valid.

[24] Witness Interview, Attachment 2, Fourth Addendum, *Human Performance Factual Report*, Nov. 8, 1996.

C. Crew Performance Does Not Support System Failure

Analysis shows that the performance of the Flight 427 flight crew is inconsistent with scenarios in which the accident sequence was caused by an airplane rudder system failure. Three points provide compelling support for this conclusion:

1. Any rudder jam would have alerted the crew, since all jams result in pedal movement (i.e., left pedal in and right pedal out).
2. The crew's physical straining ceased when the autopilot was turned off.
3. In the scenario involving a secondary slide jam with primary slide overtravel, one or the other of the pilots must have had his feet on the rudder pedals because a crew input is required immediately prior to the jam in order to open the secondary slide enough to cause the amount of rudder deflection needed to match the kinematic analysis (see Section IV-B).

In each jam scenario, if the jam did not clear, the left pedal would move deliberately and steadily forward regardless of the amount of force exerted on the desired (right) pedal. In an NTSB Memo,[25] NTSB Human Performance Team Leader M. Brenner describes the vividness of this tactile-motion feedback, as experienced during a ground demonstration of a secondary slide jam: "The motion was steady and continued, without pause no matter how hard I pushed to counter it ('unrelenting' was a description that, at the time, seemed to capture my impression).... It was impossible to stop the motion by physically pushing against the pedal."

A dramatic and salient feedback cue of this nature would reasonably be expected to elicit crew comment at the start of the accident sequence (i.e., before the panic of a life-threatening situation arose). From a piloting standpoint, flight crews are normally aware of the direction of the control deflections they intentionally input, and generally overestimate the magnitude of the resultant deflections. Therefore, flight crews can reasonably be expected to notice the discrepancy if a control goes to extreme or full deflection *contrary* to their intended input.

Nevertheless, the CVR provides no discernible indication of crew disagreement with any flight control positions, either before or after the autopilot was disconnected. If a hardware failure had occurred, one must question why the flight crew said nothing in response to the rudder pedal moving *opposite* to the desired pedal input.

This lack of crew comment is especially surprising given the F/O's immediate reactions to other unexpected airplane system feedback during the pre-upset phase of the descent. He twice commented quickly and quite distinctly when the flight management computer (FMC) did not respond as directed (CVR times 1845:55 and 1854:44). Surely he would have been highly likely to respond in a similar manner if the rudder pedal had responded in the direction opposite to his command.

The CVR provides a final piece of evidence inconsistent with a hardware failure scenario. Two outside experts were asked to analyze the CVR tape for evidence related to breathing patterns and muscular exertion. Both experts testified that the F/O appeared to be the only pilot forcibly manipulating the controls after the upset, and that his rapid, grunting exhalations were indicative of physical straining. As described by one of these individuals who is a US Navy expert, "The muscular straining could have been an effort to control the ailerons, elevators, or rudder, requiring involvement of the arms, legs, or both."[26]

Significantly, this straining lasts only until the autopilot is disengaged seven seconds into the accident sequence. Thereafter, the CVR records *no* evidence of straining. In the words of the Navy expert, "At the point during the emergency period when the autopilot disengaged, there was no audible evidence that the F/O was physically straining to control the aircraft."

The obvious explanation for the sounds of physical straining is the F/O's upper-body efforts as he makes wheel inputs. Until the autopilot disengaged, the F/O would have felt an

[25] *Summary of Observations of Boeing Demonstration*, Malcolm Brenner, NTSB, June 12, 1997.

[26] NTSB Factual Portion of Speech Analysis Report, Oct. 22, 1996.

additional 40 pounds of force on the wheel when he made his inputs by overriding the autopilot. The second loud grunt heard on the CVR at elapsed time 138.8 (CVR time 1903: 01. 6) is coincident with the reversal in wheel direction, as identified by the kinematic analysis. Once the autopilot was disengaged and the increased wheel force disappeared, the sounds of physical straining cease on the CVR.

Had a rudder system failure occurred, autopilot disengagement would not have ended this aural evidence of exertion. The crew would have continued to strain to counteract the rudder pedal's movement in the wrong direction.

Summary Points

The material presented in this section provides a plausible explanation for a flight crew generated rudder input that, given the lack of physical evidence of an airplane induced rudder input, must be considered when determining the probable cause for this accident. The main points describing such an accident scenario are as follows:

- The F/O was the flying pilot.
- The F/O became startled by the wake.
- The F/O used wheel, column, and rudder pedal to control airplane.
- The F/O's initial left rudder input, followed by a removal of right wheel, were conscious attempts to control right roll acceleration.
- The F/O became absorbed with his upper-body commands and unaware of his lower-limb control inputs.
- The F/O stalled the airplane, eliminating any possibility of recovery from the upset.
- The captain did not verbally disagree with the F/O's inputs.
- All critical stimuli, reactions, and discussions occurred within six seconds after the encounter

Hypothetical Scenario for Full Rudder Deflection	**Indications For**	**Indications Against**	**Comments**
1. Dual slide jam	• Potentially fits a kinematic analysis	• No crew comment	*
2. Secondary slide jam and primary slide overtravel	• Potentially fits a kinematic analysis	• CVR analysis a) No comments b) Straining is limited to autopilot on	*
3. Input linkage jam	• Potentially fits a kinematic analysis	• No crew comment	*
4. Flight crew input, no aircraft malfunction	• Potentially fits a kinematic analysis • Can be explained by behaviors documented in scientific literature • CVR analysis indicates crew startled by wake • Crew encountered unusually high roll accelerations in both left and right directions that could prompt a rudder input • Crew input of left rudder can be explained by the concurrent removal of right wheel input	• No explicit statement on CVR of rudder input by crew • VMC conditions make potential for vestibular disorientation unlikely • Both pilots experienced in line operations	*

*To be filled in further in Section IV.

Table 3: Summary of Human Factors Evidence