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I. Executive Summary

Purpose of Submission Document and Executive Summary

The NTSB has requested that all parties to the USAir Flight 427 investigation submit proposed findings to be drawn from the evidence produced during the course of the investigation, identify a probable cause, and propose safety recommendations designed to prevent future accidents. This submission is Boeing's response to the NTSB's request.

The Flight 427 investigation has been lengthy and exhaustive. Boeing's Submission does not attempt to address all of the many issues that arose during the investigation. Instead, it focuses on what we believe are the significant understandings that have been gained from the investigation and the logic that leads to those understandings.

This executive summary provides an overview of our understandings and references to the areas of the document where more details are contained. The executive summary includes the following:

- Purpose of submission document and executive summary.
- Accident overview.
- Investigation history and scope.
- Focus of the investigation.
- Evidence relevant to potential airplane-related failure.
- Evidence relevant to potential flight crew input.
- Boeing conclusions.
- Improvements implemented.
- Further improvement opportunities.

Accident Overview

On September 8, 1994, the first officer (F/O) was the pilot flying USAir Flight 427 from Chicago to Pittsburgh. Using the autoflight systems, the 737-300 was just leveling off at approximately 6,000 feet and was about to land in clear weather at an airport familiar to the crew.

Suddenly, the airplane encountered turbulence from the wake vortices of a preceding 727. The wake encounter caused Flight 427 to begin a rapid roll to the left. The airplane roll to the left was arrested three times during the event. The roll rates and accelerations (to the left and to the right) experienced by the flight crew were significantly outside those normally experienced in commercial service. Ultimately, the left roll continued and the airplane pitched down resulting in pitch and roll attitudes not normally experienced by crews in transport category airplanes. Fourteen seconds after the encounter with the 727 wake, the airplane had reached its stall angle of attack and the roll angle was 70 degrees to the left with the nose pitched down 23 degrees below the horizon. The stall condition occurred at about 5,500 feet (4,300 feet above ground level) and continued for 14 seconds with the airplane continuing to pitch down and roll to the left until impact with the ground. The total time from the wake encounter until the airplane contacted the ground was approximately 28 seconds.

Investigation History and Scope

An intensive investigation of the accident events and potential causes was led by the NTSB and involved all of the parties. Possible causes investigated and dismissed included: in-flight collision, thrust reverser extension, internal explosion, structural failure, bird impact, decompression, and others. The investigation has taken over three years to complete, and has involved more than 75,000 engineering hours from Boeing alone.

The unprecedented testing and analysis that has occurred during the investigation of Flight 427 includes:

- Flight tests involving a 727 and 737, and subsequent development of computer models of airplane wake vortices.
- A comprehensive Boeing and Federal Aviation Administration design review of the 737 lateral and directional control systems.
- Kinematic analyses of the available flight data to further understand the motions of the airplane and the possible contributions of the flight control system and flight crew during the accident sequence.
- Extensive reviews of other accidents and incidents that involved airplane upsets.
- Numerous tests of the flight control system components from the accident aircraft.
- Numerous tests of 737 flight control system hardware, both in the laboratory (at Boeing and suppliers), and on the airplane.
- An NTSB appointed panel of consultants to suggest additional tests of the airplane's control systems.
- Flight tests to investigate the 737 airplane characteristics and controllability under the accident conditions.

The investigation has looked at the 737 history with unprecedented scrutiny.

New and enhanced simulation techniques were used to review previous accidents, such as the UAL Flight 585 accident near Colorado Springs. The enhanced simulation techniques showed that the rudder did not contribute to the UAL Flight 585 accident.

Boeing also evaluated a large number of reports of upsets on 737 airplanes. As a result of the analysis of these upset reports, Boeing's knowledge of the current operational environment has increased in a number of areas:

- We have learned that airplanes encounter wake turbulence from other airplanes more frequently than previously known.
- We have learned that 737 yaw damper failures occur more frequently than previously believed.
- We have learned that flight crews are sometimes startled by the airplane reactions to yaw damper failures and wake turbulence and perceive these events to be more severe than the data recorders indicate.

Focus of the Investigation

The investigation has focused on determining the control surface positions required to produce the flight path recorded on the Flight Data Recorder, identifying possible airplane and/or crew inputs to the control surface positions, and understanding reasons that may have contributed to the flight crew not recovering from the upset. Since flight tests conducted during the investigations indicated that the airplane had the control power to effect recovery for the postulated accident conditions, the human factors elements of the crew interactions with the accident conditions were also considered and investigated.

As the investigation progressed, kinematic analyses of the flight data recorder began to show that the most significant elements of the Flight 427 accident are: an unexpected encounter with wake turbulence; a sustained full-rudder deflection to the left, the specific explanation for which cannot be conclusively determined; and a full-aft control column input that led to a stall.

The wake encounter is recognized as the event initiator, but not the cause of the rudder going to its full deflection. Two remaining potential explanations can theoretically account for a sustained left rudder input:

- An airplane-related failure caused the input, or
- The crew commanded the rudder input during the attempted recovery from the wake encounter, and held it in during the events that followed.

Evidence Relevant to Potential Airplane-Related Failure

The NTSB has led an exhaustive investigation into the 737 rudder system. All conceivable rudder failure modes that can produce jams, "hardovers," or reversals have been theorized, analyzed, and tested. The effects of extreme thermal conditions, chips or particulate contamination, corrosion, and many other conditions in the rudder power control unit (PCU) have been evaluated. This intensive investigation over the last three years has documented that there is no evidence of any conditions having occurred to cause a malfunction in the Flight 427 PCU. The following summarizes potential airplane-related failure evidence covered extensively in Section IV of the document:

- Under certain hypothetical failure conditions, the rudder power control unit (PCU) may not function as intended. The hypothetical conditions necessary for anomalous behavior of the PCU were not present on USAir 427, nor are they applicable to any other commercial service scenarios.
- There is no evidence that a chip, silting, or any other contaminant jammed or adversely affected the performance of the Flight 427 power control unit (PCU).
- There is no evidence of corrosion (or the possibility of corrosion-caused momentary jams) in the Flight 427 PCU.
- There was no thermal condition on Flight 427 that could have caused anomalous rudder behavior.
- There is no evidence that any postulated rudder failure occurred to cause an uncommanded full rudder deflection on Flight 427.

The NTSB Systems Group report dated 12/21/94, summarizing the testing conducted on the Flight 427 rudder PCU, concluded that "the unit is capable of performing its intended function," and "was incapable of uncommanded rudder reversal, or movement." While other "reversal" failure modes were later identified, nothing in the analysis or testing conducted after these findings were released has provided any physical evidence to the contrary.

Evidence Relevant to Potential Flight Crew Input

An examination of aviation data sources reveals that sometimes pilots react to startling upsets by making errors in control manipulation. Generally the errors are brief and quickly corrected by the crews. On extremely rare occasions, these erroneous control inputs have been maintained for significant lengths of time. As discussed in more detail in Section V of the document, the in-service incident and accident event data accumulated during this investigation show that some flight crews:

- Are sometimes startled when they unexpectedly encounter a wake.
- Tend to perceive the roll rates and roll angles resulting from an unexpected wake

encounter as being more extreme than they really are and may react accordingly.

- Have failed, in several cases, to recognize and remove a rudder command after it is no longer needed.
- Sometimes independently command flight controls or are unaware of each other's inputs.

Both crew members of Flight 427 were initially startled by the wake vortex encounter. The wake produced a left roll acceleration in excess of that normally encountered in commercial service. The F/O responded to the initial acceleration with a large right wheel input, which in turn created a large roll acceleration to the right.

It is possible that the F/O countered the right roll acceleration by making a left rudder input coupled with a wheel reversal from the right to the left. A left rudder deflection was sustained for the remainder of the flight.

In a six-second period of time, the crew experienced large roll accelerations, potentially confusing feedback cues and made large wheel, and conceivably rudder, inputs in a rapidly deteriorating situation. Evidence from operational data, other modes of transportation, and the scientific literature suggest that the F/O could have remained focused on the control wheel as the life-threatening event developed, while being unaware of his pedal input. This scenario is consistent with the comments on the CVR.

Boeing Conclusions

The NTSB has recognized that a theoretical explanation for an accident can only be elevated to the "probable cause" of the accident when there is "conclusive" and "decisive" evidence to support that explanation.

Several elements leading to this accident are clear:

1. The crew was startled by the severity of an unexpected wake vortex encounter.
2. A full rudder deflection occurred. However, the events that led to the full rudder deflection are not so clear:
   - There is no certain proof of airplane-caused full rudder deflection during the accident sequence. The previously unknown failure conditions that have been discovered in the 737 rudder PCU have been shown to not be applicable to Flight 427 or any other conditions experienced in commercial service.
   - There is no certain proof that the flight crew was responsible for the sustained full left rudder deflection. However, a plausible explanation for a crew-generated left rudder input must be considered, especially given the lack of evidence for an airplane-induced rudder deflection.

   In Boeing's view, under the standards developed by the NTSB, there is insufficient evidence to reach a conclusion as to the probable cause of the rudder deflection.
3. The airplane entered a stall and remained stalled for approximately 14 seconds and 4,300 feet of altitude loss.

Perhaps the most significant findings from the investigation are:

- Commercial transport flight crews need to be specifically trained to handle large upsets. Transport pilot training widely used in the 1994 time frame did not prepare flight crews for recovery from the highly unusual roll rates and roll and pitch attitudes encountered by the crew of Flight 427.
- 737 yaw damper reliability enhancements are needed to reduce potential airplane

contributions to upsets.

- Highly unlikely potential 737 failure modes can be eliminated:
  - Potential 737 rudder PCU failure modes.
  - Potential 737 rudder PCU input rod fastener failure mode.
- We can reduce the impact of either airplane-related or crew-input-related rudder upsets by limiting 737 rudder control authority.
- Research is needed on better ways to detect and avoid wake vortices.
- Existing 737 flight control anomaly procedures could be improved.
- The flight data recorder information from this accident was inadequate to prove definitive events.

The following table summarizes Boeing’s findings that are discussed in detail in the body of this document:

Hypothetical Scenario for Full Rudder Deflection	Indications For	Indications Against	Reference Section
1. Jam in the rudder system	• Potentially fits a kinematic analysis	• PCU Secondary slide can shear all chips • No evidence of PCU primary slide jam • No evidence of PCU secondary slide jam • H-link protects area around PCU input crank from jam • No evidence of PCU input crank jam • Extremely high forces available to overcome jam of PCU input mechanism • No reasonable mechanism has been identified for causing PCU jam • No crew comment on CVR; CVR analysis	See Section IV
2. 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	See Section V

Improvements Implemented

It is the responsibility of all industry and government parties associated with an investigation to take practicable actions as soon as possible to preclude future accidents. Sometimes, actions can be implemented before the final report from an investigation is released.

Based on knowledge gained during the course of this investigation, Boeing, the aviation industry, and the U.S. government have already implemented the following improvements:

- The industry has begun training pilots in unusual attitude recovery techniques and continues to refine industrywide upset recovery training programs.
- Design improvements have been made to the 737 yaw damper to significantly reduce yaw damper caused airplane upsets.

- Design improvements have also been made to eliminate highly unlikely 737 failure modes:
  - A modified 737 rudder power control unit to eliminate a highly unlikely potential for a rudder reversal.
  - Revised 737 power control unit input rod fasteners to eliminate a failure mode.

The combination of these changes further minimizes the likelihood of a 737 system malfunction initiating an airplane upset:

- A hydraulic pressure reducer has been added to the 737 to better match rudder deflection capability to airplane control requirements. This reduces airplane reactions to rudder deflections no matter what the cause.
- NASA is conducting research on better ways to detect and avoid wake vortices. This important research should be continued.
- A 737 flight crew operations procedure has been published that provides a means to minimize the effects of yaw damper failures, or other system malfunctions that may affect rudder operation.
- A final design improvement adds an additional parameter to the 737 flight data recorder system to simplify any future investigations of accidents or incidents involving airplane upsets. This parameter is being delivered on new 737 airplanes beginning next year and is being retrofit on the 737 even though it is not required.

These actions address the key findings of the accident investigation. The investigation did not find any relationship between the evidence from the accident and the design improvements that are being made. These improvements will, however, enhance the safety and reliability of the 737.

Further Improvement Opportunities

Regardless of whether a “probable cause” determination can be reached in this investigation, it is the responsibility of the NTSB to determine what, if any, additional steps should be recommended to prevent future accidents.

Boeing believes the steps already taken can address all significant improvement opportunities that have been identified from the investigation. Attention now should be focused on continuing to rapidly implement the improvements that are underway.

II. Description of Accident Flight

USAir Flight 427, a Boeing 737-3B7, crashed while maneuvering to land at Pittsburgh International Airport on September 8, 1994. The 737 was flying at 190 knots, and leveling off at approximately 6,000 feet following a descent from 11,000 feet. The weather was good; sky clear, visibility 15 miles, with the wind from 250 degrees at 7 knots. The flaps were at 1 and the landing gear was retracted. The autopilot and autothrottle systems were engaged. As the accident sequence began, the airplane was rolling out of a 15 degree left turn toward wings level at a roll rate of about 2 deg/sec.

The flight is known to have encountered the wake of a 727 that preceded it by approximately 69 seconds. As a result of this encounter, Flight 427 started to roll to the left. The roll was stopped several times during the accident sequence, but control was eventually lost when the airplane stalled. During the accident sequence, after the initial roll, the rudder deflected from neutral to its blowdown limit,[1] and is believed to have remained at blowdown until impact.

A. Facts from DFDR/CVR and Radar Data

Figure 1 shows the parameters recorded on the digital flight data recorder (DFDR), annotated with the crew comments and other sounds from the cockpit voice recorder (CVR) for the final 30 seconds of the flight. The captain's and the F/O's comments are designated "C" and "F/O" respectively in Figure 1.

The following summarizes facts significant to the investigation that were obtained from the DFDR, CVR, and radar recordings:

1. A Delta 727 passed the area of the accident approximately 69 seconds prior to the start of the accident sequence.
2. Flight 427 encountered the 727's wake, passing directly through the center of the right core.
3. Both crew members made verbal utterances of surprise when startled by the effects of the wake vortex.
4. Prior to any rapid change in yaw rate, Flight 427 rolled to the left, followed by an unusually large roll acceleration[2] to the right.
5. The captain uttered the comment, "Whoa," just as the maximum roll rate to the right was reached.
6. The roll to the left was arrested three times during the accident sequence.
7. The autopilot was disconnected at time 139.4, but the horn continued to sound.
8. The control column had been pulled essentially full aft by time 144, by which time the airplane had reached a 70 degree left bank and a 19 degree nose down pitch attitude.
9. Flight 427 stalled during the accident sequence, which was caused by the aft-column input recorded on the DFDR.
10. The captain commanded, "Pull," several times just prior to impact.
11. The control column remained essentially full aft from time 144 until impact

[1] Rudder blowdown occurs when the aerodynamic loads on the rudder become equal to the force that the power control unit (PCU) can apply to the rudder. Rudder deflection is then limited to less than its full mechanical range.

[2] Note that roll rates and roll accelerations are calculated directly from bank angle which is recorded on the DFDR.

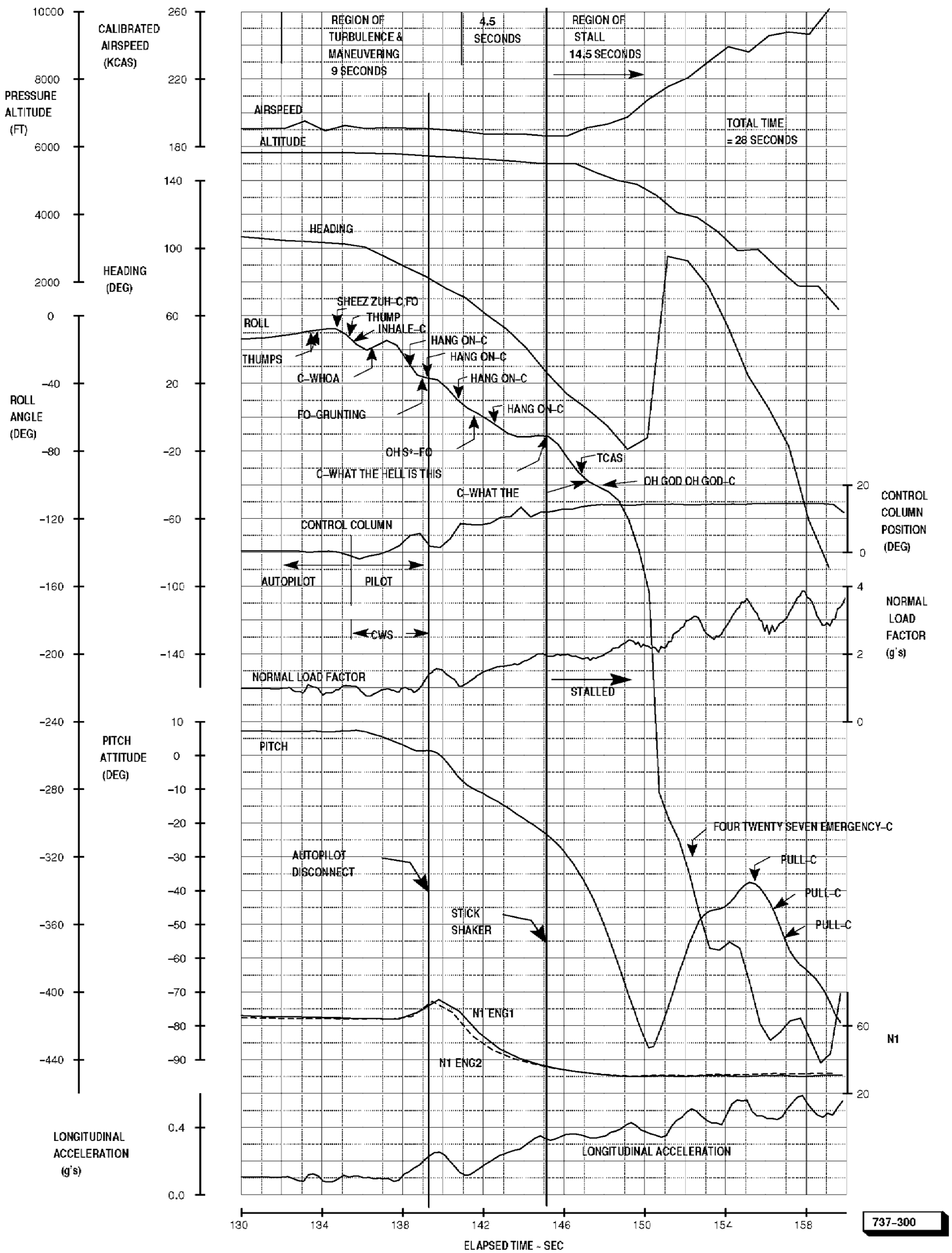

Figure 1: Flight 427 DFDR Annotated Plot

B. Kinematic Analysis of DFDR

In the course of the Flight 427 accident investigation, much effort has been directed at understanding the encounter with the 727 wake, and the flight crew's subsequent response to that encounter. As a part of this effort, an exhaustive kinematic analysis of the DFDR data was conducted to determine as much information as possible about the lateral and directional control positions (which were not recorded on the DFDR) during the accident sequence. Appendix A provides a detailed explanation of this kinematic analysis, which employs a process validated by Dennis Crider of the NTSB.[3]

The kinematic analysis required that the effects of the 727 wake on the 737 first be determined and introduced into the analysis. A flight test program[4], conducted by the NTSB Performance Group at the FAA Flight Test Center near Atlantic City, used an FAA 727 and a USAir 737-300 to acquire the required information.

This wake flight test program provided the data necessary to locate the 727 wake relative to the 737 during the accident sequence. The flight test data also allowed the mathematical model of the wake to be verified and improved based on actual data. This process is documented in an NTSB report.[5]

The results of the kinematic analysis provide significant information as to the control activity during the accident sequence. Figure 2 provides time histories of the roll angle, rate, and acceleration; and of the yaw angle (heading), rate, and acceleration; along with the estimated wheel and rudder angles. Significant pilot comments and cockpit sounds are superimposed on this plot. In Figure 2, comments by the F/O are designated "HOT2." All other comments are by the captain

Note that the roll accelerations induced by the wake and wheel, before any rudder activity, are dramatically higher than would typically be experienced by a line pilot during normal flight with the autopilot engaged. Normal autopilot roll accelerations are in the region of 2 deg/sec^2. By contrast, the initial left roll acceleration due to the wake was approximately 19 deg/sec^2, followed by a roll acceleration to the right due to pilot commands of approximately 36 deg/sec^2. It is also important to observe that the wheel time history, shown in Figure 2, is consistent with that derived during the NTSB validation of the Boeing kinematic process.

Obtaining the rudder time history is more challenging because airplane heading—the primary parameter for determining rudder position—was recorded on the DFDR only once every second, whereas roll angle—the primary parameter for determining wheel position—was recorded twice a second. The Boeing interpolation of heading resulted in the rudder position shown in Figure 2. The derived wheel and rudder positions are also shown using an expanded time scale in Figure 3, along with the column position from the DFDR and the engine RPM. Pilot comments and cockpit sounds are shown for reference.

The NTSB Performance Group looked at several other methods of interpolating the heading data. All of the results are shown in Figure 4, and are discussed in the NTSB study. Examination of the various resulting rudder traces shows that the derived rudder before time 136.8, and after time 138.8, are essentially the same. The only difference is the rudder position time history as it transitioned from near neutral to its blowdown limit. The rudder time histories that evolved from the various analyses will be used in later analysis to evaluate pilot response and rudder system failure scenarios.

In addition to Figures 1, 2, and 3, the data derived here is shown in Appendix A in a series of animation stills.

3 *Kinematic Validation Study*, NTSB Study, Feb 15, 1997.

4 *Wake Vortex Flight Test*, NTSB Factual Report, to be issued (test conducted Sep. 1995).

5 *Kinematic Study Update: Derivation of Lateral and Directional Control Surface Positions*, NTSB Study, June 11, 1997.

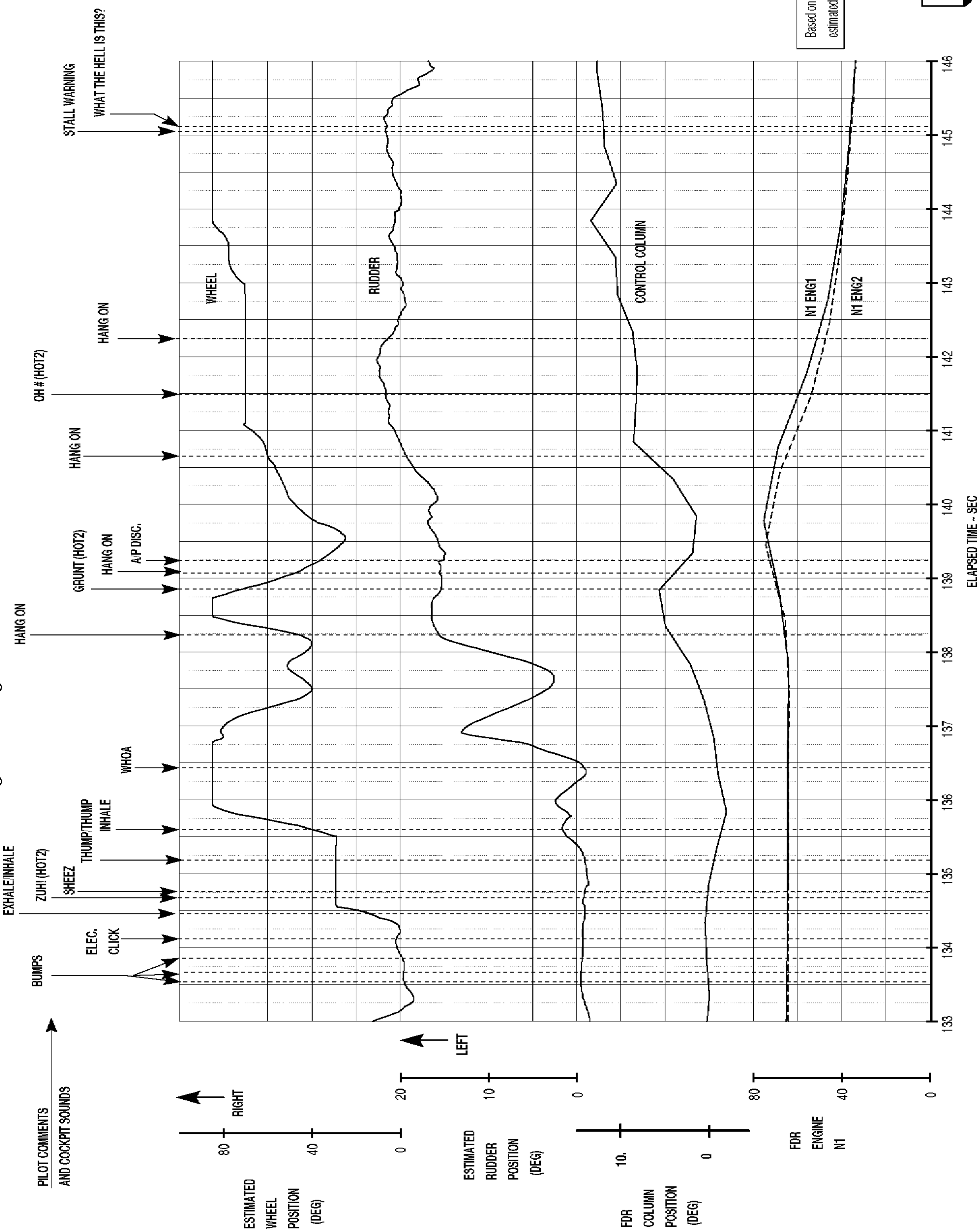

Figure 3: Flight 427 Estimated Control Position Data

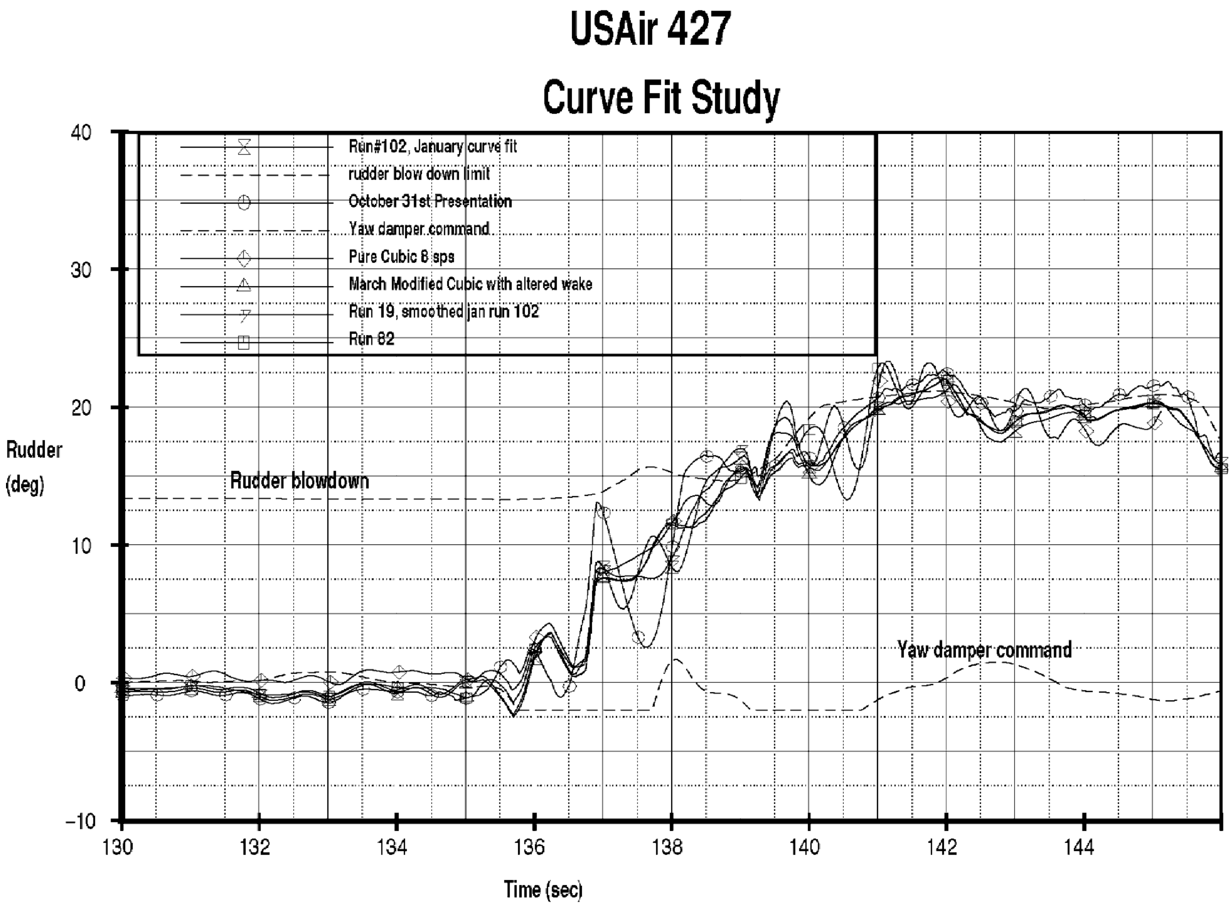

Figure 4: Results of Different Methods of Interpolating Heading Data

The following summarizes the pertinent information obtained from the kinematic analysis:

1. Application of the wheel during the accident sequence caused the roll acceleration to oscillate to values larger than those experienced during the initial upset due to the 727 wake encounter.
2. Before any rudder deflection occurred, the crew experienced two roll accelerations 10 to 18 times larger than would normally be encountered in smooth air with the autopilot engaged, first to the left due to the wake, and then to the right due to manual wheel inputs.
3. The wheel time history determined by Boeing is consistent with that derived during the NTSB validation process.
4. Several rudder traces were derived from the DFDR data by varying the interpolation methods used on the recorded heading.
5. The analysis established a boundary on possible rudder deflection time histories, and there is agreement on rudder activity before time 136.8 and after time 138.8.
6. The aircraft stalled because of the essentially full aft column deflection, as recorded on the DFDR.
7. The stall occurred at approximately 4,300 feet above ground level, 14 seconds before impact.

C. Timeline of Event

As the accident sequence begins, the airplane is rolling out of a 15 degree left bank toward wings level at 6,000 feet with the autopilot and autothrottle systems engaged. The crew had been looking for traffic reported by the Pittsburgh approach controller at "one to two o'clock, six miles, northbound Jetstream climbing out of thirty-three for five thousand." The F/O, who is the pilot flying, comments that he sees the jetstream as the accident sequence begins.

DFDR

time[6]

132.4:	At a left bank angle of 11 degrees, rolling right towards wings level, the longitudinal acceleration, normal load factor and airspeed traces on the DFDR show perturbations that are caused by the 737 intercepting the wake of a Delta 727 several miles ahead (as confirmed subsequently by radar data and flight testing).
134.2:	As a result of the encounter with the 727 wake, the roll angle begins to deviate from the intended return to wings level. In less than a second, roll acceleration peaks at approximately 19 deg/sec^2 to the left due to the wake, and the pilots utter exclamations of surprise that sound like "sheeez" and "zuh." The wheel moves to approximately 30 degrees right, which is consistent with the autopilot limit.
135.2:	A distinct "thump" is heard on the CVR. Subsequent flight testing confirmed this sound to be the fuselage of the 737 encountering the center of the 727's right wake core. By this time, the roll angle—which had reached a minimum of 8 degrees left—moves through 14 degrees left at a maximum roll rate of 12 deg/sec.
135.5:	The crew overrides the autopilot roll mode (dropping the autopilot into control wheel steering [CWS] mode) by making a rapid and large right wheel command, which reaches 85 degrees of right wheel by time 136.1.
135.6:	The captain inhales deeply.
136.2:	The roll angle has reached 20 degrees left, but as a result of the right wheel inputs the roll rate to the left has stopped and roll acceleration peaks at approximately 36 deg/sec^2 to the right, causing the 737 to begin rolling back toward wings level again.
136.4-136.5:	The maximum roll rate toward the right is 8 deg/sec, but the roll angle only reaches a minimum of 14 degrees left (at 137.3). As the maximum roll rate to the right is reached, the captain says "Whoa." The rudder and heading start to move significantly to the left. This is the first significant deflection of the rudder. Up to this time, the column has been moved from neutral to slightly nose down, then back to neutral.
137.0:	Half of the right wheel input is removed, and the column begins to move aft in a nose-up command.
137.4:	The roll rate then builds to the left again, with roll acceleration peaking at 38 deg/sec^2 to the left.
138.0:	The engine rpm starts to increase coincident with an increase in longitudinal acceleration.

[6] All times are given as elapsed time in seconds with zero at DFDR relative time 10:30:00 and CVR relative time 1901:42.8. These elapsed times are consistent with all NTSB Performance Group analysis times.

138.2:	Roll rate reaches a maximum of 20 deg/sec to the left, and the captain comments, “Hang on.”
138.2:	The wheel is returned quickly to its full right position.
138.7:	The roll acceleration peaks at 39 deg/sec^2 to the right, and the right wheel again starts moving left, back toward neutral.
138.2-138.8:	The rudder reaches the left blowdown limit and remains at blowdown until impact. The F/O is grunting as the column begins to move back toward neutral and the right wheel input is reduced.
138.9:	The load factor starts to increase, peaking at 1.5 g’s.
139.2:	The roll rate is again brought to zero at a roll angle of 36 degrees to the left. The captain again comments, “Hang on.”
139.4:	The autopilot disconnect wailing horn sounds and remains on during the remainder of the flight, indicating that the crew had disconnected the autopilot but had not silenced the horn by pushing the disconnect button on the wheel a second time.
139.7:	The roll acceleration peaks at 16 deg/sec^2 to the left.
139.8:	The engine rpm starts to decrease at the maximum engine deceleration rate to idle, where it remains until impact.
139.8-140.8:	The column moves sharply aft to counteract the nose drop caused by the roll, then continues aft until full-nose-up column is being commanded by time 148.
140.9:	The captain yet again comments, “Hang on.” Pitch attitude by this time is about 8 degrees nose down.
140.9-144.5:	The load factor—which had returned to approximately 1g—increases steadily to 2 g’s.
141.1:	Near full right wheel is applied.
142.5:	The captain yet again says, “Hang on.”
143.8:	Full right wheel is applied and held until impact.
144.0:	Roll rate has again nearly stopped, with the roll angle at 72 degrees left bank and pitch attitude 19 degrees nose down. The control column is essentially full aft.
144.8:	The onset of stall buffet is heard on the CVR.
145.4:	The stick shaker activates. The pilot comments, “What the hell is this?” as the stall begins. Load factor, now 2 g’s, starts oscillating, increasing to 3.7 g’s at impact.
146.0:	Airspeed and altitude remained relatively constant up to this time, with airspeed decreasing just 5 knots and altitude decreasing just 300 feet. Beyond this time, airspeed increases and altitude decreases rapidly.
148.0:	Full aft column, is applied and continues until less than a second before impact.
150.2:	The greatest nose-down pitch attitude of 86 degrees is reached.
152.3:	The captain comments, “Four-twenty-seven, emergency.”
155.4:	The captain comments, “Pull.”
156.4:	The captain comments, “Pull.”
157.0:	The captain comments, “Pull.”
160.1:	The airplane impacts the ground.

III.“Road Map” for Understanding Possible Causes

Section II described how the accident scenario began when Flight 427 intercepted the wake vortex of a 727 flying ahead of it. This unusually severe wake encounter was followed by exclamations of surprise by the flight crew; roll accelerations caused by the wake, autopilot, and crew; a rudder deflection to its blowdown limit; and a full-aft column input.

The investigation initially focused on possible aircraft failures that might have contributed to the lateral/directional upset observed on the DFDR. Evaluation of these possible failures—by examination of the airplane structure or by determination of the aerodynamic effects of the potential failure—led all investigators to the conclusion that only a large rudder deflection, in the direction to contribute to the left roll, could have caused the heading trace recorded by the DFDR. Appendix B contains a list of all aircraft scenarios considered and ruled out during the course of the investigation.

One of the main issues of the investigation is what caused the rudder to go to its blowdown limit, since this played a key role in the chain of events leading to the accident. During the course of the investigation, various hypothetical scenarios were put forth as the cause. These fall into three main categories: the rudder went to blowdown due to an atmospheric disturbance, a rudder system failure, or a flight crew input. Figure 4 shows the various rudder time histories determined by the kinematic analysis described in Section II. Figure 5 shows the different scenarios that have been proposed. This section discusses these possibilities and then lays out the plan for reviewing the evidence as to whether these hypothetical scenarios could have occurred on the accident flight.

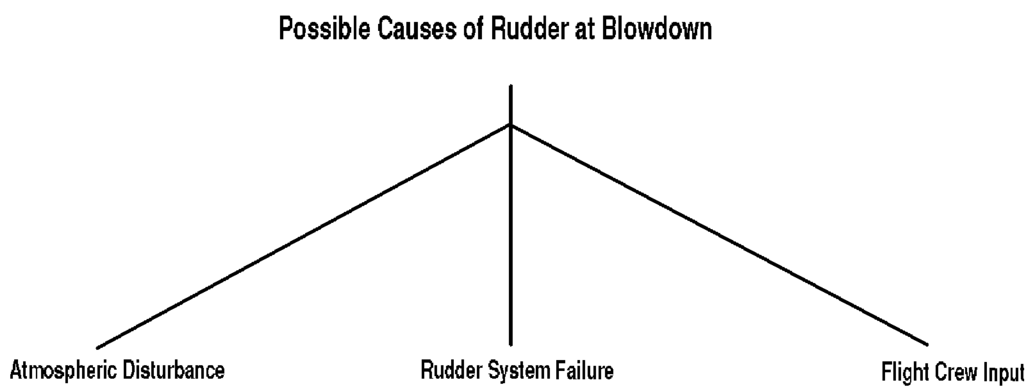

Figure 5: “Road Map” for Understanding Possible Scenarios

A. Hypothetical Scenarios Causing Rudder to Go to Blowdown

Atmospheric Disturbance Scenarios

While the accident event began when the airplane encountered the wake vortex, there is no evidence of any rudder control anomaly being associated with an atmospheric disturbance. Although there are documented cases in which pilots have been startled by unexpected wake encounters and used the rudder, there are no documented cases where the rudder has moved by itself due to atmospheric conditions, such as a wake encounter or turbulence. In addition, under the auspices of the NTSB, both flight testing[7] and lab testing[8] were conducted that demonstrated no anomalies for all combinations of air loads, yaw

[7] *Wake Vortex Flight Test*, NTSB Factual Report, to be issued.

[8] *Addendum, Main Rudder PCU Dynamic Testing*, Apr. 18, 1997.

damper inputs, and pilot inputs.Rudder System Failure Scenarios

These scenarios, all of which involve the rudder power control unit (PCU), are those in which the system could theoretically fail and drive the rudder to its blowdown limit:

- Dual slide jam.
- Secondary slide jam and primary slide overtravel
- Input linkage jam

Flight Crew Input Scenarios

These scenarios are those in which the flight crew commands the rudder to blowdown, without any system failure.

As a result of the above discussion, Figure 5 can be updated as shown in Figure 6. The atmospheric disturbance branch has been dropped, and the various rudder failure modes have been added.

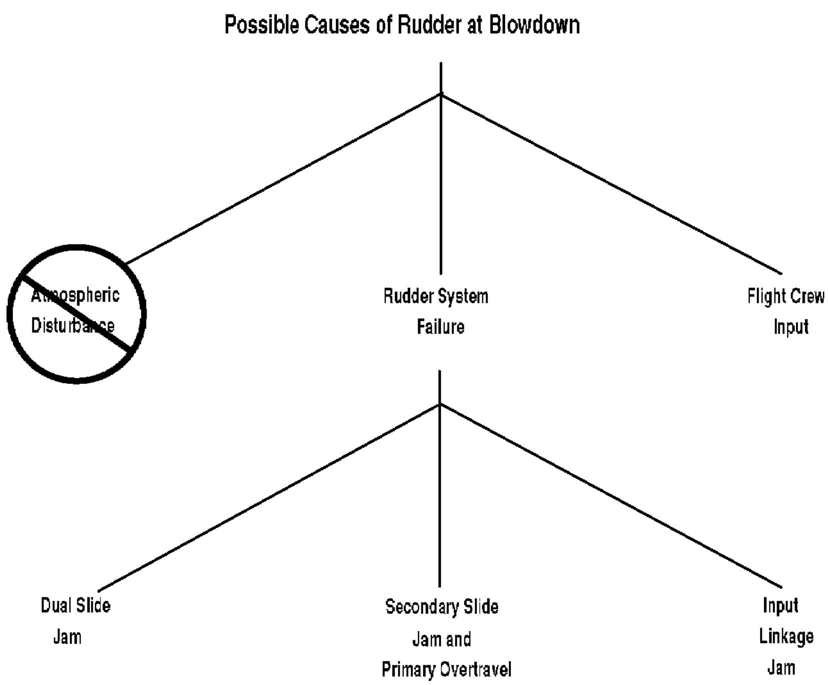

Figure 6: Revised "Road Map" for Understanding Possible Scenarios

B. Plan to Review Evidence in the Following Sections

In the remainder of this submission document, we will examine each of the scenarios on the road map. Section IV of this document identifies, describes, and evaluates the possible rudder system failures that could lead to the rudder going to its blowdown limit, and provides an overview of the investigations conducted relative to the rudder system. That section examines the various hypothetical scenarios involving failures of the rudder system by discussing what they are, cues these failures would give the pilots, and evidence for or against their occurrence. Relevant factual data, analysis, and in-service experience are examined for any evidence that a system malfunction could have caused the rudder deflection encountered by Flight 427. Other rudder system failure scenarios that do not fit the kinematic analysis, but have been discussed in the industry at large, are discussed in Subsection B of Section IV.

Section V provides a detailed discussion of the human factors and operational issues that relate to the accident. It considers scenarios in which the flight crew could have induced the rudder to go to blowdown. Relevant factual data, analysis, and in-service experience are examined for evidence that the crew might have caused the rudder deflection experienced by Flight 427.

Section VI then summarizes these system and flight crew scenarios. Based on facts and data, it indicates which scenarios cannot be considered as a possible cause of the accident.

Summary Table

The following table shows the scenarios that will be considered in greater detail in the following sections. Each scenario can be made to fit one of the kinematic analysis profiles, which then constitutes the initial evidence for it having caused the rudder to go to blowdown. The table will be updated in Sections IV and V with the available evidence supporting or contradicting the various scenarios. In Section VI, a final evaluation will be made of which scenarios can be considered a possible cause of the accident.

Hypothetical Scenario for Full Rudder Deflection	Indications For	Indications Against	Comments
1. Dual slide jam	Potentially fits a kinematic analysis *	*	*
2. Secondary slide jam and primary slide overtravel	Potentially fits a kinematic analysis *	*	*
3. Input linkage jam	Potentially fits a kinematic analysis *	*	*
4. Fight crew input, no aircraft malfunction.	Potentially fits a kinematic analysis *	*	*

*To be filled in further in Sections IV, V, and VI

Table 1: Hypothetical Scenarios Causing Rudder to Go to Blowdown

IV. Rudder System Scenarios

Following a brief overview of the 737 rudder system, this section looks at hypothetical failures that might conceivably induce a 737 rudder to deflect to blowdown. Factual data is then reviewed for evidence that any such event might have occurred, and the section concludes with an examination of the overall service history of the 737.

A. Rudder System Overview

Pilot control of the rudder is provided through the captain's and F/O's rudder pedals. The pedal motion is transmitted by a single cable system to the aft quadrant, and then through linkages to the main and standby PCUs, as shown in Figures 7 and 8. Except for the yaw damper, as discussed below, the rudder surface follows the pedal command. The pedals provide the flight crew with an indication of rudder surface positioning.

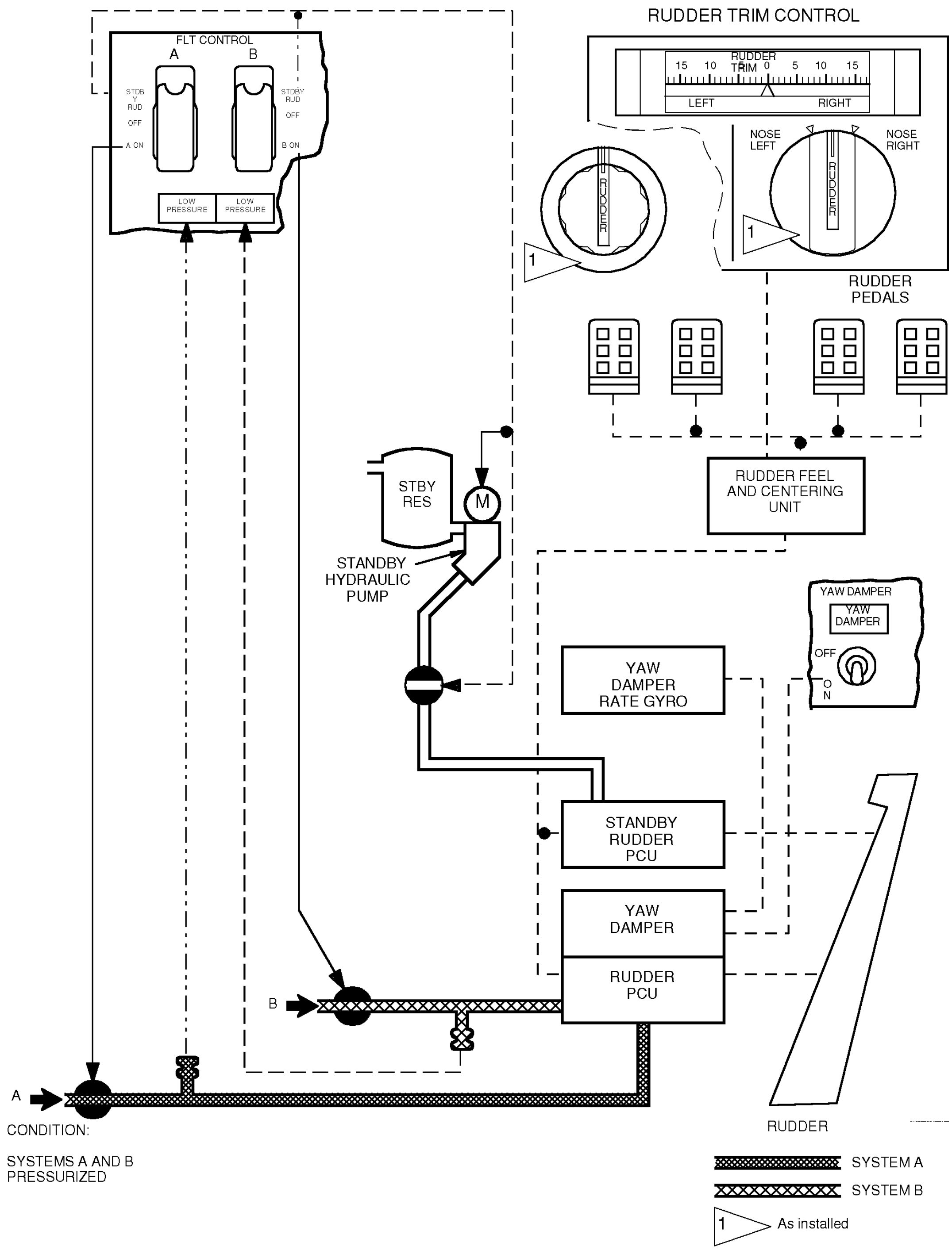

Figure 7: Rudder Control System Schematic

Figure 7 also shows the yaw damper system, which is designed to improve airplane ride quality by minimizing small-amplitude yaw oscillations.The yaw damper electronic module, or coupler, provides an electrical signal to the yaw damper actuator, which is part of the main rudder PCU.The yaw damper and pilot inputs are summed within the PCU such that yaw damper rudder inputs do not move the pedals.

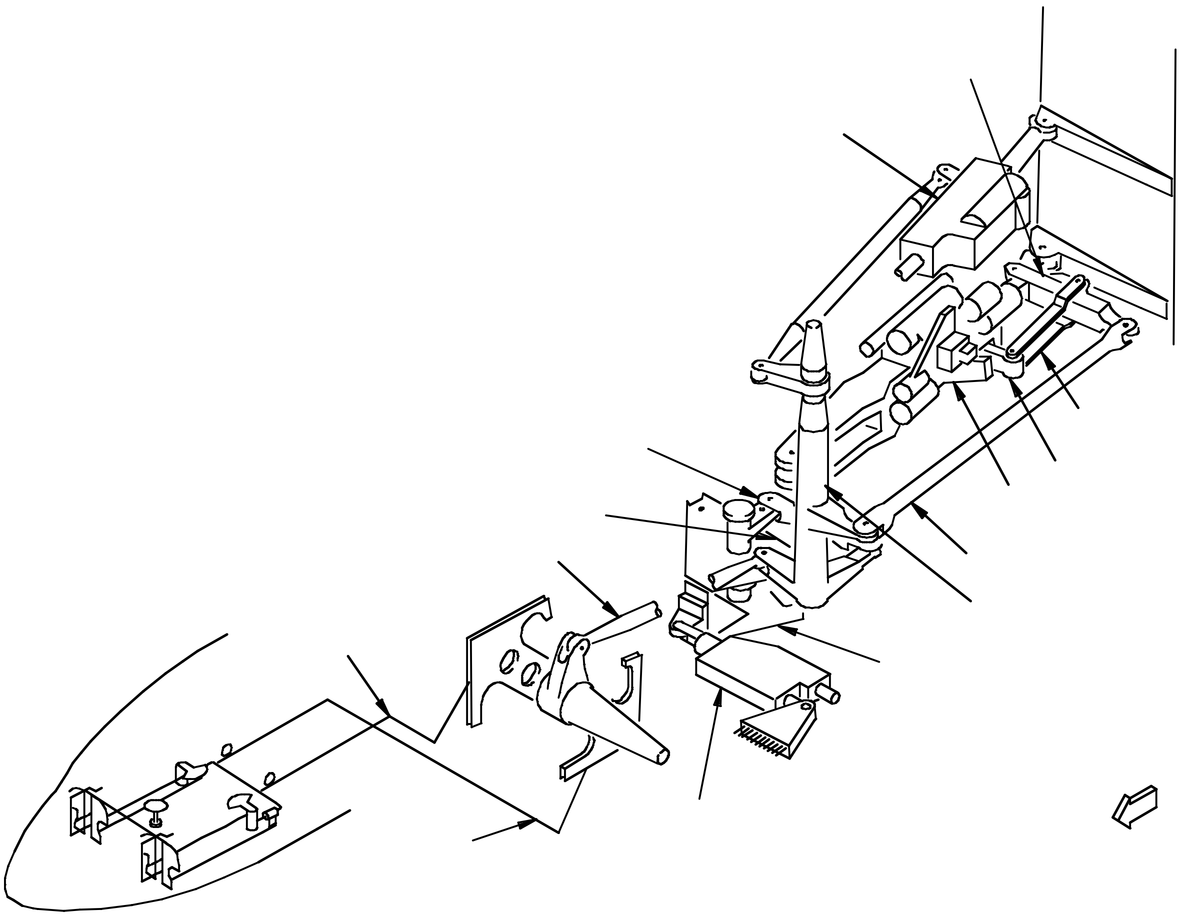

Figure 8: Main and Standby PCU Installation

The rudder feel and centering mechanism attaches to the aft quadrant, and applies a force to the quadrant—and thus to the pedals—that is roughly proportional to the rudder deflection. The pedal force required for full rudder deflection is approximately 70 pounds. Rudder trim allows the pilots to maintain a rudder deflection without having to hold in a pedal deflection. This trim is provided by an electric trim actuator that rotates the feel and centering unit, thereby changing the centered or neutral rudder position.

Aft quadrant rotation is transmitted to the main PCU through a dual-load-path linkage, and to the standby PCU by a single-load-path linkage. During normal operation, the main PCU is powered by the A and B hydraulic systems, and the standby PCU is depressurized. The standby PCU is pressurized by the standby hydraulic system after failure of one or both of the hydraulic systems (A and B). The standby PCU contains a pressure-operated bypass valve that allows it to be backdriven by the main PCU during normal operation.

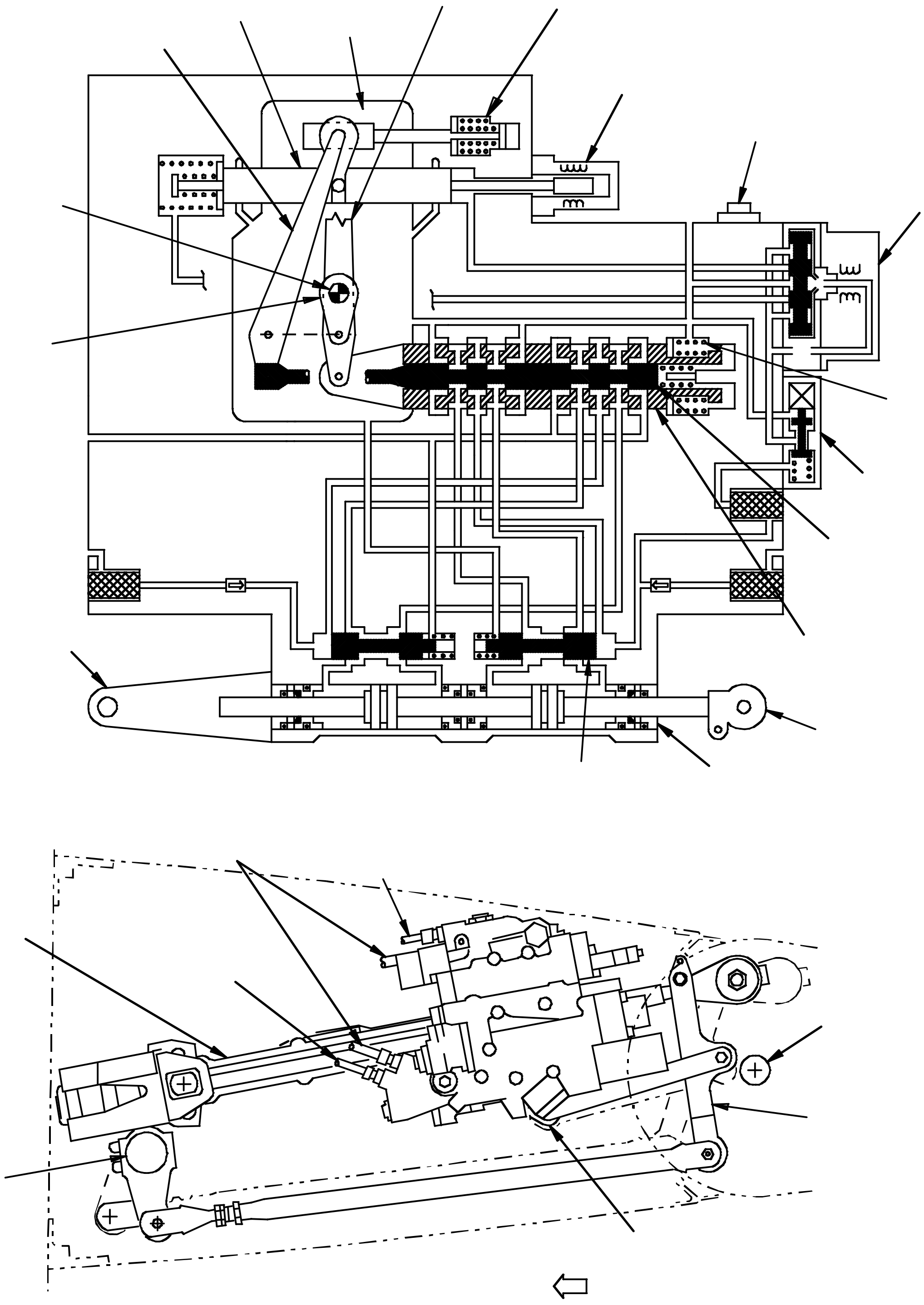

Figure 9: Main PCU Functional Schematic

Figure 9 provides a schematic view of the main PCU. The main control valve is connected through a dual-load-path linkage to both the yaw damper piston and to the pilot input linkage. The linkage sums inputs by the pilots and yaw damper to the control valve. The yaw damper piston is controlled by an electro-hydraulic servo valve that receives an electrical input from the yaw damper coupler. The yaw damper piston in the Flight 427 PCU (as in all 737-300 airplanes) is limited by a mechanical stop that only allows it to command three degrees of rudder.

When the PCU control valve is displaced by either a pilot or yaw damper input, it directs hydraulic flow to one side or the other of the actuator. The actuator then continues to move until the actuator piston rod moves the feedback linkage sufficiently to return the valve to its centered or neutral position.

The main PCU control valve is a dual concentric valve; that is, it contains two concentric slides with each of these slides controlling two hydraulic systems. The inner valve slide is the primary slide and the outer slide is the secondary slide. During normal operation, the primary slide is displaced first, and the secondary slide is displaced only when the primary slide does not provide enough hydraulic flow to keep up with the input command.

The two slides are designed to provide approximately equal flow. Thus, the primary slide can provide a rudder rate of approximately 33 degrees per second (no air load), while the primary and secondary slides acting together can provide a rate of approximately 66 degrees per second. The valve is designed in this way so that if one of the slides jams, the other slide can negate the effect of the jam and, in the worst of cases, allow the air load to force the rudder back to approximately neutral.

The main PCU also has a hydraulic bypass valve for each hydraulic system. Each bypass valve allows hydraulic flow between the two sides of the associated piston. When one side of the PCU is not pressurized, its bypass valve is open and allows essentially unrestricted flow. This allows the PCU to maintain full rate capability after a failure of one hydraulic system. When the PCU is pressurized, the bypass valve is closed and the only flow is through a fixed orifice included in the valve to assure that the actuator is stable (i.e., that it does not oscillate). This orifice flow does not significantly affect normal operation, but it can have a very significant effect on actuator performance after a valve jam.

B. Rudder Failure Modes

Section II provided the results of the Flight 427 kinematic analyses, which showed that the rudder deflected to its full aerodynamic limit (blowdown). In theory, either a mechanical failure or a pedal input by the flight crew could have caused this deflection to blowdown. Section III outlined the failure modes that can cause the 737 rudder to deflect all the way to blowdown.

There is no known occasion in the service history of the 737 of an in-flight failure that resulted in an uncommanded rudder deflection to its blowdown limit. There are, however, hypothetical malfunctions that can produce this effect. This section describes the various hypothetical failure modes, concentrating on those that can cause a rudder deflection to blowdown matching that indicated by the kinematic analyses. Examination of evidence for or against each of these failure modes will be presented in Section IV-C.

Failure Modes That Do Not Fit the Failure Scenario

There are some theoretical failures that can result in an anomalous rudder deflection or in a rudder offset, but not cause the rudder to deflect all the way to blowdown. For this reason, the following failure modes—which were investigated by the NTSB—were rejected as a possible cause of the Flight 427 rudder deflection: cable failure or jam, cable deflection due to a floor failure, standby PCU input crank binding, and a trim system runaway. The results of these investigations have been documented by the NTSB Systems Group[9] and will not be further addressed in this submission.

[9] *Systems Group Chairman's Factual Report of Investigation,* Dec. 21, 1994; Jan. 12, 1995; July 17, 1996; Oct. 24, 1996.

Failure Modes That Can Result in Full Rudder Deflection

This subsection examines the following three hypothetical failure modes, which can result in a full rudder deflection like that in the Flight 427 accident:

- A dual slide jam of the rudder PCU.
- A PCU secondary slide jam with primary slide overtravel.
- A rudder PCU linkage jam.

These three failure modes, including their cockpit effects, are discussed below. The evidence for or against these failure modes will be discussed in Section IV-C.

Dual Slide Jam

A jam of both the primary and secondary slides will result in full rudder deflection if one or both slides are jammed significantly off neutral. If the slides are near neutral, the effect of the PCU bypass valve will greatly reduce the PCU output force capability, and thus the blowdown value will be less than that required to match the kinematic analysis.

Secondary Slide Jam With Primary Slide Overtravel

Normally, if the secondary slide were to jam to the control valve housing, the PCU feedback linkage would move the primary slide in the opposite direction, negating the effect of the secondary slide jam. In this event, a secondary slide jammed fully open would leave the rudder surface very near a faired position (i.e., not deflected).

A new failure effect of a secondary slide jam was discovered during analysis of data from NTSB thermal testing.[10] The effect can occur when the secondary slide is jammed and a forceful rudder pedal command is applied in the direction opposite to the jam. In this case, the internal PCU linkages can be deformed, allowing the primary slide to travel further than normal. The primary slide can actually travel far enough to effectively shut itself off. When the primary slide shuts off, the only remaining command within the PCU is the jammed secondary slide. This PCU command, however, is in the direction opposite to the pilot's currently applied rudder pedal command. The rudder continues deflecting to blowdown. This scenario is known as "rudder reversal."

NTSB testing of the Flight 427 valve showed that a primary overtravel condition can only occur when the secondary slide is jammed at least 12% open, and a force of at least 190 pounds (60 pounds at the pedal) has been applied to the primary slide. Analysis provided to the NTSB[11] shows that the yaw damper in normal operation cannot open the secondary slide. Furthermore, NTSB testing of the Flight 427 actuator demonstrated that, in the event of a secondary slide jam, the yaw damper cannot cause a reversal condition.

The scenario for this failure mode requires the following: A very large or very high rate left rudder deflection must be commanded by the pilot to get the secondary slide sufficiently open. The secondary slide would then jam, followed by a right pedal input sufficient to apply the 190 pounds to the valve without breaking the jam free. If the pilot force is reduced below 190 pounds, the rudder will either center or deflect in the same direction as the rudder command.

A simulation of a secondary slide jam with primary slide overtravel was conducted to determine if that scenario could cause a rudder deflection that would replicate the Flight 427 flight path. This analysis showed that the secondary slide would have to jam while more than 50 percent open for the actuator to have sufficient rate and output force to match the DFDR heading trace. The yaw damper does not have the capability to open the secondary slide that amount. Therefore, for a secondary slide jam to be involved in the Flight 427 accident, the flight crew would have had to initially command a very rapid left rudder deflection.

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[10] *System Group Chairman's Factual Report of Investigation,* Jan. 31, 1997.

[11] *Simulation and Evaluation, RPCU Valve Slide Jams, USAir 737-300 Accident, N513AU,* Boeing Letter B-B600-16220-ASI, July 27, 1997.

Linkage Jam

If the PCU feedback linkage were to jam so that the main control valve could not close when the rudder reached its commanded position, the rudder could deflect to blowdown. In this scenario, because the slide travel is so small, the jam would have to be extremely rigid. For this reason, and because of NTSB testing discussed in Section IV-C, a linkage jam is not considered a reasonable failure scenario for Flight 427.

Secondary Slide Overstroke

There is one other failure mode that requires the secondary slide to travel to its internal stop. This can occur if the primary slide jams to the secondary slide, or if the summing linkage stop is ineffective. If this occurs and the secondary slide stop is not properly positioned, then the valve can move to a position that results in a flow reversal (commonly known as the "Mack Moore" condition). However, NTSB testing[12] showed that the stops on the Flight 427 valve were properly located, and that a flow reversal due to secondary slide overtravel was not possible.

Cockpit Effects of Failure Scenarios

Each of the above failure scenarios will cause the rudder pedals to be backdriven by the deflection of the rudder. When the rudder hits its blowdown limit (which varies between 14 and 21 degrees for Flight 427), the left pedal will have moved forward approximately 3 inches and the right pedal will have moved aft the same amount. If the pilots then applied a pedal force, the pedals could be moved only a very small amount (as allowed by stretching the control cables). The pedals would not free themselves unless the jam condition spontaneously cleared.

The rudder pedals do not move during normal yaw damper operation. However, if there is a dual valve slide jam or a linkage jam during a yaw damper input, the rudder will backdrive the pedals in the direction of the last yaw damper input. If the jam occurs while the pilot is commanding the rudder, the pedals will continue moving in the same direction as commanded by the pilot when the jam occurred.

For the scenario of a secondary slide jam with primary slide overtravel, the pilot would initially deflect the pedals for left rudder, at which time the valve would jam. When the pilot forcefully countered with right rudder, the pedals would initially deflect for right rudder, then be driven by the PCU back in the left direction as long as the pilot continued to apply a large right rudder pedal force. If the pilot relaxed the force, the rudder would return to neutral.

Rudder System Investigations

All the above rudder system failure modes are extremely unlikely, and there has never been a known case of any of the hypothesized failure scenarios in the history of the 737 fleet. The fact that a failure mode has not been observed during 30 years and more than 80 million flight hours of 737 operation, however, is not a sufficient reason to dismiss such a possibility in the case of Flight 427. The next section will evaluate the evidence that has been accumulated concerning these failure modes during the course of an intense three-year investigation.

In addition to the investigations discussed in the next section, the FAA commissioned a panel of experts to examine all aspects of the 737 lateral and directional flight control systems. This panel determined that the 737 flight control systems meet all applicable certification requirements, and that no specific scenarios could be identified that could explain the accident. The NTSB also commissioned a panel, drawn from government and industry, that reviewed the NTSB investigation of the rudder system, and made suggestions for additional investigations. All these suggestions were pursued and eliminated as possible failure scenarios for the accident.

In spite of nearly three years of investigation, no reasonable mechanism has been discovered for a system failure that could produce a full rudder deflection such as occurred in Flight 427. The lack of evidence for

[12] *System Group Chairman's Factual Report of Investigation,* Dec. 21, 1994.

a system malfunction is addressed at greater length in the following section.

C. Evidence of Hypothetical Scenarios

The following discussion will review the evidence relating to the hypothetical failures discussed in Section IV-B that could cause the rudder to go to blowdown. The discussion will first examine the evidence related to jams within the control valve, and then examine the evidence related to jams of the PCU linkage mechanisms.

Evidence of Hypothetical Control Valve Slide Jams

Of the hypothetical failure modes that are capable of producing rudder deflection to blowdown, two involve a jam of one or both slides of the control valve. The following paragraphs discuss the various mechanisms by which a slide can theoretically become jammed, as well as the evidence that such a jam would create. A comparison is then made with the actual hardware removed from the accident aircraft.

Control Valve Slide Jam Due to a Chip of Foreign Material

If a chip of foreign material were to become lodged in the metering orifice of the control valve, it could theoretically prevent the control valve from closing. However, much like a pair of scissors, the control valve has the ability to shear, or cut, a chip. Also like scissors, the size of material that can be sheared is dependent on the force applied to the slides. In this case, the applied force is not limited by human strength, but rather by the design of the PCU.

The architecture of the PCU's internal linkages limits the chip shearing force to approximately 50 pounds for the primary slide and 190 pounds for the secondary slide. NTSB tests[13] were conducted to examine the effects of chips placed into the metering orifices of the primary and secondary slides. The force applied to the slides during these tests was limited to the appropriate values.

[13] *System Group Chairman's Factual Report Addendums,* Jan. 12, 1995, and Apr. 30, 1997.

The secondary slide was able to shear all chips placed into the metering orifice, including a 52100 steel chip that almost completely filled the orifice. 52100 steel is the hardest material (approximately R_c 60 - 65) used in the manufacture of the PCU, and therefore represents a worst-case chip shear test. Only 140 pounds of force was required to shear this relatively large chip. The primary slide could shear all chips, except for a 52100 steel chip, with 40 pounds or less. Significant damage was created on the land edges of both slides during all of the tests when forces greater than 20 pounds were applied.

It is important to understand that the metering orifices of the control valve are approximately the same width, and only 3 times longer than the period at the end of this sentence (0.015 inches x 0.045 inches). Therefore, even completely filling the metering orifice with a hard steel chip still results in an extremely small amount of material to withstand the available chip shear force. It is therefore impossible for a chip to jam the secondary slide, and nearly impossible for one to jam the primary slide.

The primary and secondary slides removed from the accident PCU were examined by means of visual, microscopic, and scanning electron microscope (SEM) methods. No evidence of a jam due to a chip was found.

Based on the evidence, the primary and secondary slides removed from the accident aircraft were not jammed due to chips within the metering orifices.

Control Valve Slide Jam Due to Corrosion

Corrosion is another method by which the control valve could theoretically become jammed and thus be prevented from closing. Typically, corrosion within a hydraulic component is caused by excessive water content or degradation of the hydraulic fluid's anti-corrosion additive.

The PCU removed from the accident aircraft did not exhibit corrosion on any of its internal parts. Specifically, the primary and secondary slides of the control valve were free of any corrosion products.

Based on the evidence, the primary and secondary slides removed from the accident aircraft were not jammed due to corrosion between the interfacing diameters.

Control Valve Slide Jam Due to Hydraulic Fluid Particulate Contamination

It has been hypothesized that small particulates within the hydraulic fluid could jam one or both of the control valve slides by creating a contaminant lock condition. Contaminant lock is when very small particles (less than 5 microns, a micron being 0.000039 inches) suspended in the hydraulic fluid migrate to the clearance between the slides. The theory is that particles collected in the clearance prevent relative movement of the slides.

The contaminant lock theory is based on the fact that when a control valve is in a static condition at hydraulic neutral, only a small amount of flow exists. This small flow is a result of the "trim" of the valve and also the clearance between the slides. Since some of this flow will ultimately pass through the clearance between the slide and sleeve, very small particles will be pushed into the clearance. If enough particles are suspended in the fluid and the valve remains static long enough, the particles will fill the clearance and, in theory, require high forces to cause relative movement of the slides.

NTSB tests[14] were conducted to examine the effects of hydraulic fluid contaminated with particulates. These tests were performed at the same time as the thermal testing recommended by the NTSB's consultant panel. A main rudder PCU was allowed to remain in a static condition for approximately one hour while pressurized with "dirty" hydraulic fluid. The dirty fluid was approximately equivalent to the fluid found in the link cavity of the accident PCU. After remaining static for one hour, the input force of the PCU was measured. The force had increased only slightly to approximately 1.0 pounds (normal is 0.5 pounds).

Additional tests were conducted at Boeing[15] to examine the effects of hydraulic fluid that was heavily contaminated with particulates. The level of contamination was varied during the testing to approximately 50 times the level measured in the accident PCU link cavity. The PCU's inlet filters were removed during the testing to prevent containment of the particulates. The PCU's inlet filters are nominally rated at 10 microns, which ensures that 98 percent of all particles 10 microns or larger in any single dimension and all particles with any single dimension larger than 25 microns will be removed from the fluid.

Throughout the entire test, the PCU responded correctly to the input commands. At no time was there uncommanded movement of the PCU. The input forces did increase slightly due to particulate matter in the balance grooves of the primary slide. Post-test disassembly of the PCU and the control valve determined that the primary and secondary slides contained hard-packed contaminates in the balance grooves and annular passages. The metering edges of the slides were heavily worn to the point of being fully radiused, and the minor diameter of the slides contained polished craters below the metering edges.

The primary and secondary slides removed from the accident PCU did not contain any particulate matter packed into the balance grooves or annular passages. The metering edges were crisp and sharp, and no polished craters were present below the metering edges.

The tests proved that the main rudder PCU is tolerant of highly particulate contaminated hydraulic fluid even with the PCUs own protective filters removed, and that operation within that environment produces a distinct signature of wear and particulate accumulation on the primary and secondary slides. The primary and secondary slides removed from the

[14] *System Group Chairman's Factual Report Addendum,* Apr. 18, 1997.

[15] *Rudder PCU Particulate Test Report, B-G61R-C95-037, Mar. 7, 1995.*

accident aircraft did not exhibit any wear or particulate accumulation.

The following can be concluded from the testing and hardware examination:

1. Small particulates migrating to the clearance between the slide and sleeve do not significantly increase the force required to move the slide.
2. Packing the clearance between the slide and sleeve with particulate matter does not jam the slide.
3. Operation of the PCU with hydraulic fluid heavily contaminated with particulates creates a distinct signature of wear and particulate accumulation. This signature was not found on the accident PCU's control valve.

Based on the evidence, the primary and secondary slides removed from the accident aircraft were not jammed due to hydraulic fluid particulate contamination.

Control Valve Slide Jams Due to Thermal Conditions

The NTSB panel of consultants recommended that testing be conducted to determine if the Flight 427 rudder control valve would seize when subjected to a thermal shock condition. A test program was initiated at Canyon Engineering, a facility associated with one of the consultants, to test the Flight 427 PCU by subjecting it to hypothetical worst-case operating conditions. This was to be done by cold-soaking the PCU in the range of -27° to -40°F. The hydraulic system was then to be heated in the range of 160° to 170°F over a five-minute period.

The test setup, however, was unable to keep the PCU sufficiently cold. The test plan was modified to cool the PCU while it was depressurized and apply the hot fluid directly to the PCU inlet. It was recognized that this condition could not occur on an in-service airplane. Under these unrealistic conditions, it was found that the slide would momentarily seize while stroking the input linkage.

Because of the shortcomings of the Canyon test setup, it was decided to rerun the test at the Boeing Airplane Systems Laboratory (ASL). The setup used for this testing allowed the simulation of a variety of potential thermal-shock conditions. The test setup included a large cold chamber that enclosed the PCU, as well as hydraulic tubing that represented the airplane tubing from the aft pressure bulkhead to the PCU. Subsequent to the testing, a flight test was conducted that verified that the temperatures used for the cold chamber were conservative.

The following test conditions were run, during which the Flight 427 PCU operated normally:

1. Ambient fluid and cold chamber temperatures.
2. PCU cold-soaked to -27° and fluid at ambient.
3. PCU cold-soaked to -27° and A and B hydraulic fluid at 170°. Hot fluid introduced at inlet to cold chamber
4. PCU cold-soaked to -27°, System A at 170° and B at 60°. System A fluid introduced directly into PCU.
5. PCU cold-soaked to -27° with System A depressurized. Both A and B hydraulic systems were heated to 170° with hot fluid introduced directly into the PCU.
6. Same as condition 5 except just System A was heated.

In addition, the following condition was run to repeat the Canyon Engineering test in which the valve seized. In the ASL test, the valve also seized after the Flight 427 PCU was rapidly stroked several times through its maximum displacement.

7. PCU cold-soaked to -40° with System A depressurized. System A heated to 170° and introduced directly into the PCU.

Conditions 1, 2, and 3 represented a worst-case airplane scenario after a hydraulic system overheat failure (there was no indication of such a failure on Fight 427). Conditions 4, 5, and 6 represented a condition more severe than any that could occur on an airplane, because a valve cannot cold-soak to those extremes and then be immediately subjected to hot fluid. These latter test conditions were intended to determine whether the valve had a substantial thermal margin. Condition 7 was designed to replicate the highly unrealistic Canyon test condition that resulted in valve seizure.

The testing demonstrated that the valve could not seize during any airplane operational scenario, and also that it would not seize even for a thermal shock condition that is much more severe than that which might ever be encountered by an airplane in service.

Additional testing and analysis[16] was done by Boeing on control valves with minimum clearances. These tests showed that a minimum-clearance valve did not seize under worst-case test conditions and the highest level of rudder activity that could be encountered in flight.

[16] Boeing letter to the NTSB, B-B600-16147-ASI, May 29, 1997.

Evidence of a Hypothetical Linkage Jam

Another type of hypothetical failure mode capable of producing rudder deflection to blowdown is a jam of the PCU's input linkage mechanism. The jam must be inside the PCU's feedback loop in order to cause a full deflection. Jams outside the PCU's feedback loop will only result in the rudder remaining at the position commanded when the jam occurred. This was confirmed by the NTSB testing of March 1995.[17]

NTSB testing identified only one jam location within the PCU's feedback loop capable of producing a rudder deflection to blowdown. Such a result could theoretically occur if there were a jam at the input crank. The jam must either prevent the crank from moving relative to the PCU's manifold, or prevent the crank from rotating relative to the H-link (external link connecting the input crank to the external summing lever). NTSB tests[18] confirmed that no other locations produced anomalous rudder deflections. These NTSB tests included clamping the bearing in the external feedback mechanism, and actually welding the bearing of the primary internal summing lever.

The input crank is located on the bottom of the PCU, preventing foreign objects from falling between the input crank and the manifold. In addition, the PCU's H-link provides a shroud above the input crank and the manifold stop. Inspection of the Flight 427 input crank and manifold stop did not reveal any indications of a jam at this location. Also, the bearings at the crank and H-link interface were not seized at the time the PCU was inspected immediately after the accident.

[17] *System Group Chairman's Factual Report Addendum,* Jul. 17, 1996.
[18] *System Group Chairman's Factual Report Addendum,* Jul. 17, 1996.

Summary of Evidence

Hypothetical scenarios exist that would produce a full rudder deflection to blowdown. However, very specific conditions are required for each hypothetical failure scenario. Based on these specifics, it can be determined whether the failure scenario existed during Flight 427 by examining the condition of the main rudder PCU's control valve slides and input linkage mechanism. The examination conducted by the NTSB[19] found no evidence of a control valve slide jam or an input linkage jam during Flight 427.

The table developed in Section III is updated below to include the information obtained from the above tests and examinations.

[19] *System Group Chairman's Factual Report Addendum,* Dec. 21, 1994.

Hypothetical Scenario for Full Rudder Deflection	Indications For	Indications Against	Comments
1. Dual slide jam	• Potentially fits a kinematic analysis	• Secondary slide can shear all chips • No evidence of jam due to: - Chips - Corrosion - Particulates - Thermal cond.	*
2. Secondary slide jam and primary slide overtravel	• Potentially fits a kinematic analysis	• Secondary slide can shear all chips • No evidence of jam due to: - Chips - Corrosion - Particulates - Thermal cond.	*
3. Input linkage jam	• Potentially fits a kinematic analysis	• No evidence of input crank jam • Extremely high forces required to jam input mechanism • Design geometry protects this area	*
4. Flight crew input, no aircraft malfunction	• Potentially fits a kinematic analysis	*	*

*To be filled in further in Sections IV, V, and VI

Table 2: Hypothetical Scenarios Causing Rudder to Go to Blowdown

In summary, the NTSB has thoroughly scrutinized the Flight 427 PCU, which was not significantly damaged in the accident. Immediately following the accident, the PCU was carefully preserved and then examined, X-rayed, photographed, measured, and tested. The PCU operated normally. There was no evidence of binding, sticking, chattering, or a jam. There was no abnormal result of any kind in the functional testing, nor was there any evidence of a jam found when the components of the servo valve were individually inspected.

The NTSB Systems Group in its factual report dated December 21, 1994, summarized the testing conducted on the PCU when it had been preserved in its accident condition. The Systems Group concluded that:

- Testing and examinations conducted on the rudder PCU validated that the unit is capable of performing its intended functions, as specified by Boeing.
- Testing validated that the unit was incapable of uncommanded rudder movement or reversal.

These conclusions are as valid today as they were in December 1994. While the NTSB Systems Group, the NTSB's outside consultants, the FAA, Boeing, and Parker have spent the last three years postulating and evaluating failure modes and effects for the 737 rudder system, the fact remains that the accident PCU has continued to perform in tests exactly as is should in any condition in which it would be used during airline operations.

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D. Service History

The 737 has accumulated more than 80 million flight hours of service during its thirty years of commercial operation. During this extensive service history, there has never been a documented case of full uncommanded rudder deflection or rudder reversal in flight.

There have been pilot reports of upsets and uncommanded roll, yaw, and rudder events on 737 airplanes, which have increased in number during the years in which the NTSB has investigated the Flight 427 accident. The increase in the number of reported events coincides with the publicity surrounding this investigation.

A number of comments can be made about these reported upsets. First, the NASA ASRS Multi-Engine Turbojet Uncommanded Upsets Structural Call Back, dated November 8, 1995, contains a compilation of loss-of-control factors in multi-engine turbojet upsets from January 1987 to May 1995. 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 the next leading cause. As discussed more fully in Section V, 737 pilots, like pilots of all commercial airplanes, have reported large uncommanded roll and yaw upsets that are in fact attributable to wake encounters.

Second, in specific response to recent reports from 737 operators about uncommanded roll, yaw, and rudder events, Boeing assembled a "Roll Team" to make a detailed investigation into each of the reported events (summarized in Appendix C). The Roll Team analyzed the airline reports, the DFDR, and the equipment used in each event. The Roll Team's report concluded that a significant number of the reported upsets occurred as a result of wake turbulence encounters. Other events were caused by unrelated system failures. Still other events seem to have been normal airplane maneuvers that were misunderstood by the crew. All of the reported events were controllable by the flight crews.

Third, as a part of this investigation, the NTSB commissioned a study with a major European operator to monitor its 737s for a period of six months. The goal of the study was to obtain objective in-service data on the 737 that would identify any unusual rudder activity, or aircraft motion that could be attributed to unexpected rudder activity. By downloading the Quick Access Recorders (QAR) of twenty-six 737-400 airplanes, a record of rudder activity was gathered that covered approximately 21,000 flights encompassing more than 24,000 flight hours. In-flight data pertaining to rudder, rudder pedal, and control wheel positions were recorded. Additionally, post-flight monitoring routines were established to evaluate aircraft motion that might be caused by unusual rudder inputs. This mass of data showed that the rudder system operated exactly as expected, with no unexpected rudder activity. There were no rudder system anomalies of any kind.

Although this information does not identify any safety-of-flight rudder problem that can explain the Flight 427 accident, the service history has demonstrated that certain product improvements are appropriate. The improvements that Boeing supports on the rudder system are directed to improving the reliability of the system and eliminating the potential for extremely unlikely failures, none of which was present on Flight 427.

The NTSB, during the course of this investigation, has revisited the March 3, 1991, accident involving UAL Flight 585. The NTSB has also examined a June 9, 1996, event that involved an Eastwind 737-200 airplane. A brief synopsis of the data and analysis surrounding these occurrences follows.

United Flight 585 at Colorado Springs

Flight 585, a 737-200 ADV, crashed while on final approach to Colorado Springs, Colorado, on March 3, 1991. When the accident sequence began, the aircraft was flying at 160 knots just below 7,000 feet (approximately 1,400 feet above ground level) and was in a landing configuration with 30 degrees of flaps and gear down. It appeared to be turning right onto the runway heading when it rolled sharply to the right until inverted, hitting the ground in a near-vertical dive.

Prior to and at the time of the crash of Flight 585, the weather conditions—including wind speed and direction—were conducive to the formation of mountain waves and associated vortices and turbulence. There were numerous reports of severe weather from aircraft flying in the area and observers on the ground, including reports of unusually strong and shifting wind conditions near the time and place of the crash.[20] There were reports of rotors (horizontal-axis vortices) in the area.

During the investigation into the Flight 585 crash, the NTSB did not make a definitive probable cause determination. The limited amount of data on the DFDR (just airspeed, altitude, heading, and load factor were recorded) made it difficult to determine the flight path of the aircraft, or the control inputs required to match the DFDR and radar data. The NTSB report on the accident[21] stated that the two events most likely to have resulted in a sudden uncontrollable lateral upset were either a malfunction of the airplane's lateral or directional control system, or an encounter with an unusually severe atmospheric disturbance.

Studies of the Flight 585 accident were subsequently conducted at Boeing[22] using techniques and tools developed during the Flight 427 investigation. These studies showed that:

- The rudder was not involved in the Flight 585 accident.
- A malfunction in the airplane's lateral control system could not have caused the data traces recorded on the DFDR.
- A severe atmospheric disturbance was the most likely cause of the accident.

The results of the Boeing kinematic study of Flight 585 have been shared with the NTSB staff. Details are provided in Appendix C.

Eastwind

The Eastwind aircraft was a 737-200 that experienced a yaw event to the right on June 9, 1996, while on approach to Richmond, Virginia. The aircraft was not damaged during the event, nor was anyone injured. Instrumented flight testing of the Eastwind aircraft after the incident did not produce any anomalous behavior, nor was there any evidence of a rudder jam observed in the post-incident examination.

Examination of the rudder PCU by the NTSB did not reveal any evidence of PCU malfunction, other than a misrigged yaw damper LVDT position sensor. Examination of the control valve at NTSB offices in Washington, DC, on March 12, 1997, did not reveal any evidence of a jam in the primary or secondary control valve slides. Analysis of this event has shown that:

1. The yaw damper position sensor was misrigged, causing a larger-than-normal rudder input due to the yaw damper hardover (i.e., 4.5 deg instead of 3 deg).
2. Bank and heading data from the incident were obtained from gyros that were found in subsequent testing to be producing erroneous data.
3. The crew responded to the upset with near-simultaneous inputs of wheel, throttle, and conceivably rudder. If additional rudder inputs were made, only two degrees of rudder input in the direction of the yaw

[20] More details on the reported weather anomalies in the area of the accident can be found in the document *Boeing Contribution to the USAir Flight 427 Accident Investigation Board*, October 1996.
[21] *Aircraft Accident Report – United Airlines Flight 585 - Boeing 737-291, N999UA*, NTSB, Dec. 8, 1992.
[22] Boeing letter to NTSB, B-B600-16186-ASI, June 23, 1997.

damper hardover are required to match a derived rudder deflection.

4. The roll angle actually reversed from a right to a left bank during recovery, but both crew members perceived that theaircraft remained in a 25- to 30-degree right bank.
5. There is no evidence of any jam in the rudder control valve slides.
6. NTSB testing demonstrated that the Flight 427 valve could not seize during any operational scenario, and that it would not seize even for a thermal shock condition much more severe than what could have been encountered by an airplane in service. The Eastwind control valve clearances were greater than clearances for the Flight 427 control valve; therefore, neither the Flight 427 control valve nor the Eastwind control valve could seize during any airplane operational scenario.
7. There is no evidence of a linkage jam in the rudder PCU, and a linkage jam does not match the kinematic analysis.

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

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

control the AC." FDR showed actual roll to be 18 degrees. (5), (55), (56) and (57).

- 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 <u>wrong</u> 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 an 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

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

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

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 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

VI. NTSB Determination of Probable Cause

This document has previously focused on assessing the evidence available from the accident investigation and the data from testing. This information has been analyzed in terms of whether or not various hypothetical scenarios could have contributed to the accident. Scenarios considered have included those induced by either the system or the flight crew.

In this section, the "probable cause" standard to be applied to this investigation is discussed. The evidence is then summarized, and those scenarios that do not fit the definition are eliminated.

A. Definition of Probable Cause

Federal law directs the National Transportation Safety Board to investigate and *"establish the facts, circumstances, and ... probable cause"* of an aircraft accident. Everyone involved in this lengthy investigation has a strong interest in finding the "probable cause" of the accident. The clamor for a definite and expeditious explanation has been intense. In this atmosphere, the utmost care to ensure correctness is especially appropriate. As Chairman Hall recently testified, "The only thing worse than not waking up and giving the answer would be to wake up and give incorrect information or the wrong answer."[27]

In order to avoid the wrong answer, it is essential than any cause identified by the Board in this accident investigation be supported by facts and evidence. Mere suspicion, inference, and conjecture must not suffice. The Board has recently acknowledged, in the investigation of the United Airlines Flight 585 accident, that a theory cannot be elevated to a "probable cause" unless "conclusive" and "decisive" evidence exists in support of that explanation:

> The National Transportation Safety Board, after an exhaustive investigation effort, could not identify *conclusive* evidence to explain the loss of United Airlines Flight 585.
>
> The two most likely events that could have resulted in a sudden, uncontrollable lateral upset are a malfunction of the airplane's lateral and directional control system or an encounter with an unusually severe atmospheric disturbance. Although anomalies were identified in the airplane's rudder control system, none would have produced a rudder movement that could not have been countered by the airplane's lateral controls. The most likely atmospheric disturbance to produce an uncontrollable rolling moment was a rotor (a horizontal-axis vortex) produced by a combination of high winds aloft and the mountainous terrain. Conditions were conducive to the formation of a rotor, and some witness observations support the existence of the rotor at or near the time and place of the accident. However, too little is known about the characteristics of such rotors to conclude *decisively* whether they were a factor in this accident.[28]

Using this standard for the USAir Flight 427 accident, the Board must first determine whether there are conclusive facts and evidence to support any theory before that theory can be identified as the "probable cause." If a "probable cause" cannot be ascertained under this standard, the Board can still issue transportation recommendations to promote safety and reduce the likelihood of future accidents.

B. Summary of Evidence and Determination of Probable Cause

Table 4 summarizes the various hypothetical scenarios, both rudder system

[27] Testimony of NTSB Chairman James Hall before the House Committee on Transportation and Infrastructure, Subcommittee on Aviation, regarding TWA Flight 800, July 10, 1997.

[28] *United Airlines Flight 585, Boeing 737-291, N999UA, Uncontrolled Collision With Terrain for Undetermined Reasons Four Miles South of Colorado Springs Municipal Airport, Colorado Springs, Colorado, Mar 3, 1991,* NTSB Aircraft Accident Report 92/06 (PB92-910407), Dec. 8, 1992, p. 102.

induced and flight crew induced. The scenario description, and any evidence supporting it, are included. The column on the right concludes whether the scenario can be considered for further evaluation as a probable cause based on the definition given in Section IV-A.

Hypothetical Scenario Description	Indications For	Indications Against	Comments
1. Dual slide jam	• Potentially fits a kinematic analysis	• Secondary slide can shear all chips • No evidence of jam due to: - Chips - Corrosion - Particulates - Thermal cond • No crew comment	• Evidence does not support finding as probable cause
2. Secondary slide jam and primary slide overtravel	• Potentially fits a kinematic analysis	• Secondary slide can shear all chips • No evidence of jam due to: - Chips - Corrosion - Particulates - Thermal cond • CVR analysis a) No comments b) Straining is limited to autopilot on	• Evidence does not support finding as probable cause
3. Input linkage jam	• Potentially fits a kinematic analysis	• No evidence of input crank jam (H-Link protects input crank from a jam) • Extremely high forces available to overcome jam of input mechanism • No reasonable mechanism has been identified for causing jam • No crew comment	• Evidence does not support finding as probable cause
4. Flight crew input, no aircraft malfunction	• Potentially fits a kinematics 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	

Table 4: Summary of Evidence

As this table shows, there is no evidence to support a conclusion that an uncommanded full rudder deflection occurred. While there is no conclusive evidence of a crew-commanded, sustained left-rudder input, such a possibility is plausible and must be seriously considered, especially given the lack of evidence of an airplane-induced rudder deflection.

VII. Recommendations

Boeing recommends, and is pursuing, several actions to improve an already safe rudder system, and enhance flight crew recovery technique and preparedness. This section of the document:

- Summarizes these improvements, which are being taken in the areas of flight crew training, flight crew procedures, rudder system design, and flight data recording.
- Assesses the relevance and adequacy of these improvements.
- Refers readers to Appendix E, Boeing-Recommended Training and Procedures, and Appendix F, Boeing-Recommended Design Changes, for specific details of these improvements

A. Improvements Made

Exhaustive analysis shows that the vast majority of in-flight upsets are caused by either *external* sources (wake vortices, turbulence, windshear) or *internal* sources (yaw damper, autopilot, and autothrottle malfunctions; asymmetric flap/slat deployment; crew action/inaction). Highly unlikely but hypothetically possible rudder system malfunctions may also cause such events, although there is no recorded instance of such an event ever occurring in the more than 78 million hours logged by 737s since the late 1960s. The improvements being pursued by Boeing reflect the understanding gained from this fact-based analysis.

Flight Crew Training and Procedures

The known and likely causes of unanticipated yaw and roll events, listed above, will continue to exist. Throughout these events, the 737 remains controllable. Nevertheless, the potential for these events to startle flight crews is well documented, as are instances of improper control inputs made in response to upset events.

The preparedness of today's flight crews to deal with upset events can be improved. Pilots have highly varied backgrounds and experience. Many have never experienced attitudes in excess of those associated with normal line flying and typical training maneuvers. Moreover, precisely what constitutes appropriate knowledge and skill for airplane upset recovery is today neither well defined nor universally agreed upon.

Therefore, Boeing supports enhanced training to ensure that flight crews are provided with the knowledge and skill they need to effect beneficially the outcome of unanticipated yaw and roll events. To this end, Boeing has worked with the industry to develop an upset training aid that will provide increased awareness of all types of in-flight upsets, as well as their recommended recovery techniques.

Additionally, Boeing has made changes to its flight procedures to provide more specific guidance to the flight crew for response to an uncommanded yaw or roll, and a confirmed jammed rudder. Mandated by FAA Airworthiness Directive 96-26-07 in January 1997, these enhanced procedures are:

- A revision of the existing *Uncommanded Yaw or Roll Procedure.*
- A new *Jammed or Restricted Rudder Procedure.*

See Appendix E for a detailed overview of the new Upset Recovery Training Aid, and these revised and new procedures.

Rudder System Changes

Despite exhaustive investigation, Boeing, the NTSB, and the FAA have been unable to find any evidence that a failure of the 737 rudder control system caused an accident, or that an uncommanded full rudder deflection has taken place in the history of the 737.

Nevertheless, investigations and design reviews did identify possible areas where the 737 rudder system could be improved. In addition, extremely unlikely failure modes were identified that could hypothetically result in unwanted rudder deflections.

Therefore, Boeing recommends and is making rudder system changes to preclude these extremely unlikely system failures, better meet the original design intent, and improve overall system reliability. These changes improve on an already safe and reliable system by drawing from lessons learned through exhaustive testing, service experience, and analysis. The design changes being pursued include:

- **Rudder PCU valve redesign**—eliminates PCU failure effect associated with PCU servo valve secondary slide jam and primary valve over-stroking.
- **New PCU input rod fasteners**—redesigned outer bolts eliminate a failure condition that can compromise dual-load-path redundancy but, by itself, cannot affect rudder system operation.
- **Yaw damper system redesign**—uses updated technology to make the yaw damper significantly more reliable.
- **Hydraulic pressure reducer**—reduces rudder authority by about one-third during those phases of flight when large rudder deflections are not required, to lessen the effects of an excessive full rudder deflection, however initiated.
- **Rudder input force transducer**—allows the flight crew's rudder inputs to be recorded as a separate parameter by the flight data recorder. This will enhance future incident or accident investigations by facilitating an understanding of flight crew/rudder system interaction.

The first four of these changes have been mandated by the FAA by AD97-14-04 (PCU changes) and AD97-14-03 (yaw damper and pressure reducer). See Appendix F for a description of these Boeing-recommended and initiated design and retrofit changes.

B. Assessment of Relevance and Adequacy

It is the Boeing belief that the above actions adequately and effectively address the key findings from the investigation of the Flight 427 accident. Specifically, they address theoretical failure conditions that were not present in this accident, and are not known to have ever occurred in the service history of the 737. This judgment is supported by the exhaustive analysis of facts and data assessed by the NTSB and the other parties over a period of three years.

Based on this extensive industry effort, the Boeing-recommended corrective actions cover the spectrum of improvement areas to yield safety benefits on these four fronts:

- **Airplane design**—the changes will make the 737 rudder flight control system even more reliable and robust than it already is, resulting in fewer airplane-initiated yaw and roll events.
- **Improved training**—the changes will help assure that flight crews have the knowledge and skill to properly respond to startling in-flight upsets, whatever their cause.
- **New procedures**—the changes will provide flight crews with specific procedures for handling directional/lateral upsets and rudder jams.
- **Future incident/accident analysis**—the changes will ensure that the flight data recorders of the 737 world fleet have parameters for rudder positioning and rudder pedal inputs. This will facilitate a definitive understanding of flight crew/rudder system interaction in any future investigation.

C. Additional Recommendations

Analysis performed in the course of this investigation confirms the need to better understand the varying reactions of flight crews to upset events. Documented incidents highlight the industry's current lack of knowledge regarding crew behavior in upset situations.

In August 1997, for example, a 737 encountered wake turbulence during its descent for landing. The flight crew reacted to the roll oscillation by disengaging the autopilot, the yaw damper, and both flight control hydraulic systems in a period of less than 10 seconds. This extreme response is not a technique for recovering from lateral upsets, but is the final recommended procedure in the event of a firmly jammed or restricted rudder that is significantly deflected.

It seems likely that the flight crew acted on the incorrect, uninvestigated supposition that the roll oscillation was caused by anomalies in the airplane's flight control system. If an actual failure in a lateral flight control system had occurred, this incorrect flight crew response might have been catastrophic.

Therefore, Boeing makes the additional recommendation that the appropriate organizations within the industry take steps to improve industry understanding of possible flight crew responses to wake vortex encounters and other upset events. Boeing believes that such an effort would be valuable to training organizations worldwide.

Appendix A
Kinematic Analysis of Flight 427 DFDR

This appendix describes the processes used to derive Flight 427's lateral and directional control positions—two parameters not recorded by the Flight 427 DFDR—during the accident sequence. To understand the wake upset, and the flight crew's subsequent response to this startling event, it was first necessary to determine the effects of a 727 wake on a 737, and introduce these effects into the kinematic analysis.

A flight test program, conducted by the NTSB Performance Group at the FAA Flight Test Center near Atlantic City,[29] used an FAA 727 and a USAir 737-300, to acquire the required information. The process used during this analysis has been validated by Dennis Crider of the NTSB and is documented in an NTSB report.[30]

The first step in determining lateral and directional control positions was to expand the basic 11 parameters recorded on the DFDR by deriving the angular rates and accelerations from the Euler angles, and integrating the linear accelerations to determine a flight trajectory. Comparisons of derived and measured data were performed to achieve a final converged solution, from which angle-of-attack and sideslip angle were derived.

The next step was to use Newton's second law to obtain the total aerodynamic forces and moments acting on the aircraft using the derived and measured angular and linear accelerations. Next, the aerodynamic forces arising from known or derived effects—such as those due to angle-of-attack, sideslip, elevator position, engine rpm, and so on—were computed using the 737-300 engineering simulator database.

[29] *Wake Vortex Flight Test*, NTSB Factual Report, to be issued.

[30] *Kinematic Validation Study*, NTSB Study, February 15, 1997.

These effects were then subtracted from the total, leaving behind the sum of all unknown aerodynamic effects. This sum includes the effects of wake turbulence, lateral and directional control-surface deflections, DFDR processing errors, possible structural damage, and deficiencies in the simulator aerodynamics math model.

The magnitude of any DFDR processing errors was shown to be very small by the inertial reference unit (IRU) platform testing undertaken by the NTSB Performance Group in February 1995 at the Honeywell facility in Clearwater, Florida.[31] The 737-300 engineering simulator aerodynamic math model is a proven, valid model of the aircraft, with a very small magnitude of error in the aerodynamic data throughout the normal flight envelope. The model was updated to an even higher degree of accuracy using the data obtained in the NTSB flight testing conducted as part of this investigation.

Once the examination of the aircraft structure eliminated structural damage[32] as a potential cause, only the effects of wake turbulence, and the lateral and directional control positions, were of a magnitude significant for further consideration. The wake flight test program conducted in Atlantic City provided the data necessary to locate the 727 wake relative to the 737 during the accident sequence. The flight test data also allowed the mathematical model of the wake to be verified and improved based on actual data. This process is documented in an NTSB report.[33]

The results of the kinematic analysis provide significant information as to the control activity during the accident sequence. It is important to note that the wheel time history

[31] *Honeywell Tilt Table Test*, NTSB Factual Report, to be issued.

[32] NTSB Structures Factual Report, Dec. 13. 1994.

[33] *Kinematic Study Update: Derivation of Lateral and Directional Control Surface Positions*, NTSB Study, June 11, 1997.

derived using the kinematic process was consistent with those derived during the NTSB validation of the Boeing kinematic process.

Obtaining the rudder time history from available DFDR data is more challenging because airplane heading—the primary parameter for determining rudder position—was recorded on the DFDR only once every second, whereas roll angle—the primary parameter for determining wheel position—was recorded twice every second. When the heading data is sampled at less than twice a second, the rudder position derived using kinematics becomes contaminated with an overlying "noise" signal that shows up as an oscillation in derived rudder, with a period of about 0.75 seconds and a peak-to-peak amplitude that can exceed ten degrees. Proper interpolation of the heading data can reduce the "noise," providing more reliable information on rudder movement.

In regions of the flight envelope where the rudder position is known or can be inferred (such as when the rudder is believed to be at its blowdown limit), it is possible to derive a continuous heading trace between the low-sample-rate data points that are known from measurement. This heading trace accurately represents the airplane heading during the period of time where rudder position is known or can be inferred.

The end result of this effort is an improved knowledge of the boundary conditions of the heading trace at the edges of the adjoining regions where rudder position is not known or cannot be inferred. Applying these new boundary conditions, while maintaining a smooth continuous heading trace that goes through all known heading data points, resulted in an improved representation of the airplane's heading from time 133 to 140. This new heading-trace interpolation has been used, along with the derived wake-induced yawing moment, to derive a final, best estimate of rudder position.

This is not the only method of interpolating the heading trace. The NTSB Performance Group looked at several other methods of interpolation and the results are discussed in the NTSB Study.[30]

Figures A1 to A14 show an animation of the accident sequence[34] with the following information:

- Animated following view of the accident aircraft.
- Animated cockpit view from the accident aircraft.
- Estimated wake location.
- Derived roll and yaw accelerations and rates.
- DFDR recorded roll and heading angles.
- DFDR recorded column position.
- Estimated wheel and rudder deflections.
- CVR comments/sounds.
- General comments.

[34] First presented in *Boeing Contribution to the USAir Flight 427 Accident Investigation Board*, Sep. 25, 1996.

Appendix B
Summary of Investigated Failure Possibilities

This appendix lists scenarios considered and eliminated as possible causes of Flight 427.

Scenarios	Status
In-flight collision	No (radar track)
Thrust reverser extension	No (actuators locked, no vibration or noise)
Engine malfunctions	No (parameters normal)
Internal explosion	No (no indications)
Internal fire	No (no indications)
Landing gear extension	No (gear in place)
Decompression	No (doors or locks in place)
Structural failure	No (no indications)
Tire/wheel internal burst	No (no indications)
Maintenance action	No (no open items)
Bird impact	No (black light check)
HIRF/EMI	No (no indications)
Lateral system	No (ailerons operative, based on analysis)
Effect of fluid in the E/E bay	No (examination of electrical impedance)
Elevator malfunction	No (system intact)
Flap malfunction	No (system intact)
Rudder servo overtravel	No (tolerance correct)
Rudder trim actuator	No (functional, in null position, too slow)
Slat malfunction	No (insufficient aerodynamic load)
Autopilot malfunction	No (kinematic analysis)
Standby actuator induced	No (within service limits, test demo)
Cable failure induced	No (all overload failures, test demo)
Auxiliary tank failure induced	No (no failure indication)
Thumps heard on CVR	No (wake vortex test sounds)
Rudder PCU control rod interference	No (in-service survey shows no contact)
Rudder blowdown authority	No (flight test, two additional degrees)
Standby actuator PCU linkage/valve jam	No (testing complete, rudder controllable)

Appendix C
Other Incidents and Accidents

United Flight 585 at Colorado Springs

UAL Flight 585, a 737-200 ADV, crashed while on final approach to Colorado Springs, Colorado, on March 3, 1991. The aircraft was in its landing configuration, flaps 30 with the gear down, flying at 160 knots and just below 7,000 feet, when the accident sequence began. The aircraft appeared to be turning right onto the runway heading when it rolled sharply to the right until inverted, hitting the ground in a near-vertical dive.

Prior to and at the time of the crash of Flight 585, the weather conditions—including the wind speed and direction—were conducive to the formation of mountain waves and associated vortices and turbulence. There were numerous reports of severe weather from aircraft flying in the area and observers on the ground, including reports of unusually strong and shifting wind conditions near the time and place of the crash.[35]

During the initial investigation into the Flight 585 crash, the NTSB did not come to a definitive probable cause. The limited amount of data on the DFDR (only airspeed, altitude, heading and load factor were recorded) made it difficult to determine the flight path of the aircraft, or the control inputs required to match the DFDR and radar data. The NTSB report on the accident[36] stated that the two events most likely to have resulted in a sudden uncontrollable lateral upset were a malfunction of the airplane's lateral or directional control system, or an encounter with an unusually severe atmospheric disturbance.

Studies of the Flight 585 accident were subsequently conducted at Boeing using techniques and tools developed during the Flight 427 investigation. These later studies have added to the information available concerning the Flight 585 accident.

Using the 737-200 ADV engineering simulator, it was possible to closely match the limited DFDR data using only the wheel and column as control inputs. The rudder was not used during the match except as commanded by the yaw damper, which was operational. The airspeed, altitude, normal load factor, and heading[37] from the simulation agree well with the DFDR data. In addition, the track of the airplane during the simulation matches the radar data recorded during the accident. The roll angle, pitch angle, and heading of the simulation at impact also agree with the data obtained at the accident site. The attitude of the aircraft during the accident sequence was also compared to results obtained in an NTSB study[38] conducted during the initial investigation, and was found to compare very well.

A match was also attempted using a simulated rudder hardover. For this scenario, it was possible to force a match of three of the four recorded DFDR parameters: airspeed, altitude, and heading. However, the load factor trace showed some significant discrepancies, and the track of the aircraft no longer matched the radar data from the accident. More significantly, the roll angle time history required to match the DFDR traces of airspeed, altitude, and heading no longer matched the witness reports of the Flight 585 accident.

Any introduction of rudder into the accident sequence requires a significant roll attitude change to maintain the DFDR heading. For the 5 deg/sec rudder input introduced in this case, the roll attitude had to be changed to more than 50 degrees to the left to maintain the heading recorded on the DFDR. This lateral orientation

[35] More details on the reported weather anomalies in the area of the accident can be found in the document *Boeing Contribution to the USAir Flight 427 Accident Investigation Board*, distributed to the NTSB Oct. 1996

[36] *Aircraft Accident Report - United Airlines Flight 585 - Boeing 737-291, N999UA*, NTSB, Dec. 8, 1992.

[37] Heading agrees well up to the point where the single axis directional gyro is affected by the pitch and roll attitudes.

[38] *Flight Path Study*, NTSB Study, DCA 91-M-A023, Apr. 17, 1992.

does not agree with what was observed by the many witnesses to the accident.

It should also be noted that, as demonstrated several times in flight testing conducted both by Boeing and the FAA, at flight conditions and flap settings similar to those existing at the onset of the Flight 585 accident, the rolling moment resulting from a rudder deflection to blowdown could easily be countered using only about half the travel of the control wheel.

The new simulation match involving no rudder input can also be used to evaluate the possibility that a lateral control system failure caused the upset.

Since the Flight 585 match requires full right wheel to duplicate the upset, it follows that a portion of the system going hard over to the right could not cause the roll attitude required to obtain the match. This was demonstrated in the simulation using several hypothetical spoiler hardovers. In addition, the lateral control system is designed so that, in the event one element fails, the flight crew can override that failure and generally regain a controlling portion of the lateral control system.

The remaining potential cause of the Flight 585 accident identified in the NTSB report is a mountain rotor. Studies conducted by Boeing have determined that the simple rotor model used during the original investigation may not have been the most realistic model to use. Weather simulations based on the conditions present in the Colorado Springs area on the day of the accident have produced a different rotor model that has more realistic wind fields than those used during the earlier investigation, and that appears to cause a greater upset.

Figure 10 shows the match of the simulator to DFDR data given the rotor strength plotted as “P” shear. Also shown in the figure are the attitudes and wheel and rudder deflections consistent with the DFDR data. Work continues in this area, and simulations to date using the new rotor model appear to provide a reasonable match to the Flight 585 accident sequence.

The results of these studies have been shared with the NTSB staff, and additional work is being conducted in response to questions posed during NTSB review of these studies. The following summarizes the pertinent information obtained from simulator analysis of the Flight 585 accident:

1. The available DFDR data can be accurately matched with wheel and column control inputs only.
2. The introduction of rudder into the simulation causes the roll angle required to match the DFDR heading trace to deviate greatly from witness reports.
3. Only half wheel is required to control full rudder at the landing flap setting of Flight 585 at the onset of the upset.
4. Failure of the lateral control system could not have caused the upset since full lateral control to the right would be required.
5. A new model of a mountain rotor appears to provide a reasonable match to the Flight 585 accident sequence.

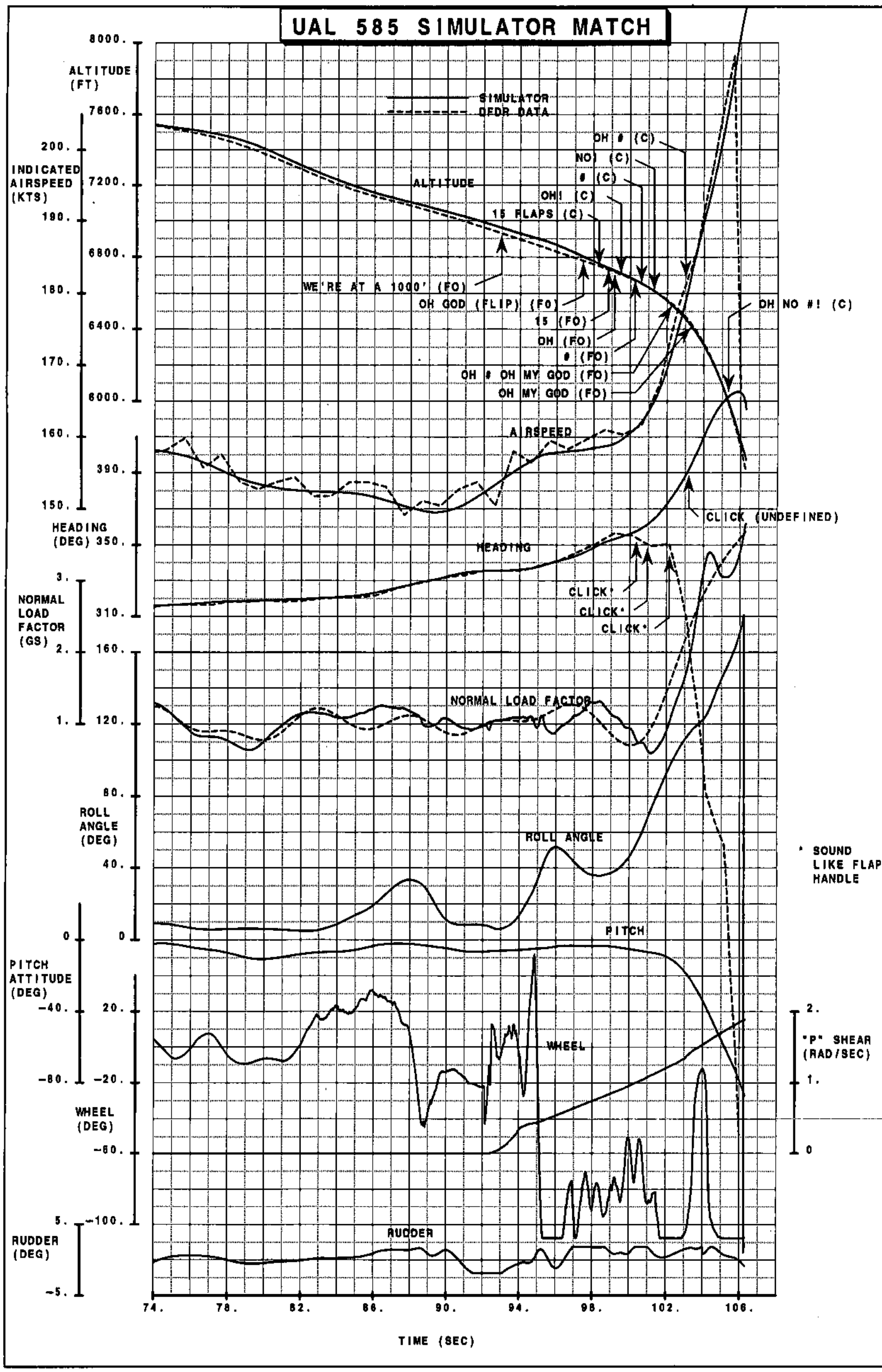

Figure 10: Flight 585 Simulator Match

Eastwind

The Eastwind aircraft was a 737-200 that experienced a yaw event to the right on the night of June 9, 1996, while on approach to Richmond, Virginia. The aircraft was not damaged during the event, and no one was injured. Instrumented flight testing of the aircraft after the incident did not produce any anomalous behavior, nor was there any evidence of a rudder jam observed in the post-accident examination.

This event is believed to have started with an electrical fault that caused a yaw damper hardover to the right. A kinematic analysis of this maneuver indicated that the initial rudder position reached during the yaw damper hardover was about four degrees.[39] This position is larger than the normal three-degree yaw damper limit, but is consistent with what a yaw damper hardover would produce, given that the damper position sensor on the Eastwind aircraft was found to have been misrigged.

It was also discovered that the incident aircraft's directional and vertical gyros produced errors, making estimations of rudder position difficult. Based on these somewhat questionable measurements, there was additional rudder movement in the same direction as the hardover. If this was the case, the rudder deflected to about six degrees, returned to near the yaw damper limit for that model 737, then returned to the greater deflection again, before finally returning to the expected yaw-damper-off position.

It is possible that the initial yaw damper hardover startled the crew. The event was more severe than a three-degree yaw damper hardover because of the misrigged position sensor. While the crew of the incident aircraft reported making left rudder inputs during the event, it is significant that the captain responded with wheel, throttle, and conceivably rudder inputs, all essentially at the same time. These near-simultaneous control responses were made at a time when the crew was encountering significant yaw and roll forces.

[39] The DFDR on this airplane recorded only 11 parameters and did not include any control parameters other than column.

The DFDR shows that the roll angle actually recovered back to wings level, and rolled in the opposite direction (to the left) during the recovery. Nevertheless, both crew members stated that the airplane was in a 25- to 30-degree bank to the right, when in fact the DFDR shows the airplane had rolled past wings level to the left.

Examination of the rudder PCU by the NTSB did not reveal any evidence of PCU malfunction, other than a misrigged yaw damper LVDT. Examination of the servo valve at NTSB offices in Washington, DC on March 12, 1997, did not reveal any evidence of a jam in the primary or secondary control valve slides.

The following summarizes the pertinent information obtained from analysis of the Eastwind incident:

1. The yaw damper position sensor was misrigged, causing a larger-than-normal rudder input due to the yaw damper hardover (i.e., 4.5° instead of 3°).
2. Bank and heading data from the incident was obtained from gyros that were producing erroneous data.
3. The crew responded to the upset with near-simultaneous inputs of wheel, throttle, and conceivably rudder. If additional rudder inputs were made, only two degrees of rudder input in the direction of the yaw damper hardover are required to match a derived rudder deflection.
4. The roll angle actually reversed from a right to a left bank during recovery, but both crew members perceived that the aircraft remained in a 25- to 30-degree right bank.
5. There is no evidence of any jam in the rudder servo valves.
6. The Flight 427 control valve testing demonstrated that the valve slides could not seize during any airplane operational scenario and also that it would not seize even for a thermal shock condition much more severe than what could ever be encountered by an in-service airplane. The Eastwind control valve slide clearances were greater than clearances for the Flight 427 control valve slides; therefore, neither the Flight 427 control valve nor the Eastwind control valve could seize during any airplane operational scenario.
7. There is no evidence of a linkage jam in the rudder PCU, and a linkage jam does not match the kinematic analysis.

Sahara India

The Sahara India Airlines aircraft was a 737-200ADV that crashed during a training flight at Palam Airport near Delhi, India. The accident occurred following a touch-and-go landing at the airport. It was the instructor's first time as an instructor pilot, the training pilot's first time piloting a 737, and the airline's first attempt to do its own training.

The aircraft was equipped with a DFDR that recorded the following parameters of interest: roll angle, pitch angle, heading, normal load factor, longitudinal acceleration, column position, engine pressure ratio, airspeed, and altitude. The heading parameter is measured by a single-axis gyro that is subject to known errors when large bank and pitch angles are encountered.

The pilot in training was conducting a touch-and-go maneuver, which is commonly used during training to minimize flight time. Even though the instructor pilot had not briefed his trainee pilot that an engine-out exercise would be conducted, the instructor pilot apparently decided to introduce a simulated engine failure during the takeoff following the touch-and-go. As the aircraft rotated, the DFDR indicated that engine thrust was slowly reduced on the left engine. This reduction was halted momentarily after liftoff—while the instructor pilot retracted the landing gear after positive rate of climb was achieved—then continued until idle thrust levels were reached.

As thrust was reduced, the aircraft rolled left about 8 degrees and then returned to wings level. It then rolled sharply to the left to a maximum roll angle of 100 degrees. The bank angle was reduced to 60 degrees to the left before again rolling off to 80 degrees left at impact. Pitch angle was 20 degrees nose down at the time.

Figure 11 presents the results of a simulator study showing that wheel and some rudder were used to return the aircraft to wings level during the simulated engine failure. At about this time, the instructor pilot called out "rudder, rudder, rudder." The simulator evaluation showed that the rudder moved sharply to the left, which is the wrong direction to correct for a left engine failure. This caused the aircraft to roll rapidly to the left, even though the simulator evaluation showed that full right wheel was applied. The lateral control system was not able to overcome the roll due to sideslip, which was being generated by both the rudder and the thrust asymmetry.

As the maneuver progressed, the captain called out "leave, leave, leave," and the simulation indicates that the rudder input disappeared. This stopped the roll rate to the left, but it was too late to recover the aircraft from the large bank angle and nose-down pitch angle that had already developed.

The following summarizes pertinent information obtained from the simulator analysis:

1. The rudder was operational during the simulated engine failure.
2. The rudder was operational during the final seconds of the Sahara accident.[3]
3. Wheel alone was not sufficient to reverse the rapid roll to the left; only the removal of the left rudder could have resulted in the bank angle time history recorded on the DFDR.

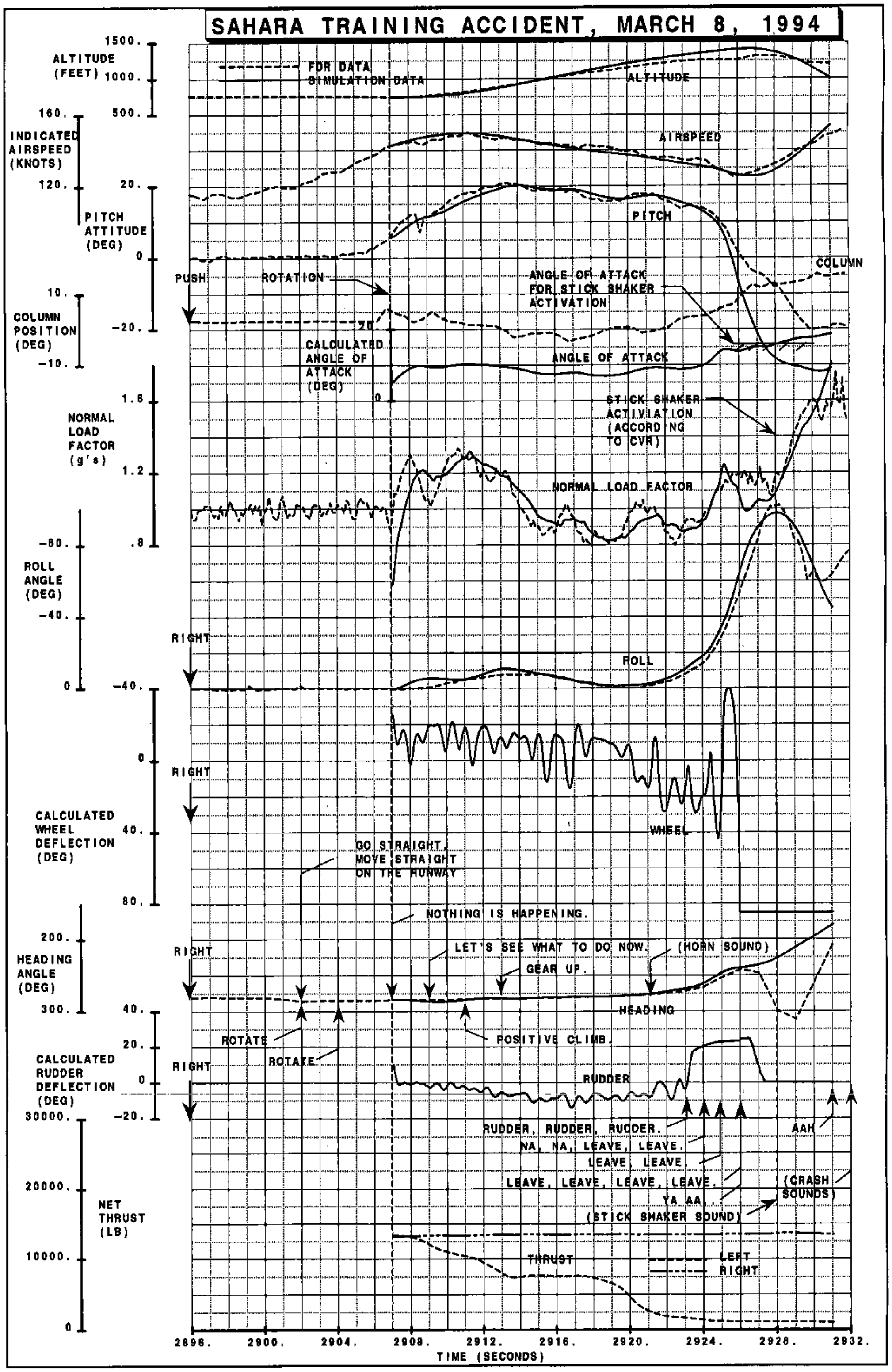

Figure 11: Sahara India Airlines Training Accident

Other "Uncommanded" Yaw and Roll Events

The analysis of 737 yaw and roll events that occurred between July 1995 and November 1996 are summarized in Table 5. Of the 78 events, a probable cause was identified for 53 events. Flight data were available for 59 of the total 78 events. The probable causes of the events are placed into four categories: system, crew, wake turbulence, and unexpected though normal aircraft response. The database from which Table 5 was constructed is shown in Table 6. All 737 roll/yaw events that were reported to the Aerodynamics Product Support group between July 1995, and November 1996 are listed. Those events which were the result of normal aircraft performance, yet were unexpected by the flight crew are listed as "normal" under the "cause" column.

The majority of events are roll events that are attributed to wake turbulence encounters. In each of the events caused by wake turbulence, perturbations in airspeed and/or normal load factor indicate that the event is due to a disturbance that is external to the aircraft systems. For many of the wake turbulence encounters, the flight data recorder data show wheel or aileron deflections in opposition to the roll. Also, for some of the events, analysis of the air traffic control radar data shows that the event aircraft location and the location of the wake turbulence from the preceding aircraft are coincident.

There were about twice as many roll events as there were yaw events which were attributed to system faults: 9 roll and 4 yaw events. More than one event was caused by faults in each of the autopilot (4) and yaw damper (3) systems. The autopilot faults resulted in disengagement of the autopilot and produced roll upsets smaller in magnitude than that demonstrated during certification of the autopilot system. During this certification, a fault was inserted into the autopilot which resulted in a lateral control deflection to the limit of the autopilot authority. The events attributed to yaw damper faults were the result of rudder deflections within the authority limit of the yaw damper. For each of the remaining system-caused events, a single event was attributed to each of the following: rudder trim switch fault, autothrottle asymmetry, landing gear oleo pressure asymmetry, manual reversion flight controls selection, spoiler actuator fault, and leading edge slat actuator fault.

The flight crew was the primary contributor to six events, all of which involved rolls. Two caused nacelle strikes during landing following control inputs made at touchdown. In another three events, the airplane responded properly to crew actions that involved FMC confusion, exceedance of the autopilot bank angle target, and roll due to fuel imbalance. In this last event, a roll-off at stall occurred when the flight crew apparently allowed the airplane to be stalled by the autopilot.

A probable cause was not determined for 27 of the 80 events. For 19 of these, no flight data were available for analysis.

						Unknown		
		System	Crew	Unexpected Airplane Response	Wake	With Data	Without Data	Totals
Roll	9	A/P Fault (4) Gear Asymmetry Manual Reversion Autothrottle Spoiler Actuator L. E. Slat Actuator	6	2	30 1 (wind shear)	2	9	59
Yaw	4	Yaw Damper (3) Trim Switch	0	1	0	5	11	21
Roll-Yaw Events Combined		16% (13)	8 (6)	4 (3)	39 (31)	9% (7)	25% (20)	80
						34 (27)		
Roll-Yaw Excluding Unknown		25%	11%	6%	58%	Total Unknown Events 27		

Table 5: Uncommanded Yaw and Roll Event Summary

					FDR Data			
Airplane	**Occurred**	**Event Description**	**Axis**	**Cause**	**Avail.**	**Received**	**Closed**	**Flight Phase**
737-500	9/20/95	Exceedance of A/P Bank Limit	Roll	normal	Y	Y	5/24/96	Takeoff
737-500	4/13/96	Exceedance of A/P Bank Limit	Roll	normal	Y	Y	8/23/96	Takeoff
737-300	7/6/95	Wake Turbulence	Roll	wake	Y	Tab	9/27/96	Approach
737-300	7/18/95	Wake Turbulence	Roll	wake	Y	Y	1/17/96	Descent
737-300	8/5/95	Wake Turbulence	Roll	wake	Y	Y	1/17/96	Approach
737-300	8/25/95	Wake Turbulence	Roll	wake	Y	Y	1/17/96	Descent
737-300	8/30/95	Wake Turbulence	Roll	wake	Y	Y	1/17/96	Descent
737-500	9/6/95	Wake Turbulence	Roll	wake	Y	Y	1/15/96	Approach
737-300	9/29/95	Wake Turbulence	Roll	wake	Y	Y	1/17/96	Descent
737-300	9/30/95	Wake Turbulence	Roll	wake	Y	Y	1/17/96	Cruise
737-300	10/15/95	Wake Turbulence	Roll	wake	Y	Y	7/24/96	Approach
737-300	10/26/95	Wake Turbulence	Roll	wake	Y	Y	7/28/96	Approach
737-300	10/27/95	Wake Turbulence	Roll	wake	Y	Y	7/28/96	Approach
737-300	10/31/95	Wake Turbulence	Roll	wake	Y	Y	4/9/96	Descent
737-400	11/6/95	Wake Turbulence	Roll	wake	Y	Y	12/18/95	Approach
737-300	12/5/95	Wake Turbulence	Roll	wake	Y	Y	3/18/96	Final
737-400	1/18/96	Wake Turbulence	Roll	wake	Y	Y	3/29/96	Takeoff
737-200	2/9/96	Reported Wake Turbulence	Roll	wake	Y	N		Approach
737-500	2/15/96	Wake Turbulence	Roll	wake	Y	Tab	9/27/96	Descent
737-400	2/26/96	Reported Wake Turbulence	Roll	wake	Y	N		
737-300	4/1/96	Reported 777 Wake Turbulence	Roll	wake	Y	N		Approach
737-500	4/20/96	Reported 747 Wake Turbulence	Roll	wake	Y	N		Descent
737-400	5/8/96	Reported Wake Turbulence	Roll	wake	Y	N		Descent
737-300	6/29/96	Wake Turbulence	Roll	wake	Y	Y		Descent
737-500	7/24/96	Wake Turbulence	Roll	wake	Y	Y	9/27/96	Descent
737-200	8/12/96	Reported 747 Wake Turbulence	Roll	wake	N			Approach
737-300	8/13/96	Wake Turbulence	Roll	wake	Y	Y	9/12/96	Approach
737-400	8/18/96	Wake Turbulence	Roll	wake	Y	Y	9/30/96	Approach

Table 6: Aerodynamics Product Support – 737 Roll/Yaw Events

Airplane	Occurred	Event Description	Axis	Cause	FDR Data Avail.	FDR Data Received	Closed	Flight Phase
737-500	9/5/96	Wake Turbulence	Roll	wake	Y	Y	9/27/96	Descent
737-500	9/6/96	Wake Turbulence	Roll	wake	Y	Y	9/27/96	Descent
737-300	10/13/96	Wake Turbulence	Roll	wake	Y	11/14/96	3/3/97	Descent
737-200	11/8/96	Wake Turbulence	Roll	wake	Y	Y	1/3/97	Approach
737-300	3/15/96	Windshear	Roll	weather	Y	Tab		Approach
737-400	7/16/95	Reported A/P Induced Roll	Roll	system	N			Climb
737-300	7/25/95	Unexpected A/P Disconnect	Roll	system	Y	Y	1/17/96	Approach
737-400	8/11/95	Gear Strut Asymmetry	Roll	system	Y	Y	7/9/97	Takeoff
737-200	9/25/95	Reported Uncommanded Roll A/P Eng/Diseng.	Roll	system	N			
737-300	10/22/95	Uncommanded Roll at A/P Engage	Roll	system	Y	Y	4/10/96	Approach
737-300	4/28/96	Reported Uncommanded Roll w Asymmetric A/T	Roll	system	Y	N		Descent
737-200	8/18/96	Reported Roll at Manual Reversion Check	Roll	system	N			Cruise
737-200	11/2/96	#3 L.E. Slat Failed	Roll	system	N			Climb
737-200	11/29/96	Reported Uncommanded Roll w/ Spoiler Actuator Fault	Roll	system	N			Approach
737-400	7/25/95	Crew/FMC Confusion	Roll	crew	Y	Y	1/17/96	Approach
737-500	10/2/95	Nacelle Strike	Roll	crew	Y	Y	2/26/96	Landing
737-500	11/10/95	A/P Bank Angle Exceedance	Roll	crew	Y	Y	5/24/96	Takeoff
737-400	7/28/96	Wingtip Strike and Hard Landing	Roll	crew	Y	Y	1/13/97	Landing
737-400	9/18/96	Fuel Imbalance, Roll at A/P disconnect	Roll	crew	Y	N		Climb
737-200	11/14/96	Apparent Flaps Up Stall	Roll/Pitch	crew	Y	Y		Test
737-300	11/10/95	Uncommanded Roll	Roll	unknown	N			Approach
737-200	1/2/96	Uncommanded Lateral Oscillation	Roll	unknown	N			Climb
737-200	1/14/96	Uncommanded Roll	Roll	unknown	Y	Y	9/27/96	Approach
737-300	7/14/96	Wingtip Strike and Hard Landing	Roll	unknown	N			Landing
737	7/24/96	Nacelle Strike	Roll	unknown	N			
737	7/24/96	Nacelle Strike	Roll	unknown	N			
737-300	7/25/96	Uncommanded Roll at Flare	Roll	unknown	Y	Y		Landing
737-200	8/8/96	Hard Landing, Nacelle Strike	Roll	unknown	N			Landing
737-500	8/23/96	Roll Exceedance	Roll	unknown	N			Climb

					FDR Data			
Airplane	**Occurred**	**Event Description**	**Axis**	**Cause**	**Avail.**	**Received**	**Closed**	**Flight Phase**
737-400	10/16/96	Reported Yaw/Roll Motion	Roll/Yaw	unknown	N			Climb
737-200	UKN	Uncommanded Roll	Roll	unknown	N			Cruise
737-300	7/10/96	Uncommanded Yaw	Yaw	normal	Y	Y	1/8/97	Takeoff
737-300	7/25/95	Reported Y/D Hardover	Yaw	system	Y	Y	4/9/96	Approach
737-300	9/29/95	Rudder Trim Runaway	Yaw	system	Y	Y	2/20/97	Climb
737-200	10/22/95	Sustained Dutch Roll, Y/D Fault	Yaw/Roll	system	Y	Y	11/28/95	Cruise
737-200	7/25/96	Uncommmanded Yaw	Yaw	system	Y	Y	9/27/96	Takeoff
737-200	7/24/95	Reported Uncommanded Rudder	Yaw	unknown	N			Climb
737-200	8/1/95	Uncommanded Yaw w/ Loud Thud	Yaw	unknown	Y	N		
737-400	8/18/95	Reported Yaw just Prior to T/D	Yaw	unknown	Y	N		Approach
737-200	8/21/95	Reported Yaw Anomaly at Takeoff	Yaw	unknown	Y	Tab		Takeoff
737-200	9/10/95	Reported Yaw Prior Takeoff Rotation	Yaw	unknown	Y	N		Takeoff
737-300	3/6/96	Uncommanded Yaw	Yaw	unknown	N			
737-200	4/21/96	Runway Excursion w/ A & B Hyd Loss	Yaw	unknown	N			Landing
737-200	5/14/96	Uncommanded Yaw w/o Pedal Deflect.	Yaw	unknown	Y	Y		Climb
737-200	6/1/96	Uncommanded Yaw	Yaw	unknown	Y	Y		Descent
737-200	6/8/96	Uncommanded Yaw w Y/D Disengaged	Yaw	unknown	Y	N		Unknown
737-200	6/9/96	Uncommanded Yaw w/ Stiff Pedal Feel	Yaw	unknown	Y	Y		Descent
737-300	8/2/96	Runway Excursion, Heavy Rain	Yaw	unknown	N			Landing
737-500	8/3/96	Uncommanded Yaw w/ Pedal Motion	Yaw	unknown	N			Takeoff
737-400	8/3/96	Runway Excursion, Rain & Wind	Yaw	unknown	N			Landing
737-500	8/15/96	Uncommanded Yaw	Yaw	unknown	N			Approach
737-300	11/16/96	Uncommanded Yaw	Yaw	unknown	Y	Y		Takeoff

Table 6: Aerodynamics Product Support – 737 Roll/Yaw Events

The following conclusions and recommended actions were extracted from the *737 Roll Team Report* dated January 18, 1996.

6. Conclusions and Recommended Actions:

6.3 Specific Event-Related Actions

The team was unable to find a single system fault mode that would explain the high rate roll upsets for flaps-up operation. The combined system fault modes investigated were capable of generating the higher roll rates, but the load factor and airspeed perturbations, evident in many of the roll upset events, are absent from the system failure responses.

There were several in-service events that were isolated to specific system failures or to crew interface issues. The hardware failure cases (autopilot disconnect, rudder trim switch fault, gear strut charging, and the failed aileron actuator) are unrelated. The rudder trim switch fault represents a "dual" fault state since the single failure bypassed both the "arm" and "command" features of the trim control. It is recommended that component Service Bulletin 69-73703-27-02 dated 9/24/92 be incorporated by all operators to take advantage of the improved trim switch design.

All of the studied events produced upsets that were controllable by the flight crew.

Three crew interface events were examined. In the first event, the crew misunderstood the interaction between autopilot Heading Select and FMC L-NAV path control. The second relates to a report of an unexpected roll whereas the FDR data appears to reflect normal Heading Select operation. The third condition resulted from inadvertent activation of the lateral trim system while the autopilot was engaged. This resulted in a roll upset upon autopilot disengagement. The first and last events appear to be crew awareness issues and may relate to crew training. The second is a puzzle. There appears to have been some crew interaction with the MCP since the Bank Angle limits are different for two Heading Select changes that occurred in little over a minute. No recommendation is made for these crew issues.

The remaining events, where the team was able to identify a possible root cause, indicated wake turbulence encounters. These short-duration events have high roll rates and caused crew concerns on several occasions. The recovery techniques vary between flight crews with some crews using rudder inputs as part of the recovery technique. The upsets for wake encounters need to be reviewed by the Boeing crew training organization to determine if special crew training, alternate means of informing the crew is required, and/or to determine if recommended recovery techniques need to be established.

This completes the team conclusions and recommendations.

Appendix D
Operational Evidence Regarding Crew Performance

Topic	Reference Event
A. Encounters with wake turbulence can surpriseor startle flight crews,	(35) ASRS 269033 (April 1994) (61) ASRS 271187 (May 1994) (62) ASRS 279517 (August 1994) (63) ASRS 251874 (September 1994) (04) ASRS 280998 (August 1994) (64) ASRS 288796 (November 1994) (65) ASRS 190748 (October 1991) (66) ASRS 156250 (August 1990) (70) ASRS 145972 (May 1990) (71) ASRS 189664 (September 1991) (74) ASRS 299779 (March 1995) (75) ASRS 271385 (May 1994) (95) 737 Event (November 1995) (15) ASRS 280652 (August 1994) (67) ASRS 149927 (June 1990) (68) ASRS 256700 (November 1993) (69) ASRS 276427 (July 1994) (60) ASRS 293944 (January 1995) (05) 737 Event (June 1995) (55) 737 Event (June 1995) (56) 737 Event (June 1995) (57) 737 Event (June 1995) (09) ASRS 286702 (October 1994) (16) ASRS 49794 (January 1996) (10) ASRS 188899 (September 1991) (91) 737 Event (August 1995) (51) ASRS 314668 (August 1995) (11) ASRS 107506 (December 1988) (13) ASRS 298642 (February 1995) (72) ASRS 216232 (July 1992) (73) ASRS 285274 (October 1994) (12) ASRS 72048 (July 1987) (14) ASRS 213928 (June 1992) (54) 737 Event (October 1995) (94) 737 Event (November 1995)
B. Crews typically over-perceive the magnitude of unexpected rolls by a factor of two or three, and may react accordingly.	(32) CAA Air Traffic Control (Wake Vortex Reporting) (86) FAA Safety Analysis of Uncommanded Rolls (05) 737 Event (June 1995) (55) 737 Event (June 1995)

	(56) 737 Event (June 1995) (57) 737 Event (June 1995) (20) 737 Event (June 1995) (06) 737 Event (July 1995) (91) 737 Event (August 1995) (33) 737 Event (March 1995) (51) 737 Event (August 1995) (77) ASRS 260432 (January 1994) (95) 737 Event (November 1995) (24) 737 Event (October 1995) (45) 737 Event (September 1995) (46) 737 Event (February 1996) (52) 737 Events (September 1996) (58) 737 Event (April 1997)
C. Flight crews typically respond to unexpected upsets by immediately manipulating the flight controls. Both wheel and rudder control inputs are often used during the recovery.	(06) 737 Event (July 1995) (47) Ozark DC-9 (December 27, 1968) (03) ASRS 144064 (April 1990) (04) ASRS 280998 (August 1994) (20) 737 Event (January 1995) (48) 737 Event (February 1995) (42) ASRS 220642 (September 1992) (43) ASRS 225605 (October 1992) (44) ASRS 251615 (September 1993) (13) ASRS 298642 (February 1995) (64) ASRS 288796 (November 1994) (80) ASRS 92829 (August 1988) (79) ASRS 63448 (January 1987) (90) 737 Event (September 1995) (91) 737 Event (August 1995) (05) 737 Event (June 1995) (96) 737 Event (April 1993) (51) 737 Event (August 1995) (24) 737 Event (October 1995) (53) 737 Event (July 1995) (65) 737 Event (October 1991)
D. 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,	(97) Donald Widman (I Learned About...Nightmare on Final) (02) United Airlines Engine Failure (27) United Airlines Advanced Maneuvers (single engine) (33) 737 Event (March 1995) (37) NTSB Aircraft Accident Report (03) ASRS 144064 (April 1990) (06) 737 Event (July 1995) (22) 737 Event (January 1979) (23) United Airlines Standards Captain L. S. Walters

	(34) Comfortable in the corners of the envelop (25) 737 Event (October 1986) (49) P. Fitts (Analysis of Factors Contributing to 460 Pilot-Error...) (96) 737 Event (April 1993) (59) 737 Event (April 1993) (29) 737 Sahara accident (March 8, 1994) (92) Airline training
E. 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.	(62) ASRS 279517 (August 1994) (79) ASRS 63448 (January 1987) (80) ASRS 92829 (August 1988) (12) ASRS 72048 (July 1987) (81) ASRS 276165 (July 1994) (33) 737 Event (March 1995) (05) 737 Event (June 1995) (97) 737 Event (June 1980)

(For further details, see Boeing's *USAir 427 Submissions Supplement: Human Factors,* Sep. 25, 1997.)

Appendix E
Boeing-Recommended Training and Procedures

Boeing is taking two steps to help flight crews better recover from in-flight upsets, regardless of the cause:

- Unusual attitude training.
- Improved flight crew procedures.

Unusual Attitude Training

Exhaustive investigation into the two 737 accidents led to an extensive review of virtually all flight crew-reported upset events during the past three years. The investigation revealed that many airplane upset events occur as a result of atmospheric conditions such as windshear, mountain rotors, turbulence, or wake vortices of other airplanes. Boeing is working with industry representatives to develop an Airplane Upset Recovery Training Aid, which is scheduled for release in late 1997. Intended to support education and training for flight crews of large swept-wing airplanes, this training aid will provide effective methods for recovering from in-flight upsets, whatever their cause.

Boeing recommends that the training aid should stress the technique of prioritizing roll control as the method for recovering from large nose-down bank upsets. This technique assumes the airplane is not stalled. If it is stalled, the flight crew must first recover from the stall condition before recovering from the upset. The nose-down upset recovery technique requires the flight crew to:

- Reduce airplane angle-of-attack, allowing the airplane to accelerate, which improves lateral-control ability.
- Roll wings level, using all available flight controls.
- Apply up elevator to recover toward the desired airplane pitch attitude and airspeed.

Recovery techniques will be discussed more thoroughly in the training aid. Operators may adapt and tailor the training aid to meet their individual program needs.

Improved Flight Crew Procedures

In January 1997, the FAA mandated changes to the Airplane Flight Manual that require revisions to the existing yaw or roll procedures and a new procedure for a jammed or restricted rudder. In February 1997, Boeing issued an operations manual bulletin that provided specific recommendations to operators on how to implement the changes. The bulletin was the direct result of an industrywide effort to enhance the existing procedures. Participants included the Air Transport Association (ATA), Airline Pilots Association (ALPA), FAA, and several airlines.

The revised *Uncommanded Yaw or Roll Procedure* recognizes that timely and appropriate response to large lateral/directional disturbances can significantly reduce the resulting bank angle. It employs the Boeing-recommended technique of prioritizing roll control as the method for recovering from large, nose-down lateral upsets. Rolling wings level significantly reduces the chance of an accelerated stall.

The new *Jammed or Restricted Rudder* Procedure is more extensive than the previous jam procedure. It addresses recovery from a jammed or restricted rudder, taking into account all potential causes—known and hypothetical—of a rudder system malfunction. The procedure emphasizes the importance of first restoring control (wings level flight), using all available flight controls, before trying to isolate the suspected cause of an uncommanded yaw or roll event.

The procedure is based on three concepts:

- The flight crew may not know the exact fault.
- Following the procedure eliminates the effect of the fault conditions in a sequence that leaves the most normal configuration for continued safe flight and landing.

- While neutralizing the faults, the flight crew takes no steps that would jeopardize safe flight.

The new procedure was validated through ground and flight tests at Boeing before it was released.

In addition to this procedural change, some operators have adopted a 10-knot increase for block speeds for certain flap settings, where block speeds are the minimal maneuvering speed for a given flap setting. An increase in these block speeds above the Boeing-recommended levels, although not required, will provide a marginal increase in lateral-control capability relative to directional (rudder) control capability. Boeing has no technical objection to this technique.

Appendix F
Boeing-Recommended Design Changes

The design improvements Boeing has identified are based on lessons learned during extensive testing and thousands of hours of analysis. The company intends to improve upon an already safe and reliable control system by incorporating the following redesigns and new features:

- Rudder power control unit (PCU) valve redesign.
- New PCU input rod fasteners.
- Yaw damper system redesign.
- New hydraulic pressure reducer.
- Rudder input force transducer.

These changes are intended to protect against some highly unlikely failures, improve reliability, and aid in investigations in the event a future incident or accident should occur.

Rudder PCU Valve Redesign

Housed in the base of the vertical fin, the 737 main rudder PCU directs power from two independent hydraulic systems to deflect the rudder in response to rudder pedal inputs from the flight crew, and from yaw damper inputs. It does not receive commands from the 737 autopilot system.

For safety through redundancy, the 737 rudder PCU employs a dual concentric valve design. If either the primary or secondary valve slide jams (a highly unlikely event), the other slide moves to counteract its unwanted input.

Thermal shock tests performed in October 1996 revealed a previously unknown failure effect. A secondary valve slide seized when an unpressurized PCU, cold-soaked to -40°F, was suddenly hit with hydraulic fluid heated to 170°F, a temperature that is well outside the normal operating limits of the unit. In this test, the redundant features of the valve did not work as intended, resulting in a rudder movement to full authority in the direction opposite to the rudder pedal input.

In actual operations, however, PCUs are pressurized with warm hydraulic fluid and maintain an in-flight temperature no lower than 35°F—or some 75°F warmer than in this extreme test—while the hydraulic fluid temperature is normally not much warmer than the PCU. Even for hot weather or hydraulic system failure conditions, the system does not experience temperature extremes between the PCU and hydraulic fluid that would approach the conditions necessary to seize the valve.

All of the testing and data indicate that a thermal-induced secondary-slide jam is impossible in flight. Nevertheless, Boeing believes that it is prudent to eliminate the failure effect demonstrated in the thermal shock tests. Boeing issued service bulletin (SB) 737-27A1202 advising operators to test for any latent valve jams of this nature. Reinforced by FAA Airworthiness Directive (AD) 96-23-51, this examination of the world fleet is required every 250 flight hours. More than 2,500 737s have been inspected so far, with no evidence of a secondary slide jam. No such event has ever been recorded in the more than 80 million flight hours logged by 737s to date.

This inspection requirement will end once operators install a new rudder PCU dual valve in the current-generation 737 fleet (737-300, -400, and -500). This valve—which will be nearly identical to that used in the rudder PCU of Next-Generation 737s (737-600, -700, and -800)—restores the redundant features of the valve for any hypothetical jam condition.

New PCU Input Rod Fasteners

During routine in-service maintenance, two fractured outer bolts were discovered on 737 rudder PCU input rods. In both cases, the fracture was initiated when the shank of the bolt ran into the nut threads. Because this fastener is a dual-load-path design with inner and outer elements, either of which is sufficient to retain the input rod, these fractures did not affect system operation.

A fractured input rod fastener was not involved in the Flight 427 accident event. However, because any condition that could eliminate one of the redundant load paths in this 737 rudder control system linkage is undesirable, a new fastener has been designed to prevent the cause of these fractures. These fasteners were made available in August 1997 and may be retrofit concurrently with the PCU valve retrofit.

Yaw Damper System Redesign

A redesigned yaw damper is included in the enhancements to the 737 rudder control system. This new unit will reduce any flight-path upsets that could be caused by yaw damper system malfunctions.

The yaw damper serves to counteract Dutch roll, a natural flight oscillation characteristic of swept-wing airplanes. Because the 737 is less prone to Dutch roll than most jetliners, its design does not require a yaw damper. Nevertheless, one is included to improve ride comfort.

The 737 yaw damper is mechanically limited. It can deflect the rudder no more than three degrees either way in current-generation 737s, and from two to four degrees in earlier models (737-100, -200, and -200ADV).

As a result, a malfunctioning yaw damper is controllable by the flight crew, and will not affect safety of flight. The flight path upsets that may result from such a malfunction can startle the flight crew, however, and can potentially lead to injuries among passengers and cabin crew.

The Flight 427 accident investigation found no evidence that a yaw damper malfunction occurred during the event. However, an investigation into the service history of this yaw damper system showed opportunities to significantly improve its reliability using technologies available today. The resulting redesigned system:

- Replaces the current system's single electro-mechanical rate gyro with a dual solid-state rate sensor that is more reliable and free of mechanical wear problems.
- Retains the form and fit of the existing yaw damper coupler to simplify incorporation on in-service airplanes.
- Adds control and indication electronics for the new rudder PCU pressure reducer.
- Provides detailed system monitoring and fault analysis through improved built-in test equipment.
- Includes improved wire shielding and isolation to eliminate problems caused by electrical interference.

This new system is scheduled to be incorporated into current-generation 737 production in July 1998, when retrofit kits will be available.

New Hydraulic Pressure Reducer

Excessive rudder deflections at high speed can damage the vertical stabilizer on many airplanes. To avoid the risk of excessive loads on the vertical fin, these airplanes have rudder ratio changers or pressure reducers to limit rudder travel at higher speeds, when the rudder is proportionately more effective. Because these potentially damaging loads are not present in the current-generation 737 family, a rudder authority limiter is not required in its design.

However, Boeing decided to incorporate a hydraulic pressure reducer that reduces the amount of rudder available to the flight crew. Incorporation of a pressure reducer will reduce available rudder authority by about one-third during those phases of flight when large rudder deflections are not required. This reduced authority will further enhance 737 safety by reducing the airplane’s reaction to full rudder inputs, giving flight crews more time to recover from any excessive rudder deflections. It will also make 737 lateral controls (ailerons and spoilers) proportionately more effective in countering excessive rudder inputs.

The new hydraulic pressure reducer does not adversely affect airplane handling characteristics. This system is inactive in the three situations when full rudder authority is desirable:

- Below 1,000 feet above ground level (AGL) during takeoff climb.
- Below 700 feet AGL during landing approach.
- When one engine has failed, regardless of altitude (737-300, -400, and -500 only).

Added to the "A" hydraulic system near the rudder PCU, this reducer unit lowers the hydraulic pressure from 3,000 psi (737-300, -400, and -500) or 1,400 psi (737-100, -200, and -200ADV) during conditions other than those listed above. It does not interfere with the yaw damper, which makes inputs to the servo valve controlled by the "B" hydraulic system. Because the control and indication logic for the hydraulic pressure reducer will reside in the new yaw damper, these two changes will be implemented together.

Rudder Input Force Transducer

FAA Notice of Proposed Rulemaking (NPRM) 96-7 mandates additional flight data recording parameters, including rudder-surface and pedal positioning. This change applies to new-production 737s and requires retrofit to 737s already in service.

Rudder pedal force—another valuable flight data recorder parameter —is part of NPRM 96-7 for new-production airplanes only. The FAA encourages, but does not mandate, the retrofit installation of pedal-force sensors to the 737 fleet.

Recording rudder input force on all 737s will benefit operators, manufacturers, and certification and investigation agencies. Because this parameter records crew input forces through the rudder pedals, not just pedal positioning, it will help the industry better understand possible future rudder-related incidents.

Had Flight 427 been equipped with a rudder input force transducer, accident investigators would have been able to quickly determine whether the questioned rudder deflection was airplane-caused or crew-commanded.

The aft quadrant control rod is being designed with a force transducer to record this parameter. A service bulletin and retrofit kit for the world fleet may be available as early as May 1998. Also at that time, the identical installation will be incorporated in current-generation 737 production. A similar design is in development for Next-Generation 737 models.