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.