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National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

Date: April 16, 1999

In reply refer to: A-99-20 through -29

Honorable Jane F. Garvey
Administrator
Federal Aviation Administration
Washington, D.C. 20591

On September 8, 1994, about 1903:23 eastern daylight time, USAir (now US Airways)[1] flight 427, a Boeing 737-3B7 (737-300), N513AU, crashed while maneuvering to land at Pittsburgh International Airport, Pittsburgh, Pennsylvania. Flight 427 was operating under the provisions of 14 Code of Federal Regulations (CFR) Part 121 as a scheduled domestic passenger flight from Chicago-O'Hare International Airport, Chicago, Illinois, to Pittsburgh. The flight departed about 1810, with 2 pilots, 3 flight attendants, and 127 passengers on board. The airplane entered an uncontrolled descent and impacted terrain near Aliquippa, Pennsylvania. All 132 people on board were killed, and the airplane was destroyed by impact forces and fire. Visual meteorological conditions prevailed for the flight, which operated on an instrument flight rules flight plan.[2]

After analysis of the cockpit voice recorder, computer simulations, and human performance data (including operational factors), the National Transportation Safety Board determined that the probable cause of the USAir flight 427 accident was a loss of control of the airplane resulting from the movement of the rudder surface to its blowdown limit.[3] The Safety Board further determined that the rudder surface most likely deflected in a direction opposite to that commanded by the pilots as a result of a jam of the main rudder power control unit (PCU)

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[1] For consistency, US Airways is referred to as USAir throughout this safety recommendation letter.

[2] For more detailed information, see National Transportation Safety Board. 1999. ***Uncontrolled Descent and Collision With Terrain, USAir Flight 427, Boeing 737-300, N513AU, Near Aliquippa, Pennsylvania, September 8, 1994.*** Aircraft Accident Report NTSB/AAR-99/01. Washington, DC.

[3] The rudder's blowdown limit is the maximum amount of rudder available for an airplane at a given flight condition/configuration. Rudder blowdown occurs when the aerodynamic forces acting on the rudder become equal to the hydraulic force available to move the rudder.

servo valve[4] secondary slide to the servo valve housing offset from its neutral position and overtravel[5] of the primary slide.

Because of early indications that the initial upset of USAir flight 427 might have been caused by an unintended or uncommanded rudder movement, which was considered (but not established as a cause or factor) in connection with the 1991 crash of a 737 at Colorado Springs, Colorado (United Airlines flight 585),[6] the Safety Board reviewed all of the information collected for its investigation of that accident during the investigation of the USAir flight 427 accident.’ In addition, the Safety Board investigated a 1996 yaw/roll incident involving a 737 near Richmond, Virginia (Eastwind flight 517), to determine if the upset event may have been related to an anomalous rudder movement.

The Safety Board concluded that it is possible that, in the main rudder PCUs from the USAir flight 427, United flight 585, and Eastwind flight 517 airplanes (as the result of some combination of tight clearances within the servo valve, thermal effects, particulate matter in the hydraulic fluid, or other unknown factors), the servo valve secondary slide could jam to the servo valve housing at a position offset from its neutral position without leaving any obvious physical evidence and that, combined with a rudder pedal input, could have caused the rudder to move opposite to the direction commanded by a rudder pedal input. After analysis of the cockpit voice recorder, computer simulations, and human performance data (including operational factors), the Safety Board concluded that the upsets of USAir flight 427, United flight 585, and Eastwind flight 517 were most likely caused by the movement of the rudder surfaces to their blowdown limits in a direction opposite to that commanded by the pilots and that the rudder surfaces most likely moved as a result of jams of the secondary slides to the servo valve housings offset from their neutral position and over-travel of the primary slides.

In addition to this reversal potential, the Safety Board's investigation revealed two other potential failure mechanisms’ within the 737 rudder control system that could result in a

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[4] The 737 main rudder PCU servo valve is used to control rudder direction and rate of movement. The servo valve comprises a primary slide that moves within a secondary slide that, in turn, moves within the servo valve housing. These slides direct hydraulic fluid through passages to cause rudder movement.

[5] Overtravel is the ability of a device to move beyond its normal operating position or range. Within the main rudder PCU servo valve, over-travel of the primary or secondary slides would be the result of elastic deformation of the mechanical input mechanism.

[6] See National Transportation Safety Board. 1992. ***United Airlines Flight 585, Boeing 737-291, N999UA, Uncontrolled Collision With Terrain for Undetermined Reasons, 4 Miles South of Colorado Springs Municipal Airport, Colorado Springs, Colorado, March 3, 1991.*** Aircraft Accident Report NTSB/AAR-92/06. Washington, DC.

[7] Because the USAir flight 427 accident and other 737 accidents and incidents raised questions regarding the 737's flight control systems, on October 20, 1994, the Federal Aviation Administration (FAA) initiated a Critical Design Review of the 737 flight control systems with emphasis on the roll control and directional flight control systems. The Critical Design Review team included seven flight control systems specialists from the FAA, Transport Canada, and the U.S. Air Force. For additional information, see the team's report, entitled "B-737 Flight Control System Critical Design Review," dated May 3, 1995. One of the recommendations in the report was that the Safety Board begin a combined investigation of the United flight 585 and USAir flight 427 accidents.

[8] A third potential failure mechanism—a jam of the primary to the secondary slide with overtravel of the secondary slide—was identified as a result of testing after a July 1992 United Airlines rudder anomaly that occurred

deflection to the rudder's blowdown limit. One of these potential failure mechanisms is a physical jam in the rudder system input linkage (between the PCU's input crank and body stop), preventing the main rudder PCU control valve from closing; the other is a jam of the primary to the secondary slide of the main rudder PCU servo valve combined with a jam of the secondary slide to the servo valve housing at positions other than neutral (known as a dual jam). These failure mechanisms probably did not play a role in the USAir flight 427, United flight 585, and Eastwind 517 upsets.[9] Nonetheless, the failure mechanisms are cause for concern because they further illustrate the vulnerability of the 737 rudder system to jams that could produce rudder deflections and result in catastrophic consequences.

Adequacy of the Boeing 737 Rudder System Design

Boeing has recently made significant design changes in the 737 rudder system, especially on the 737 next-generation (NG) series airplanes. (The design changes on the NG series airplanes include a redesigned main rudder PCU servo valve in which the hydraulic fluid ports are spread, thus eliminating the reversal mechanism identified in the thermal tests; a redesigned yaw damper system; a hydraulic pressure limiter; a rudder input force transducer; and a new standby rudder PCU input bearing.) The 737-100 through -500 series airplanes are being retrofitted with the redesigned servo valve and a hydraulic pressure reducer designed to limit the extent to which the airplanes would be vulnerable to the rudder overpowering the roll authority of the ailerons and spoilers.”

As a result of airworthiness directives (AD) issued by the FAA, the redesigned main rudder PCU servo valve should eliminate the possibility of a rudder reversal from the specific circumstances of a secondary slide jam to the servo valve housing combined with overtravel of the primary slide. Other ADs issued by the FAA should result in improved operational procedures and pilot training programs for addressing the more general problem of uncommanded movement of the rudder, including rudder reversal. The Safety Board concludes that, when completed, the rudder design changes to the 737 should preclude the rudder reversal failure mode that most likely occurred in the USAir flight 427 and United flight 585 accidents and the Eastwind flight 517 incident.

However, even with these changes, the 737 series airplanes (including the NG) remain susceptible to rudder system malfunctions that could be catastrophic. In October 1997 briefings

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during a ground check. Although the testing determined that this mechanism could cause a rudder reversal, Boeing indicated that subsequent design changes in the servo valve eliminated this possibility.

[9] The Safety Board's postaccident examination of the USAir flight 427 rudder components revealed that the rudder system feedback control loop was probably not jammed during the accident sequence because there was no evidence of foreign material to cause such a jam and there were no nicks or gauges on the input linkage to indicate that a jamming material might have been present at impact. Further, the main rudder PCU's external input linkage effectively covers (blocks) the opening between the input crank and the PCU body stop for the left rudder command direction, preventing jamming material from entering the area. The Safety Board considers that a dual slide jam is a less likely accident scenario than a jam of the secondary slide to the servo valve housing because the dual jam would require two extremely rare failures to exist in the servo valve at the same time.

[10] The speed below which the maximum roll control (full roll authority provided by control wheel input) can no longer counter the yaw/roll effects of a rudder deflected to its blowdown limit is known as the crossover airspeed.

to the FAA, Boeing acknowledged that a rudder hardover on the 737-NG during the most critical phases of flight-takeoff and/or landing (which Boeing estimated as 60 to 90 seconds per flight)-would be catastrophic. Although this period of vulnerability appears limited, the takeoff and landing phases are when the pilot is most likely to use the rudder, particularly to apply a high-rate rudder input. Pilots can apply rudder inputs during the takeoff or landing ground roll as they use the rudder pedals for nose wheel steering; these inputs can occur at low altitude with a loss of engine power or during a turbulence encounter. Any malfunction resulting in uncommanded rudder motion during an engine failure or in turbulence at low altitude may be catastrophic because of the limited time, altitude, and roll control authority to regain control of the airplane.

The Board is also concerned that the limited period of vulnerability to rudder malfunction is based on the assumption that a pilot will perform perfectly and that all airplane systems will perform normally. For example, according to Boeing's fault tree analysis for the 737-NG, the combination of a jammed servo valve with a loss of engine power during takeoff would be catastrophic only during a 7-second window from V_1 through liftoff, at which point roll controls could be used to help control the airplane in the event of a loss of engine power. However, Boeing's analyses apparently assumed that a pilot would always react immediately and correctly and that the hydraulic pressure limiter would not fail. Such assumptions may not be fully warranted.

The Safety Board recognizes that the potential for the specific rudder malfunction that was most likely involved in the accidents of USAir flight 427 and United flight 585 and the incident involving Eastwind flight 517 appears to be have been eliminated by the redesigned servo valve. However, the Board remains concerned that other rudder system malfunctions might potentially lead to rudder reversal or hardover conditions in the 737.

The 737 has a history of rudder system-related anomalies, including numerous instances of jamming. Examples of jamming events include the following:

- a shotpeen ball lodged in a servo valve, causing the rudder to move full right on landing;
- shotpeen balls found in a servo valve during a PCU examination;
- contamination of a PCU by metal particles, causing the rudder pedals to jam during taxi;
- internal PCU contamination and worn seals, causing the rudder to lock up on approach;
- internal PCU corrosion found during a PCU overhaul;
- a loose servo valve retaining nut, causing rudder binding during a flight check and reduced rates, stall, and reversals during testing;
- corrosion of a standby rudder PCU, causing full left rudder deflection during taxi;
- installation of an incorrect servo valve spring guide, allowing for rudder reversal when the primary slide was jammed to the secondary slide and a rapid rudder input was applied;

- fluid contamination of a yaw damper coupler, causing rapid full yaw damper inputs and a severe oscillatory roll;
- installation of an incorrect fastener in the summing lever bearing, resulting in a cracked bearing race; and
- a jammed or restricted input arm, causing full rudder to move to its full deflection.

The Safety Board is concerned that the new features of the redesigned main rudder PCU do not address all of these malfunctions, some of which are related to improper maintenance, installation, or modification. These malfunctions demonstrate that some jamming conditions resulted in a loss of rudder control. Other jamming conditions were fortuitously found during maintenance. However, because the main and standby rudder actuators receive maintenance only "on condition," possible jamming conditions could exist and not be discovered until they result in an in-flight failure.

Further, the Safety Board is concerned that, in three events during the 1980s, rudder system anomalies occurred in flight but remained unresolved during followup component testing. These events, two reports of in-flight "rudder lockup" (in 1982) and a rudder "hardover condition" (in 1984), indicated that potentially serious problems could exist 'and cause anomalous behavior without leaving evidence. (These events were first reported to the Safety Board in January 1999 by Parker Hannifin Corporation—the manufacturer of the main rudder PCU servo valve.) It is significant that the 1984 event involved a PCU that produced an in-flight hardover condition on two different aircraft within the operator's fleet. (According to Parker, the PCU was removed and tested after the first upset event. When no fault was found, the PCU was installed on another aircraft but subsequently failed another time. Once again, no fault was found during followup testing.)

The most troubling anomalies are those that could result in reverse rudder movement. During the investigation of the United flight 585 accident, many technical experts indicated that it was not possible to jam the main rudder PCU in such a way as to generate a reversal of the rudder movement. However, since that time, two such failure modes have been identified in the original servo valve design. The first failure mode was discovered in tests after the July 1992 main rudder PCU jam during a United Airlines flight control ground check. The tests demonstrated that, when the primary slide was jammed to the secondary slide, a jam/reversal scenario was possible. (The servo valve was subsequently redesigned to preclude the possibility of this reversal failure mechanism.) The second identified failure mode was discovered during the USAir flight 427 accident investigation. Thermal tests revealed the existence of a jam/reversal scenario (which prompted another redesign of the servo valve to address this potential reversal failure mechanism.) The Safety Board notes that the two failure modes associated with reversal were identified only after many years of 737 operation and only after extensive tests and examination during the investigation of the United flight 585 and USAir flight 427 catastrophic accidents.

The difficulty that was encountered in identifying these two reversal failure modes is not surprising, given the complexity of the 737 rudder system. The entire rudder system assembly—the standby rudder actuator, main rudder PCU servo valve, yaw damper, feel and centering mechanism, rudder trim actuator, torque tube, input rods, cranks, links, and summing levers-is an extremely complicated design. Further, each main rudder PCU servo valve must be individually hand finished to pass the manufacturer's acceptance test procedures, so no one valve is exactly the same as another.

In addition to the failure modes and malfunctions of the 737 rudder system that have already been identified, the Safety Board is concerned that the causes of certain other reported 737 anomalies remain unresolved. For example, the Safety Board has reviewed many reports of 737 pilots feeling "bumps" on the rudder pedals, yet in several cases the cause has not been determined.

The Safety Board's concerns about the possibility that additional failures or malfunctions may result in uncommanded rudder motion are supported by the early service history of the redesigned servo valve currently being installed in the 737-NG and retrofitted in all other 737 series airplanes. For example, on February 19, 1999, an anomalous rudder response was noted during a rudder ground check in Seattle on a United Airlines 737 equipped with the redesigned servo valve. Both the flight crew and maintenance personnel found that greater force than usual was necessary to move the right rudder pedal. Preliminary investigative findings indicate that the anomalous rudder response was the result of a mispositioned servo valve spring guide. Maintenance records indicated that, 71 flight hours earlier, the servo valve was tested for indications of cracking of the secondary slide. (The test for cracking was performed twice on this valve. The PCU passed the acceptance test procedure after the first test. The acceptance test procedure was not performed after the second test.)

This event raises concern because it suggests that it is possible to successfully install a servo valve in a PCU when the spring guide is out of place. Although such a r&positioning would have been detected if an acceptance test procedure had been performed after the second cracking test, it is troubling that the mispositioned spring guide was not detected during postmaintenance systems tests after the PCU was reinstalled on the airplane. Further, the mispositioned spring guide was not detected during the numerous flight control checks and flights that occurred before the ground check during which the anomalous rudder response was noted. Another troubling scenario is the possibility that the spring guide may only have been partially mispositioned at the time the PCU was reinstalled and became further mispositioned sometime later while the airplane was operating in service.

A second incident involving the redesigned servo valve occurred on February 23, 1999. A USAirways Metrojet 737 apparently experienced an unexplained rudder hardover in flight. The flight crew regained normal rudder control only after it activated the standby rudder system, as prescribed in USAirways' "Jammed or Restricted Rudder" abnormal procedure. The flight crew then made a successful emergency landing at Baltimore-Washington International Airport. This event could have resulted in an unrecoverable loss of control if it had occurred at a lower altitude or airspeed.

Preliminary results of kinematic analysis and computer simulations of the Metrojet incident using flight data recorder (FDR) data indicate that the rudder traveled slowly to its blowdown limit. Examination of the rudder system (including the servo valve) to date has found no evidence of a failure or jam either in the servo valve or outside the servo valve (such as a blockage in the rudder system feedback loop) that would explain an uncommanded rudder hardover.

In addition to its concern about these recent in-service events involving the redesigned servo valve, the Safety Board is also concerned that cracks have been found in the secondary slide legs of several of the redesigned servo valves and that one slide was found to be chipped.[11] Boeing indicated that metal chips liberated from a crack are not likely to cause uncommanded rudder motion. However, Boeing's conclusions are based on preliminary analyses and testing. Little is known about the initiation or progression of the cracking or the migration of chips, and there is no long-term operational experience with the redesigned servo valve to identify with certainty how this cracking is, or will be, affected by in-service conditions.

The Safety Board recognizes that 737s have flown for over 92 million flight hours since the 737-100 was certificated in December 1967 and that the airplane's accident rate is comparable to that of similar-type airplanes. Nonetheless, the Safety Board concludes that, rudder design changes to 737-NG series airplanes and the changes currently being retrofitted on the remainder of the 737 fleet do not eliminate the possibility of other potential failure modes and malfunctions in the 737 rudder system that could lead to a loss of control.

Redundancy in critical flight control systems is a basic tenet in the design of commercial transport aircraft. It serves to reduce, to acceptably low levels, the probability of catastrophic outcomes from flight control malfunctions. Redundancy is especially important in the 737 rudder system because of the size and control power of the rudder (necessitated by the twin wing-mounted engine configuration of the airplane).

The 737 is the only air carrier airplane with two wing-mounted engines that was designed with a single-panel rudder controlled by a single actuator, albeit with a dual-concentric servo valve design. Other rudder system designs use multiple rudder surfaces and/or multiple rudder actuators. For example, the rudder system designs of the Boeing 757 and 767, which were certificated in 1982 (2 years before certification of the 737-300 series), use three actuators and do not rely on dual-concentric servo valves. In the event of a jammed or failed valve, the three-actuator design permits the failed actuator to be immediately overpowered, or "broken out," by pilot input using the other two actuators so that the jammed or failed PCU no longer controls the movement of the flight control surface.

Although Boeing has indicated that three actuators were incorporated in the 757 and 767 design to allow for features such as autopilot control of the rudder during autolanding and removal or reduction of the mass used to balance the rudder, the multiple actuator design clearly provides an increased level of safety. Because the three actuators are fully independent (such that a valve jam would not have an adverse effect on another valve), they provide redundancy to the

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[11] The chipped slide was found on a servo valve awaiting installation on an Olympic Airways airplane. Boeing stated that it believed the chip was caused by a rigging tool that was used to calibrate the servo valve.

757 and 767 rudder system. It is noteworthy that the 757 and 767 have not experienced the rudder-related anomalies, incidents, or accidents that have occurred in the 737 series.

Although dual-concentric servo valves are used in some other aircraft control systems for activation of ailerons or elevators, the multiple control surfaces and breakout features in those systems were designed to ensure that a jam of one control surface does not affect other control surfaces. However, these redundant systems or breakout features do not exist in the design of the 737 rudder system.

Further, although the 737 rudder system has a standby rudder PCU that is independent of the main rudder PCU, that system would have to be manually activated by the flight crew in the event of a servo valve jam. If a jam were to occur close to the ground or result in an unusual attitude, the pilots could lose control of the airplane before they were able to diagnose the problem and engage the standby rudder. Therefore, redundancy in the current 737 rudder system is limited to the dual-concentric design of the main rudder PCU servo valve (and the dual load path design of the linkages in the rudder system).

The October 7, 1993, incident involving a British Airways 747-400, G-BNLY, illustrates the need for greater redundancy in flight control systems that include a dual-concentric servo valve. Shortly after takeoff, about 100 feet above ground level, the airplane's right elevator PCU reversed travel when a hydraulic pressure surge, resulting from retraction of the landing gear, caused the dual-concentric servo valve secondary slide to overtravel to the internal retract stop and the primary slide to move to the limit of the extend linkage stop. The flight crew was able to maintain control because the 747's elevators are operated by separate PCUs and are not interconnected. As a result, the flight crew was able to move the left-side elevators upward to counter the right-side downward deflection. Given the low altitude of the occurrence, the airplane would likely have crashed if the 747's elevators had been a single control surface, single-actuator design.

The Safety Board's review of the dual-concentric servo valve design indicates that redundancy is compromised in the existing 737 main rudder PCU for several reasons. First, no method may exist by which a pilot can reliably detect the presence of a jammed primary or secondary slide within the main rudder PCU servo valve that drives the actuator.[12] Second, the dual-concentric servo valve design allows for failure modes in which one slide can directly affect the operation of the other slide. Third, recent design changes do not eliminate the possibility that a maintenance error (such as the shotpeen balls that were discovered in main rudder PCU servo valves) could result in a servo valve anomaly. Last, although the dual load path is structurally redundant, it does not provide functional redundancy. The mechanical elements of the main rudder PCU external to the servo valve may be subject to jams (such as blockage between the input crank and the external body stops), possibly leading to uncommanded rudder motion that the dual-concentric design of the servo valve cannot overcome. These failure modes markedly reduce the redundancy that was intended to be provided by the dual-concentric design of the

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[12] Although the Safety Board considers it critical that the main rudder PCU be inspected at regular intervals, such inspections do not guarantee the detection of latent failures within the main rudder system that occur between inspections.

servo valve and, in effect, could result in a single-point failure in the 737 rudder PCU actuation system. Because no other full-time actuator could oppose an uncommanded rudder motion, an airplane operating with such a latent failure would require only a single additional event, such as a rapid rudder input or an additional jam, to potentially cause a rudder hardover.

The Safety Board considers it important that, if a failure/anomaly were to occur within a critical flight control system (such as the 737 rudder system), the transition to a backup system should occur automatically and immediately, making the system reliably redundant. A system in which the transition to a backup system depends on the pilots' prompt and proper perception of and reaction to the system anomaly is not reliably redundant. Accordingly, the Safety Board concludes that the dual-concentric servo valve used in all 737 main rudder PCUs is not reliably redundant.

During the initial certification of the 737-100 series, FAA certification officials expressed concern about the airplane's single-panel, single-actuator rudder system and recognized the possibility of undetected latent failures in the servo valve, thereby negating the system's redundancy. The rudder system's history of service difficulties (some of which still remain unresolved), particularly the servo valve's history of jamming, validate those concerns.

In October 1996, the Safety Board issued several safety recommendations to improve the existing 737 rudder system. Specifically, Safety Recommendations A-96-107, -109, -112, and -113 asked the FAA to

> Require the Boeing Commercial Airplane Group, working with other interested parties, to develop immediate operational measures and long-term design changes for the 737 series airplane to preclude the potential for loss of control from an inadvertent rudder hardover. Once the operational measures and design changes have been developed, issue respective airworthiness directives to implement these actions. (A-96- 107)
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> Require the Boeing Commercial Airplane Group to develop and install on all new-production 737 airplanes a cockpit indicator system that indicates rudder surface position and movement. For existing 737 airplanes, when implementing the installation of an enhanced-parameter flight data recorder, require the installation of a cockpit indicator system that indicates rudder surface position and movement. (A-96- 109)
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> Require the Boeing Commercial Airplane Group to establish appropriate inspection intervals and a service life limit for the 737 main rudder power control unit. (A-96-112)
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> Require the Boeing Commercial Airplane Group to devise a method to detect a primary or a secondary jammed slide in the 737 main rudder power control unit servo valve and ensure appropriate communication of the information to mechanics and pilots. (A-96- 113)

The Safety Board is disappointed that the FAA has taken no action to establish inspection intervals or a service life limit for the main rudder PCU or a method for detecting and annunciating a jammed servo valve slide to flight crews. The Board is also disappointed that the FAA has stated that a rudder position indicator would provide no practical information to the pilots. On July 15, 1997, Safety Recommendations A-96- 107, - 109, -112, and -113 were classified "Open-Unacceptable Response." A more direct and fundamental approach to correcting the deficiencies in the 737 rudder system is necessary.

Because of the complexity of the 737 rudder system (and the potential for unforeseen failure mechanisms), its lack of redundancy in the event of a single-point failure or a latent failure, and the continued absence of cues to help alert flight crews to latent failures, the Safety Board concludes that a reliably redundant rudder actuation system is needed for the 737, despite the significant improvements that have been made in the system's design. Accordingly, the Safety Board believes that the FAA should require that all existing and future 737s have a reliably redundant rudder actuation system. This redundancy could be achieved by developing a multiple-panel rudder surface or providing multiple actuators for a single-panel rudder surface.' Further, Safety Recommendations A-96-107, -109, -112, and -113 are classified "Closed—Unacceptable Action/Superseded."

One possible way of incorporating multiple actuators into the 737 without extensive structural modification would be to modify the standby rudder system so that its actuator could be used as a second rudder actuator. Under the current 737 design, the standby rudder actuator powers the rudder by a separate hydraulic system that activates manually or automatically in the event of a hydraulic system failure. The standby rudder actuator was not intended to be used as a full- time actuator. However, design modifications might be possible to make the standby actuator an integral part of the main rudder control system. Although it is not clear whether the standby rudder system could be modified to provide a truly redundant rudder system on all 737 series airplanes, it is possible that such a modification might provide the needed redundancy.

Another possible way to achieve redundancy in the rudder control system would be to modify it so that the standby rudder PCU would be automatically activated and the main rudder PCU would automatically be deactivated if the main rudder PCU actuator system moves the rudder without a pilot command. This redundancy could be achieved by monitoring the rudder position and comparing this position with the one being commanded by the pilot rudder pedal input. Mismatches between the two positions could then trigger a logic circuit that would command a hydraulic valve unit to automatically shift hydraulic control of the rudder from the main rudder PCU (that is, depressurize its hydraulics) to the standby rudder PCU. This action would allow the flight crew to resume normal control of the rudder using the standby rudder PCU. (The Safety Board recognizes that additional design issues must be considered so that the main rudder PCU is not deactivated when it should not be.)

Further, to gain a better understanding of the potential failure modes in the 737 rudder system, the Safety Board believes that the FAA should convene an engineering test and evaluation board to conduct a failure analysis to identify potential failure modes, a component and subsystem test to isolate particular failure modes found during the failure analysis, and a full-

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scale integrated systems test of the 737 rudder actuation and control system to identify potential latent failures and validate operation of the system without regard to minimum certification standards and requirements in 14 CFR Part 25. Participants in the engineering test and evaluation board should include the FAA; Safety Board technical advisors; the Boeing Company; other appropriate manufacturers; and experts from other government agencies, the aviation industry, and academia. A test plan should be prepared that includes installation of original and redesigned 737 main rudder PCUs and related equipment and exercises all potential factors-that could initiate anomalous behavior (such as thermal effects, fluid contamination, maintenance errors, mechanical failure, system compliance, and structural flexure). The engineering board's work should be completed by March 3 1, 2000, and published by the FAA.

FAA Certification System

In light of the safety concerns about the 737 rudder system design, the Safety Board is concerned about the FAA's regulatory process that resulted in the certification of that system. The Safety Board concludes that, on the basis of the results of this investigation, the 737 rudder system design certificated by the FAA is not reliably redundant. Therefore, the Safety Board believes that the FAA should ensure that future transport-category airplanes certificated by the FAA provide a reliably redundant rudder actuation system.

The Safety Board also questions the FAA's interpretation of the term "normally encountered" in the context of 14 CFR Section 25.67 1(c)(3). Section 25.671(c)(3) states the following:

> (c) The airplane must be shown by analysis, tests, or both, to be capable of continued safe flight and landing after any of the following failures or jamming in the flight control system and surfaces (including trim, lift, drag, and feel systems), within the normal flight envelope, without requiring exceptional piloting skill or strength. Probable malfunctions must have only minor effects on control system operation and must be capable of being readily counteracted by the pilot.
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> (3) Any jam in a control position normally encountered during takeoff, climb, cruise, normal turns, descent, and landing unless the jam is shown to be extremely improbable, or can be alleviated. A runaway of a flight control to an adverse position and jam must be accounted for if such runaway and subsequent jamming is not extremely improbable.

During certification of the 737-NG series airplanes, the FAA concluded that a normally encountered control position for the rudder would be a maximum of 2.5°. However, this interpretation seems unrealistic in light of the rudder's ability to travel as much as 26° in either direction and its criticality in countering a loss of engine power or crosswind gust on takeoff or landing. (It is unclear how a different interpretation would have affected the outcome of the 737-NG certification process.) Such a narrow interpretation may well reduce the level of protection that should be provided by a showing of compliance with this rule. Although the rudder may operate for much of the time in a narrow range, a jam could become critical during those times when deflections beyond this narrow range are necessary.

The Safety Board questions whether it is appropriate to define "normally encountered" so narrowly and even whether it is appropriate to include that phrase in 14 CFR Section 25.671. The Board agrees with the Critical Design Review team's position on this issue. The team stated that "if a control position is possible, it is there for a purpose, and the pilot can use that control authority." In October 1996, the Safety Board issued Safety Recommendation A-96-108, which asked the FAA to ·

> Revise 14 CFR Section 25.671 to account for the failure or jamming of any flight control surface at its design-limited deflection. Following this revision, reevaluate all transport-category aircraft and ensure compliance with the revised criteria.

In response, the FAA indicated that the last sentence of 14 CFR Section 25.671(c)(3) already required that a jam of a flight control surface at its design-limited deflection be accounted for unless such a jam is extremely improbable. However, the Safety Board is concerned that the rule does not appear to require any analysis of failure or jamming of flight controls in positions beyond those normally encountered but short of a full deflection. For example, the FAA's finding that the 737-NG series airplanes complied with this rule was apparently based on Boeing's assertion that rudder position jams in a normally encountered position were controllable and that rate jams resulting in a rudder hardover were extremely improbable. There is no indication that Boeing or the FAA considered jams in any intermediate position.

The Safety Board concludes that transport-category airplanes should be shown to be capable of continued safe flight and landing after a jammed flight control in any position unless the jam can be shown to be extremely improbable. Accordingly, the Safety Board believes that the FAA should amend 14 CFR Section 25.671(c)(3) to require that transport-category airplanes be shown to be capable of continued safe flight and landing after jamming of a flight control at any deflection possible, up to and including its full deflection, unless such a jam is shown to be extremely improbable. Because the Safety Board recognizes that the language of Safety Recommendation A-96-108 may not have adequately expressed this concern, that recommendation is classified "Closed-Reconsidered/Superseded."

Unusual Attitude Training for Air Carrier Pilots

Before the USAir flight 427 accident, the Safety Board had issued a series of safety recommendations over a 24-year period, asking the FAA to require air carriers to train pilots in recoveries from unusual flight attitudes. Throughout this period, the Safety Board was generally not satisfied with the FAA's responses to these recommendations; specifically, the Board disagreed with the FAA's responses that cited the inadequacy of flight simulators as a reason for not providing pilots with the requested training. However, after the USAir flight 427 accident and the October 3 1, 1994, Avions de Transport Regional model 72 accident involving Simmons

Airlines flight 4184 near Roselawn, Indiana,[13] the FAA issued guidance to air carriers, acknowledging the value of flight simulator training in unusual attitude recoveries and encouraging air carriers to voluntarily provide this training to their pilots. The voluntary training programs that were implemented by many air carriers (including USAir) have been excellent. In October 1996, the Safety Board issued Safety Recommendation A-96-120, asking the FAA to

> Require 14 CFR Part 121 and 135 operators to provide training to flight crews in the recognition of and recovery from unusual attitudes and upset maneuvers, including upsets that occur while the aircraft is being controlled by automatic flight control systems, and unusual attitudes that result from flight control malfunctions and uncommanded flight control surface movements.

The Safety Board's concerns about the role of automatic flight control systems in unusual attitude situations were validated when Comair flight 3272, an Embraer 120RT, crashed on January 9, 1997, near Monroe, Michigan. The investigation determined that an engaged autopilot masked the most salient cues to the flight crew of a developing uncommanded rolling moment.[14] Similarly, the challenge posed to pilots by flight control malfunctions was demonstrated by the circumstances of the accidents involving USAir flight 427 and United flight 585, the incident involving Eastwind Airlines flight 517 (which involved uncommanded rudder movement), and the accident involving Simmons Airlines flight 4184 (which involved uncommanded aileron movement).

The Safety Board recognizes the value of air carrier voluntary unusual attitude training programs. However, all air carriers may not be implementing such a program.[15] Further, the FAA has not addressed flight control malfunctions (such as uncommanded rudder surface movements) in its guidance material for air carrier unusual attitude training programs. In addition, the unusual attitude training tool developed in 1998 by industry, labor unions, and the FAA does not include guidance on flight control malfunctions.

In January 1997, the FAA informed the Safety Board that it was considering issuance of a notice of proposed rulemaking (NPRM) to require air carriers to conduct unusual attitude training. However, as of March 1999, the FAA had not issued the NPRM. The FAA indicated, in informal correspondence with the Safety Board, that it might include an unusual attitude training requirement as part of a planned general revision to the regulations governing air carrier pilot training (14 CFR Part 121, Subparts N and O).

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[13] See National Transportation Safety Board. 1996. ***In-Flight Icing Encounter and Loss of Control, Simmons Airlines, d.b.a. American Eagle Flight 4184, Avions de Transport Regional (ATR) Model 72-212, N401AM, Roselawn, Indiana, October 31, 1994.*** Aircraft Accident Report NTSB/AAR-96/01. Washington, DC.

[14] See National Transportation Safety Board. 1998. ***In-Flight Icing Encounter and Uncontrolled Collision With Terrain, Comair Flight 3272, Embraer EMB-120RT, N265CA, Monroe, Michigan, January 9, 1997.*** Aircraft Accident Report NTSB/AAR-98/04. Washington, DC.

[15] According to a January 13, 1999, letter from the FAA to the Safety Board's Director of the Office of Aviation Safety, at least 13 U.S.-based air carriers (including USAir) had implemented special events training (SET) programs by mid-1996. The letter indicated that "other carriers.. .as well as training center operators.. .were initiating SET programs."

The Safety Board is concerned that the FAA has not yet taken the necessary regulatory action to require unusual attitude training for air carrier pilots. The Board is also concerned that the guidance and programs developed to date do not include scenarios involving flight control malfunctions. Accordingly, because of the lack of progress toward requiring for air carrier pilots unusual attitude training that addresses flight control malfunctions, such as uncommanded flight control surface movements, Safety Recommendation is classified A-96- 120 "Open—Unacceptable Response." The Safety Board urges the FAA to take expeditious action to require such unusual attitude training.

Unusual Attitude Training for Boeing 737 Pilots

At the time of the USAir flight 427 accident, no air carrier training programs were specifically aimed at training 737 pilots to recognize and address a rudder jam or reversal. The guidance available at that time from Boeing advised pilots, as a first consideration, to maintain or regain full control of the airplane. Specifically, the guidance advised pilots to counter unwanted roll tendencies from a malfunctioning rudder with the application of up to full aileron control inputs. However, the guidance did not advise pilots that, at some airspeeds, an uncommanded full rudder input could not be successfully opposed by full wheel (aileron and spoiler) inputs and that a reduction in the airplane's angle of attack could improve the effectiveness of the roll controls relative to the effectiveness of the rudder. Boeing's guidance for relieving a jammed rudder informed pilots only that they should use maximum force to overpower the jam and specifically warned pilots against turning off flight control switches "unless the faulty control was positively identified." No additional guidance was provided about the effects of flight control switch selections on rudder jam conditions.

The Safety Board recognizes that, even if unusual attitude training specifically targeted at the rudder reversal situation were provided to pilots on a recurrent basis, a rudder reversal is such a confusing and distracting event that no training could completely prepare pilots to diagnose and respond to (in the few seconds that would be available) a rudder reversal that occurred without warning. Consequently, the Safety Board cannot be certain that the pilots of USAir flight 427 would have recovered control of the airplane if they had received such training. However, the Safety Board concludes that pilots would be more likely to recover successfully from an uncommanded rudder reversal if they were provided the necessary knowledge, procedures, and training to counter such an event.

In December 1996, the FAA issued AD 96-26-07, requiring that the 737 Airplane Flight Manual be revised to include procedures for maintaining control of an airplane during an uncommanded yaw or roll or a jammed or restricted rudder condition. In response to this AD, Boeing established procedures in February 1997 to provide an effective means of regaining control of the airplane under most (but not all) flight conditions? The "Uncommanded Yaw or Roll" procedure establishes the actions to be performed by pilots immediately, from memory, to halt the uncommanded motion of the airplane. The "Jammed or Restricted Rudder" procedure

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[16] During the comment period for AD 96-26-07, the Safety Board expressed its concerns to the FAA that these procedures might not be adequate if a rudder reversal were to occur at a low altitude, especially with an engine failure during takeoff.

establishes a means of handling a variety of rudder malfunctions (including rudder reversal) in a systematic manner. These procedures were subsequently added to Boeing's 737 Operations Manual and adopted by U.S. air carriers.

The Safety Board recognizes that the hydraulic pressure reducer that is being retrofitted on earlier series 737 models, and the hydraulic pressure limiter being installed in the NG models, should provide 737 flight crews with a greater margin of controllability and additional response time for executing these required procedures. However, the ability to recover from an uncommanded yaw or roll or a jammed or restricted rudder (including a rudder reversal), within the time that would be available, requires training and practice in executing the specific procedures. In October 1996, the Safety Board issued Safety Recommendation A-96-118, asking the FAA to

> Require the Boeing Commercial Airplane Group, working with other interested parties, to develop procedures that require 737 flight crews to disengage the yaw damper in the event of an uncommanded yaw upset as a memorized or learned action. Once the procedures are developed, require operators to implement these procedures.

The Safety Board had been concerned that the procedures described in AD 96-26-07 did not include disengagement of the yaw damper as an action to be performed immediately from memory. The Board's concern was based on the relatively frequent occurrence (compared with other rudder system malfunctions) of yaw damper malfunctions in the 737, which might lead pilots to unnecessarily perform the actions in the "Jammed or Restricted Rudder" procedure. The Safety Board's review of the February 1997 changes to Boeing's 737 Operations Manual, and air carriers' adoption of those provisions, indicate that U.S. air carriers are currently providing flight crews with an immediate action procedure that should effectively handle yaw damper system malfunctions. Therefore, Safety Recommendation A-96- 118 is classified "Closed-Acceptable Action."

The Safety Board is concerned that the "Jammed or Restricted Rudder" procedure established a pilot's ability to "center" the rudder pedals (that is, achieve a neutral rudder pedal position) as the criterion for successful resolution of a rudder malfunction. Specifically, the Board is concerned that, in a rudder reversal situation, compliance in the rudder system could allow the rudder pedals to reach the neutral position while the rudder surface remains deflected to the blowdown limit. As a result, the Safety Board concludes that a neutral rudder pedal position is not a valid indicator that a rudder reversal in the 737 has been relieved. Therefore, the Safety Board believes that the FAA should revise AD 96-26-07 so that procedures for addressing a jammed or restricted rudder do not rely on the pilots' ability to center the rudder pedals as an indication that the rudder malfunction has been successfully resolved, and require Boeing and U.S. operators of 737s to amend their Airplane Flight Manuals and Operations Manuals accordingly.

Although the procedures specified by AD 96-26-07 did not establish a requirement for air carriers to provide training to flight crews, Flight Standards Information Bulletin (FSIB) 98-03, issued in January 1998, directed the FAA's principal operations inspectors to require air carriers to "amend their training programs to provide initial and recurrent training in the recognition of and recovery from unusual attitudes and upsets caused by reverse rudder response." However, neither AD 96-26-07 nor FSIB 98-03 provided specific guidance on how training for these procedures was to be accomplished. In its comments on the NPRM for AD 96-26-07, the Safety Board expressed its concerns that 737 pilots needed to be explicitly trained on a regular basis in the execution of the new procedures. In February 1997, the Safety Board issued Safety Recommendation A-97-18, asking the FAA to

> Require the Boeing Commercial Airplane Group to develop operational procedures for 737 flight crews that effectively deal with a sudden uncommanded movement of the rudder to the limit of its travel for any given flight condition in the airplane's operational envelope, including specific initial and periodic training in the recognition of and recovery from unusual attitudes and upsets caused by reverse rudder response. Once the procedures are developed, require 737 operators to provide this training to their pilots.

Although the new procedures are well documented in FAA, Boeing, and air carrier publications, 3 of 12 U.S. air carrier operators of the 737 contacted by the Safety Board in July 1998 were not providing any simulator training to their pilots on these procedures. (These 3 air carriers accounted for about 20 percent of the 1,070 total 737 airplanes operated by the 12 air carriers). Further, of the nine air carriers that were providing such training, only five had specified in their training manuals that the procedures should be performed by students during simulator training at least to the point of selecting the hydraulic system B flight control switch to the standby rudder position. (These 5 air carriers accounted for about 40 percent of the total 737 airplanes operated by the air carriers.) Thus, pilots for more than one-half of U.S. air carrier operators of the 737 airplanes (7 of the 12 air carriers included in the Board's survey) were not being provided the opportunity to practice the responses to a jammed or restricted rudder (including a rudder reversal) that might be most effective in relieving or overcoming the effects of a jammed main rudder PCU servo valve.

Further, although Boeing has published and disseminated information about the crossover airspeed phenomenon,[17] only one-half of the 12 air carriers contacted by the Safety Board in July 1998 were providing 737 flight crews with a demonstration of crossover airspeed in a flight simulator. Moreover, the training materials for only one-third of the 12 air carriers (accounting for about 72 percent of the 737 airplanes) required a demonstration of the crossover airspeed to pilots in the flaps 1 configuration (in which the airplane can reach the crossover airspeed before the 1 G stickshaker speed). Thus, pilots for as many as two-thirds of the U.S. air carrier operators of the 737 were not being provided experience that demonstrated the inability to control the airplane at some speeds and configurations by using only the roll controls during a rudder hardover condition. In addition, the Safety Board is also concerned that flight tests conducted as part of the USAir flight 427 investigation showed that the simulator package

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[17] Boeing discussed crossover airspeed extensively in the July 1997 Flight Operations Review article entitled "737 Directional Control."

developed by Boeing and implemented in the air carriers' training simulators did not adequately simulate the crossover airspeed phenomenon. The Safety Board is concerned that Boeing has not updated its existing simulator package, even though the data needed to do so is readily available as a result of these flight tests.

The Safety Board concludes that the training being provided to many 737 flight crews on the procedures for recovering from a jammed or restricted rudder (including a rudder reversal) is inadequate, Therefore, the Safety Board believes that the FAA should require all 14 CFR Part 121 air carrier operators of the 737 to provide their flight crews with initial and recurrent flight simulator training in the "Uncommanded Yaw or Roll" and "Jammed or Restricted Rudder" procedures in Boeing's 737 Operations Manual. The training should demonstrate the inability to control the airplane at some speeds and configurations by using the roll controls (the crossover airspeed phenomenon) and include performance of both procedures in their entirety. Because of this new safety recommendation and the FAA's failure to fully address Safety Recommendation A-97-18, the earlier recommendation is classified "Closed-Unacceptable Response/ Superceded." In addition, the Safety Board believes that the FAA should require Boeing to update its 737 simulator package to reflect flight test data on crossover airspeed and then require all operators of the 737 to incorporate these changes in their simulators used for 737 pilot training.

Finally, the Safety Board is extremely concerned that, more than 4 years after the USAir flight 427 accident, two smaller U.S. 737 operators (accounting for 16 of the 1,070 total 737 airplanes operated by the 12 air carriers) were continuing to use minimum maneuvering speed schedules that permit operation of the 737 in the flaps 1 configuration at airspeeds (158 and 164 knots) that are as much as 30 knots slower than the 1 G crossover airspeed. (The FAA had accepted the use of these minimum maneuvering speed schedules.) In addition, the Board is concerned that the Boeing-recommended block maneuvering speeds schedule specifies 190 knots, which only slightly exceeds the 1 G crossover airspeed, as the minimum speed for a 737 operating at a gross weight of 110,000 pounds in the flaps 1 configuration. Only one-third of the 12 U.S. 737 air carrier operators contacted by the Safety Board in July 1998 (accounting for 66 percent of the 737 airplanes) actively promoted the practice of adding 10 knots to the 737 block maneuvering speeds (for which Boeing has expressed neither support nor disapproval).

The Safety Board concludes that the continued use by air carriers of airspeeds below the existing block maneuvering speed schedule presents an unacceptable hazard and that the existing block maneuvering speed for the flaps 1 configuration provides an inadequate margin of controllability in the event of a rudder hardover failure. Therefore, the Safety Board believes that the FAA should evaluate the 737's block maneuvering speed schedule to ensure the adequacy of airspeed margins above crossover airspeed for each flap configuration, provide the results of the evaluation to air carrier operators of the 737 and the Safety Board, and require Boeing to revise block maneuvering speeds to ensure a safe airspeed margin above crossover airspeed.

Flight Data Recorder Capabilities

The airplanes involved in the United flight 585 and USAir flight 427 accidents were required by existing regulations (14 CFR Section 121.343) to have FDRs that recorded 5 and 11 parameters, respectively.[18] If these airplanes had been equipped with FDRs with additional parameters, that information would have undoubtedly allowed quick identification of critical control surface movements and their sources and other airplane system conditions that could have been involved in the loss of airplane control. Thus, investigators would have been able to more quickly rule out certain factors, when warranted, and focus on other areas.

The Safety Board has addressed the importance of improving the quality and amount of data recorded by FDRs in several recent aviation accident reports and safety recommendations. In February 1995, the Safety Board issued urgent Safety Recommendation A-95-25, urging the FAA to

> Require that by December 31, 1995, all 737 airplanes be equipped with an FDR system that records "as a minimum, the parameters required by current regulations applicable to that airplane plus. . . lateral acceleration; flight control inputs for pitch, roll, and yaw; and primary flight control surface positions for pitch, roll, and yaw." .

The FAA indicated that it agreed with the intent of the Safety Board's recommendation. However, the FAA did not meet the recommendation's proposed December 31, 1995, retrofit completion date, characterizing it as "an extremely aggressive schedule." The Safety Board repeatedly expressed its disappointment with the FAA's lack of action and urged the FAA to act promptly because of the criticality of the issue and the persisting reports of unexplained 737 in-flight disturbances.

More than 1 year after the FAA's response to Safety Recommendation A-95-25 (and almost 6 months after the recommended December 31, 1995, FDR retrofit completion date), the Eastwind flight 517 incident occurred. The Safety Board's July 1, 1996, letter to the FAA indicated the Board's belief that the Eastwind incident could have become the third fatal 737 upset accident for which inadequate FDR information would have hampered an investigation. Because the FAA had not acted in the time frame proposed by the Safety Board in its urgent safety recommendation, the FDR recordings from the Eastwind incident airplane did not provide sufficient data to identify rudder surface and rudder pedal movements. If this information had been available, investigators would have been better able to understand the Eastwind incident and, more importantly, would likely have gained significant additional insight into previous upset events, such as the USAir flight 427 and United flight 585 accidents. In 1996, Safety Recommendation A-95-25 was placed on the Safety Board's list of the Most Wanted Safety Improvements.

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[18] Although existing regulations required the FDR that was installed on the USAir flight 427 airplane to record 11 parameters, the accident airplane's FDR recorded 13 parameters.

In its July 9, 1997, final rule, the FAA required that new and existing transport-category airplanes "be equipped to record the parameters recommended by the Board" with final compliance required by August 19, 2002. Although the Safety Board considered the FAA's action a major improvement over the former FDR requirements, the Board disagreed that the FAA's requirements for retrofitting existing airplanes included all parameters recommended by the Board in its urgent safety recommendation.[19] Further, the Safety Board was disappointed with the extended time frame and incremental increases allowed for compliance with the 'new FDR requirements, especially for 737 airplanes.

In its July 22, 1997, letter to the Safety Board, the FAA stated that the retrofit modification should be accomplished "at the earliest practicable time" but no later than the next heavy maintenance check after August 18, 1999. During the Safety Board's investigation of the February 23, 1999, Metrojet upset event, the Board learned that the incident airplane was scheduled for a heavy maintenance check in March 1999 but was not scheduled to receive the required FDR upgrade until its heavy maintenance check in March 2001. Therefore, the Safety Board is concerned that some air carriers may have disregarded the directive to accomplish the upgrade at the earliest practicable time and may have interpreted the rule to require no action until after August 18, 1999. However, the Safety Board notes that at least one U.S. 737 operator (Southwest Airlines) has aggressively pursued the FDR upgrade within its fleet and anticipates having all its airplanes' FDRs upgraded by December 1999 (about 1½ years before the modification completion date mandated by the FAA).

Several 737 rudder-related events have been associated with the yaw damper system, which moves the rudder without any corresponding movement of the flight crew's rudder pedals. To adequately monitor this system, FDRs would have to record several parameters that are not required by the FAA's July 1997 final rule regarding upgraded FDRs. By documenting the yaw damper's operation (command voltage to the rudder and on/off discrete indication) and the resultant rudder surface movement, a yaw damper event could quickly be distinguished from a flight crew input or a rudder anomaly.

Additionally, upgraded FDRs are expected to record the pilots' flight control inputs and the flight control surface movements. However, the FAA is not requiring the FDRs on existing airplanes, including 737s,[20] and those manufactured before August 2002 to be upgraded to record the pilots' flight control input forces. The Safety Board considers documentation of pilot flight control input forces to be critical in determining the pilots' role in a flight control-related event and notes that such documentation appears especially critical in the case of the 737. If pilot flight control input forces had been recorded for the USAir flight 427, United flight 585, and Eastwind flight 517 airplanes, these investigations would have been resolved more promptly, and actions to prevent future similar events would have been hastened.

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[19] The Safety Board recommended (but the FAA did not require) that airplanes manufactured before 1991 record data for the following parameters: pitch trim; thrust reverser position; flaps, leading edge slats, and ground spoiler positions; angle of attack; and outside and total air temperatures.

[20] Title 14 CFR Part 25.1459(e) states that "any novel or unique design or operational characteristics of the aircraft shall be evaluated to determine if any dedicated parameters must be recorded on flight recorders in addition to or in place of existing requirements." The Safety Board notes that the 737's unique rudder actuation system design and rudder system service history justifies the recording of additional parameters on 737 FDRs.

Parameters such as pitch trim, thrust reverser position, and leading and trailing edge flap positions would also provide potentially valuable information to accident investigators. The Safety Board issued Safety Recommendations A-95-26 and A-95-27 in February 1995, stating that FDRs installed on all airplanes operated under 14 CFR Parts 121, 125, or 135 should be upgraded to record these parameters. Although such an upgrade would be easily accomplished on airplanes equipped with flight data acquisition units (FDAU), the FAA, to date, has not required that affected airplanes be upgraded accordingly.

The Safety Board concludes that the FDR upgrade modifications required by the FAA for existing airplanes are inadequate because they do not require the FDR to be modified to record yaw damper command voltage; yaw damper and standby rudder on/off discrete indications; pitch trim; thrust reverser position; leading and trailing edge flap position; and pilot flight control input forces for control wheel, control column, and rudder pedals. Further, the Safety Board concludes that, on the basis of the rudder-related anomalies discussed in this report, FDR documentation of yaw damper command voltage; yaw damper and standby rudder on/off discrete indications; and pilot flight control input forces for control wheel, control column, and rudder pedals is especially important in the case of the 737, and these parameters should be sampled on 737 airplanes at frequent intervals to provide optimal documentation.

Therefore, the Safety Board believes that the FAA should require that all 737 airplanes operated under 14 CFR Parts 121 or 125 that currently have a FDAU be equipped, by July 31, 2000, with an FDR system that records, at a minimum, the parameters required by FAA Final Rules 121.344 and 125.226, dated July 17, 1997, applicable to that airplane plus the following parameters: pitch trim; trailing edge and leading edge flaps; thrust reverser position (each engine); yaw damper command; yaw damper on/off discrete; standby rudder on/off discrete; and control wheel, control column, and rudder pedal forces (with yaw damper command; yaw damper on/off discrete; and control wheel, control column, and rudder pedal forces sampled at a minimum rate of twice per second).

Further, the Safety Board believes that the FAA should require that all 737 airplanes operated under 14 CFR Parts 121 or 125 that are not equipped with a FDAU be equipped, at the earliest time practicable but no later than August 1, 2001, with an FDR system that records, at a minimum, the parameters required by FAA Final Rules 121.344 and 125.226, dated July 17, 1997, applicable to that airplane plus the following parameters: pitch trim; trailing edge and leading edge flaps; thrust reverser position (each engine); yaw damper command; yaw damper on/off discrete; standby rudder on/off discrete; and control wheel, control column, and rudder pedal forces (with yaw damper command; yaw damper on/off discrete; and control wheel, control column, and rudder pedal forces sampled at a minimum rate of twice per second).

The Safety Board notes that 737 flight crews continue to report anomalous rudder behaviors, and it is possible that another catastrophic 737 upset-related accident could occur. If such an accident occurs before August 19, 2001, it is likely that the data recorded by the accident airplane's FDR will not be sufficient for investigators to readily identify the events leading to the upset and develop corrective actions to prevent future similar accidents. Therefore, the Safety Board concludes that the FAA's failure to require timely and aggressive action regarding enhanced FDR recording capabilities, especially on 737 airplanes, has significantly hampered the prompt identification of potentially critical safety-of-flight conditions and the development of safety recommendations to prevent future catastrophic accidents.

Therefore, the National Transportation Safety Board makes the following recommendations to the Federal Aviation Administration:

> Require that all existing and future Boeing 737s have a reliably redundant rudder actuation system. (A-99-20)
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> Convene an engineering test and evaluation board to conduct a failure analysis to identify potential failure modes, a component and subsystem test to isolate particular failure modes found during the failure analysis, and a full-scale integrated systems test of the Boeing 737 rudder actuation and control system to identify potential latent failures and validate operation of the system without regard to minimum certification standards and requirements in 14 Code of Federal Regulations Part 25. Participants in the engineering test and evaluation board should include the Federal Aviation Administration (FAA); National Transportation Safety Board technical advisors; the Boeing Company; other appropriate manufacturers; and experts from other government agencies, the aviation industry, and academia. A test plan should be prepared that includes installation of original and redesigned Boeing 737 main rudder power control units and related equipment and exercises all potential factors that could initiate anomalous behavior (such as thermal effects, fluid contamination, maintenance errors, mechanical failure, system compliance, and structural flexure). The engineering board's work should be completed by March 31, 2000, and published by the FAA. (A-99-21)
>
> Ensure that future transport-category airplanes certificated by the Federal Aviation Administration provide a reliably redundant rudder actuation system. (A-99-22)
>
> Amend 14 Code of Federal Regulations Section 25.671(c)(3) to require that transport-category airplanes be shown to be capable of continued safe flight and landing after jamming of a flight control at any deflection possible, up to and including its full deflection, unless such a jam is shown to be extremely improbable. (A-99-23)
>
> Revise Airworthiness Directive 96-26-07 so that procedures for addressing a jammed or restricted rudder do not rely on the pilots' ability to center the rudder pedals as an indication that the rudder malfunction has been successfully resolved, and require Boeing and U.S. operators of Boeing 737s to amend their Airplane Flight Manuals and Operations Manuals accordingly. (A-99-24)
>
> Require all 14 Code of Federal Regulations Part 121 air carrier operators of the Boeing 737 to provide their flight crews with initial and recurrent flight simulator training in the "Uncommanded Yaw or Roll" and "Jammed or Restricted Rudder" procedures in Boeing's 737 Operations Manual. The training should demonstrate the

inability to control the airplane at some speeds and configurations by using the roll controls (the crossover airspeed phenomenon) and include performance of both procedures in their entirety. (A-99-25)

Require Boeing to update its Boeing 737 simulator package to reflect flight test data on crossover airspeed and then require all operators of the Boeing 737 to incorporate these changes in their simulators used for Boeing 737 pilot training. (A-99-26)

Evaluate the Boeing 737's block maneuvering speed schedule to ensure the adequacy of airspeed margins above crossover airspeed for each flap configuration, provide the results of the evaluation to air carrier operators of the Boeing 737 and the National Transportation Safety Board, and require Boeing to revise block maneuvering speeds to ensure a safe airspeed margin above crossover airspeed. (A-99-27)

Require that all Boeing 737 airplanes operated under 14 Code of Federal Regulations Parts 121 or 125 that currently have a flight data acquisition unit be equipped, by July 31, 2000, with a flight data recorder system that records, at a minimum, the parameters required by Federal Aviation Administration Final Rules 121.344 and 125.226, dated July 17, 1997, applicable to that airplane plus the following parameters: pitch trim; trailing edge and leading edge flaps; thrust reverser position (each engine); yaw damper command; yaw damper on/off discrete; standby rudder on/off discrete; and control wheel, control column, and rudder pedal forces (with yaw damper command; yaw damper on/off discrete; and. control wheel, control column, and rudder pedal forces sampled at a minimum rate of twice per second). (A-99-28)

Require that all Boeing 737 airplanes operated under 14 Code of Federal Regulations Parts 121 or 125 that are not equipped with a flight data acquisition unit be equipped, at the earliest time practicable but no later than August 1, 2001, with a flight data recorder system that records, at a minimum, the parameters required by Federal Aviation Administration Final Rules 121.344 and 125.226, dated July 17, 1997, applicable to that airplane plus the following parameters: pitch trim; trailing edge and leading edge flaps; thrust reverser position (each engine); yaw damper command; yaw damper on/off discrete; standby rudder on/off discrete; and control wheel, control column, and rudder pedal forces (with yaw damper command; yaw damper on/off discrete; and control wheel, control column, and rudder pedal forces sampled at a minimum rate of twice per second). (A-99-29)

Chairman HALL, Vice Chairman FRANCIS, and Members HAMMERSCHMIDT and BLACK concurred in these recommendations. Member GOGLIA did not participate.

By: Jim Hall
Jim Hall
Chairman