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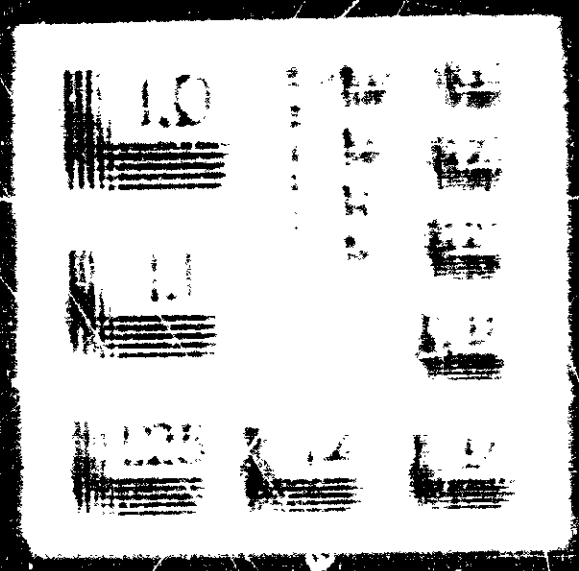

PB90-917004

Special Investigation Report - Brake Performance of the McDonnell Douglas DC-10-30/40 during High Speed High Energy Rejected Takeoffs

(U.S.) National Transportation Safety Board
Washington, DC

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U.S. Department of Commerce
National Technical Information Service
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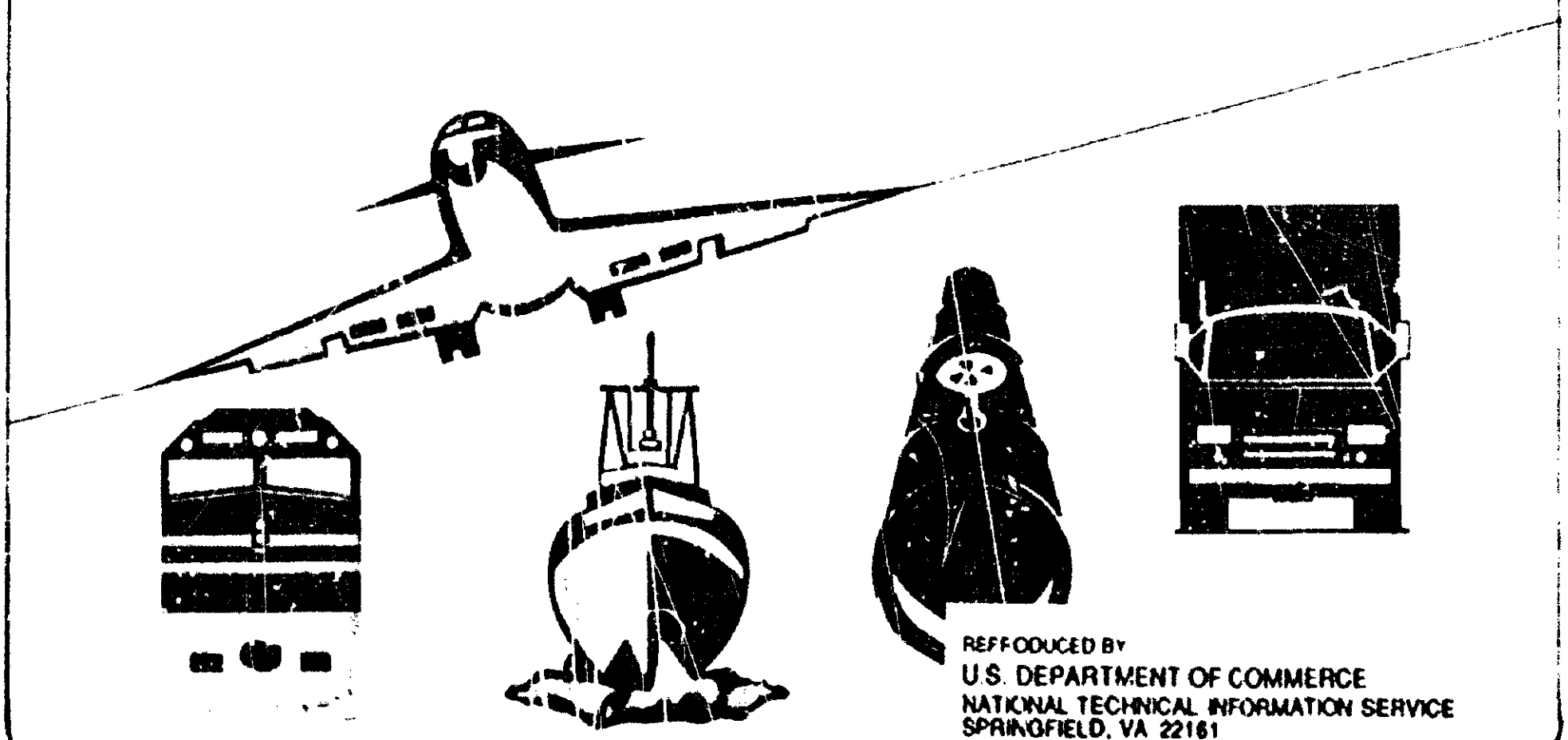
NATIONAL TRANSPORTATION SAFETY BOARD

SPECIAL INVESTIGATION REPORT

BRAKE PERFORMANCE OF THE McDONNELL DOUGLAS DC-10-30/40 DURING HIGH SPEED, HIGH ENERGY REJECTED TAKEOFFS



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16. Abstract

On May 21, 1988, a McDonnell Douglas Corporation DC-10-30 overran the runway during a rejected takeoff (RTO) at the Dallas-Fort Worth International Airport, Texas. The airplane was damaged beyond economical repair, and 8 occupants were injured. The brakes had been certified to FAA-approved procedures, yet failed at only 36 percent of the design requirement. As a result of this accident, the Safety Board conducted a special investigation of DC-10-30/40 brakes. The investigation found that the testing requirements and procedures for certifying DC-10/30/40 brakes were inadequate, only new brakes were used for the certification tests, and that worn brakes do not have the energy capacity or stopping capability of new brakes. The Safety Board also examined the potential decrease of the accelerate-stop safety margin for RTOs provided in the FAA Approved Airplane Flight Manual. The Safety Board believes that the concerns expressed about the adequacy of the certification process for the DC-10-30/40 may apply to the certification of all transport category airplanes. Recommendations were issued to the Federal Aviation Administration and focus on the following safety issues: certification tests and procedures related to the brakes of the DC-10-30/40; brake wear replacement limits; and airplane stopping distance.

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CONTENTS

EXECUTIVE SUMMARY

On May 21, 1988, a McDonnell Douglas Corporation DC-10-30 overran runway 35L during a rejected takeoff (RTO) at the Dallas-Fort Worth International Airport, Texas. No fire occurred, but the airplane was damaged beyond economical repair. Of the 254 persons on board, 2 sustained serious injuries and 6 sustained minor injuries.

The captain of the airplane executed the RTO following the sounding of a takeoff warning horn and the illumination of the slat disagree light. The warning occurred almost simultaneously with the V1 (takeoff decision speed) call, and the crew responded immediately to reject the takeoff. Although the V1 speed was slightly exceeded at the initiation of the RTO, airplane accelerate-stop data in the FAA-Approved Flight Manual indicated that the airplane was capable of stopping on or near the end of the runway.

In response to the RTO procedures followed by the flightcrew, the airplane decelerated normally for 5 to 6 seconds, slowing from a 178-knot maximum groundspeed to about 130 knots groundspeed. The deceleration then decayed rapidly, and the loss of decelerative force resulted in the airplane departing the end of the runway at about 97 knots. The nose gear collapsed in soft ground, and the plowing action of the nose slowed the airplane to a stop about 1,000 feet beyond the end of the runway.

The National Transportation Safety Board determined that the cause of the accident was total brake failure in 8 of the 10 wheel brakes as a result of inadequate certification and test procedures. The brakes had been certified to FAA-approved procedures, yet failed at only 36 percent of the design requirement.

As a result of this accident, the Safety Board conducted a special investigation of DC-10-30/40 brakes. The investigation found that the procedures for certifying the brakes and determining accelerate-stop distance data were inadequate. Although the special investigation was specifically directed to the DC-10-30/40 brake performance, the Safety Board believes that the concerns expressed about the adequacy of the certification process may apply to the certification of all transport category airplanes.

As a result of this safety investigation, safety recommendations were issued to the Federal Aviation Administration. The recommendations focus on the following issues:

- brake wear replacement limits;
- inadequate dynamometer testing;
- inadequate runway testing;
- inadequate brake energy capacity; and
- inadequate flight manual safety margins.

NATIONAL TRANSPORTATION SAFETY BOARD
WASHINGTON, D.C. 20594

SPECIAL INVESTIGATION REPORT

BRAKE PERFORMANCE OF THE MCDONNELL DOUGLAS DC-10-30/40 DURING HIGH SPEED, HIGH ENERGY REJECTED TAKEOFFS

INTRODUCTION

On May 21, 1988, a McDonnell Douglas Corporation DC-10-30 overran runway 35L during a rejected takeoff (RTO) at the Dallas-Fort Worth International Airport, Texas. No fire occurred, but the airplane was damaged beyond economical repair. The first officer and flight engineer sustained serious injuries, and the captain sustained minor injuries during the accident. An inspector with the Federal Aviation Administration (FAA), who occupied the jumpseat, and 11 flight attendants were not injured. Of the 239 revenue passengers, 5 sustained minor injuries during the emergency evacuation.

The first officer was making the takeoff until the takeoff warning horn sounded and the amber SLAT DISAGREE light illuminated. The warnings occurred as the airspeed reached the takeoff decision speed (V1) of 166 knots indicated airspeed (KIAS).1/ The captain immediately took control of the airplane and rejected the takeoff. Although the airplane should have had the capability to stop within the distance remaining on the runway or overrun,2/ the airplane departed the end of the runway at about 95 knots groundspeed (KTGS) and plowed to a stop with the nose of the airplane about 1,100 feet beyond the end of the runway.

1/ V1 speed is the preselected takeoff decision speed at and below which takeoff can be aborted and the airplane stopped within the runway confines, assuming a dry runway; and at and above which takeoff can be safely continued with the critical engine inoperative. V1 may not be less than the engine failure speed plus the speed gained with the critical engine inoperative during the time interval between engine failure and the instant at which the pilot recognizes the engine failure. Recognition is indicated by pilot application of the first decelerating device such as brakes, throttles, and spoilers. The crew callout is "VEE ONE." The V1 speed is based on the airplane's capability to accelerate and go or to accelerate and stop as defined by various combinations of weight, flap setting, pressure, temperature, wind, runway length and slope, thrust settings, and other considerations.

2/ The stopping distance calculations of McDonnell Douglas were based on the stopping capabilities of new brakes, as defined during certification flight testing.

During the accident investigation, the Safety Board determined that eight of the ten wheel brakes had failed between 5 and 13 seconds after the start of the RTO. The eight brakes that failed had been worn to near-replacement limits prior to the accident. During the RTO, excessive brake wear resulted in the depletion of the brake friction material, unporting of the brake pistons, and brake failure. The Safety Board determined that the probable cause of the accident was the failure of the FAA to require the airplane manufacturer to set appropriate brake wear replacement limits that would permit the DC-10-30 airplane to stop from a maximum kinetic energy rejected takeoff and the failure of the manufacturer to use available rejected takeoff flight test data to set brake wear limits. The Safety Board also determined that the nuisance slat warning contributed to the accident; the cause of the warning could not be determined.

The brakes had been certified to FAA-approved procedures, yet failed at only 36 percent of the design requirement. As a result of this accident, the Safety Board conducted a special investigation of DC-10-30/40 brakes. The investigation found that the testing requirements and procedures for certifying DC-10-30/40 brakes were inadequate. In addition, the investigation found that only new brakes were used for the certification tests and that worn brakes do not have the energy capacity or stopping capability of new brakes. As a result of the increased stopping distance attributed to worn brakes, the Safety Board also examined the potential decrease of the accelerate-stop safety margin for RTOs provided in the FAA Approved Airplane Flight Manual. Although the special investigation was specifically directed to the DC-10-30/40 brake performance, the Safety Board believes that the concerns expressed about the adequacy of the certification process may apply to the certification of all transport category airplanes.

THE ACCIDENT

On May 21, 1988, at 1612 local time, American Airlines flight 70 (AA70), a McDonnell Douglas Corporation DC-10-30, N136AA, en route to Frankfurt, Federal Republic of Germany, was substantially damaged when it overran runway 35L during a rejected takeoff (RTO) at the Dallas-Fort Worth International Airport, Texas. The airplane came to a stop on airport property in soft ground about 1,100 feet beyond the north end of the runway 35L.

The airplane was configured for a takeoff from runway 35L, a concrete runway 11,388 feet long by 200 feet wide. At the time of the RTO, the airplane's gross weight was 557,900 pounds and under the runway limit of 563,600 pounds. The takeoff was initiated with the trailing edge wing flaps extended 10° and the leading edge slats in the takeoff position. The surface winds were reported from 270° at 10 knots and the temperature was 78 °F. Visual meteorological conditions prevailed.

The first officer was making the takeoff, which began normally until the takeoff warning horn sounded and the amber SLAT DISAGREE light illuminated. The warnings came as the airspeed reached the takeoff decision speed (V1) of 166 knots indicated airspeed (KIAS). The captain immediately took control of the airplane and rejected the takeoff by applying the brakes, retarding the throttles, deploying the thrust reversers, and confirming the automatic deployment of the ground spoilers. The captain stated that he initially thought that the airplane would stop on the runway but soon realized the

airplane was not slowing as expected and an overrun of the runway was inevitable. The airplane departed the north end of the runway and continued across a 288-foot asphalt overrun onto soft, moist terrain where the nose wheel collapsed. The airplane plowed to a stop with the nose of the airplane about 1,100 feet beyond the end of the runway and about 100 feet short of a service road.

Tire braking marks and hydraulic fluid marks were found near the north (departure) end of runway 35L. Six sets of tire marks first appeared about 3,500 feet from the departure end of the runway and began fading about 2,000 feet from the end. The tire marks had faded to minimum or none 1,000 feet from the end except for the marks associated with the left-inboard brake sets, which continued to the end of the runway. Hydraulic fluid marks first appeared on the runway about 1,800 feet prior to reaching the departure end and continued 800 feet, ending about 1,000 feet from the end.

Readouts of the cockpit voice recorder (CVR) and the digital flight data recorder (DFDR) confirmed that the sounding of the takeoff warning horn and the illumination of the SLAT DISAGREE light occurred almost simultaneously with the "V1" call at 166 KIAS or 172 knots groundspeed (KTGS); the captain immediately rejected the takeoff. During the transition from takeoff thrust to braking, the airplane continued to accelerate to a peak groundspeed of 178 KTGS. The airplane then decelerated normally for about 5 to 6 seconds to a groundspeed of 130 knots. At that point, the recorded longitudinal accelerometer data defined a rapid decay in the deceleration level. The airplane departed the end of the runway at a groundspeed of about 95 KTGS. The onset and disappearance of tire braking marks on the runway were correlated to the longitudinal deceleration levels noted in the DFDR data. An integration of the longitudinal acceleration and speed data recorded on the DFDR showed that the disappearance of the tire braking marks on the runway corresponded to the decay in the airplane's deceleration. The deceleration increased somewhat just prior to stop. Analysis determined that this increase was the result of the plowing action of the landing gears in soft, wet soil. Had it not been for this slowing action, the airplane probably would have contacted the service road at a groundspeed greater than 60 knots instead of stopping 100 feet short of the road.

BRAKES ON THE DC-10-30 AIRPLANE

Description

The DC-10-30/40 has 10 sets of brakes. Each of the two main landing gears has four wheel/tire/brake sets: two side-by-side sets on the forward end of a bogy and two side-by-side sets on the aft end. A center body gear consists of two additional wheel/tire/brake sets arranged side-by-side.

The wheel brakes, which were designed and manufactured by the Aircraft Braking Systems Division of Loral Systems Group (formerly Aircraft Wheel and Brake Division of Goodyear Aerospace Corporation), function much like automobile disk brakes. Hydraulic system pressure, modulated by the pilot's brake pedals and antiskid control valves, is applied to pistons in each brake. The pistons act on a pressure plate to squeeze together a stack of steel disks, five of which rotate with the wheel and four of which are stationary with the axle. The rotating and stationary disks are arranged alternately so

that the application of hydraulic pressure produces friction forces between the disks to retard the wheel. Friction material attached to the rotating disks contact the steel wear pads attached to the stationary disks. As with automobile brakes, the friction material wears and must be replaced periodically. The steel wear pads also wear, typically, 20 percent of the amount of friction material depletion. The total material, steel wear pads plus friction material, is about 2.7 inches thick when the brake is new. Maintenance procedures of American Airlines at the time of the accident required that the brakes be overhauled with new friction material after a total of 2.0 inches of friction material and steel wear pad had been depleted, leaving about 0.7 to 0.9 inch of friction and steel material remaining. The American Airlines procedure had been recommended by Loral and approved by the FAA.

Two independent hydraulic/antiskid control systems are connected to each brake to provide redundancy should a single hydraulic system or antiskid system fail. Each of the systems provides force on the brake pressure plate by four pistons contained in cylindrical sleeves, eight pistons per brake. As the brake stack compresses due to depletion of friction material, the hydraulic pistons extend from their cylindrical sleeves to maintain force on the pressure plate.

Examination Before and After the Accident

Inspection of the wheel brakes the day before the accident showed that all were within the acceptable wear limits for continued use.3/ Of the 10 brakes, 2 were nearly new and the remainder were worn to 57 to 92 percent of the 2.0-inch wear replacement limit. The worn brakes had an average of 1.1 inches of friction material available, ranging from 0.85 to 1.55 inches. The eight worn brakes had incurred 762 to 1,043 landings since overhaul. The operator reported that the normal brake life was about 1,000 landings.

Examination of the airplane's brakes after the accident showed that eight brakes sustained identical failure modes. Only the two brakes that were nearly new functioned throughout the RTO. In each of the eight failed brakes, the friction material was depleted to the extent that one or more of the pistons for each of the redundant hydraulic systems had extended beyond the design limits, allowing the piston O-ring seals to escape from the cylindrical sleeve followed by the loss of hydraulic fluid. With the loss of hydraulic fluid and, thus, pressure in the brake cylinders, the brakes provided no further retardation force to stop the airplane.

3/ The wear replacement limits are normally set by the brake and airplane manufacturers when the airplane is put into service. The limits may be modified by the manufacturers, with FAA approval, based on the service history obtained by normal braking. Brake wear requirements during high energy RTOs were not used as a basis for setting the wear replacement limits for the DC-10-30 brakes (see discussion in the section "Brake Wear Limits").

Witness marks on the brake swage tubes showed that the brake pistons had traveled an average of about 1.1 inches on the eight failed brakes during the RTO. The DFDR acceleration data disclosed that some of the brakes started failing about 5 to 6 seconds after the RTO was initiated and the remainder of the brakes that failed, failed sequentially during the next 8 seconds. The speeds at failure ranged from 137 KTGS to 104 KTGS.

AA70, operating at 557,900 pounds and reaching 178 KTGS, was at a kinetic energy level of 775 million foot-pounds, equal to about 86 percent of the kinetic energy capability that had been demonstrated during the certification process with new brakes. The brakes started failing after dissipating energy equivalent to about 36 percent of the maximum demonstrated kinetic energy capacity of new brakes.

Manufacturers of the DC-10-30 airplane and its brakes, with FAA approval, had provided 0.7 to 0.9 inch of brake piston travel to be available for a maximum kinetic energy RTO. A brake failure attributed to a brake piston travel of 1.0 inch in 5 seconds at energy levels of 36 percent of the design limits clearly demonstrated that the brake wear limit for the DC-10-30 had been improperly set.

Brake Wear Limits

Engineers from both McDonnell Douglas and Loral stated that the brake wear limits had been set to assure that the friction material was not depleted from a single stack of disks during normal landing operations. If the friction material was depleted, the rotating and stationary disks would clash, resulting in costly repairs. The economic goal was to achieve maximum wear and greater number of landings without clashing before brake overhaul. According to Loral, some friction material remained available for an RTO based on the wear limits established, although the amount of wear resulting from an RTO was not considered when these brake wear limits were set before the accident of AA70.

The FAA does not have specific airplane certification requirements or operating rules that pertain to the establishment of allowable brake wear limits; brake manufacturers, therefore, may set wear replacement limits based on normal in-service braking requirements rather than RTO braking requirements. Loral had established a limit wherein the brakes would be replaced after 2.25 inches of material had been depleted. In-service difficulties soon prompted Loral to reduce the wear permissible before replacement to 1.82 inches. As a result of brake wear data obtained by American Airlines, Loral increased the permissible wear before replacement for the DC-10-30 from 1.82 inches to 2.00 inches on August 13, 1986. The data indicated that brake wear up to the 2.00-inch limit could be tolerated without clashing of the steel disk parts in the brakes during normal operation. The FAA approved the change as a part of the airline maintenance program and, therefore, did not require an engineering analysis. The Safety Board concludes that this regulatory deficiency was a causal factor in the accident of AA70 and that airworthiness and operating rules should be amended to account for worn brakes.

A worn brake is generally assumed to have a greater rate of wear of friction material during an RTO than would a new brake because a worn brake would have less mass to absorb or dissipate the generated heat. Therefore, a replacement limit that is based on the amount of friction material worn from a new brake during an RTO certification demonstration might still be inadequate for an actual maximum energy RTO conducted with partially worn brakes. Brake wear data are not required to be recorded during the certification process, but the brake wear of the new brakes was noted following the maximum kinetic energy RTO certification demonstration on the runway in 1976. These data showed that the average wear on the main landing gear brake during the RTO demonstration was 1.55 inches: the wear on two brakes exceeded 2.0 inches and two others had about 1.7 inches of wear. Some of the brakes wore very little.

The original wear limits were set for 0.45 inch to 0.65 inch of material remaining, even though the average wear during the RTO was 1.55 inches. These limits illustrate a major deficiency in FAA certification requirements for stopping capability. The Safety Board believes that the evaluation of the certification test data by the manufacturer and the FAA was inadequate and resulted in the selection of inappropriate brake wear limits on the DC-10-30/40 airplane that resulted in an unacceptable reduction of the energy capacity of the brakes.

The Safety Board believes that the airframe manufacturers have a responsibility, whether or not specified by regulations, to assure that the airplane can achieve the certificated braking performance during service operations. Thus, the manufacturer should have considered the potential for a loss of brake kinetic energy capacity with wear when setting brake wear limits. Failure of the manufacturer to do so was another causal factor in the accident of AA70.

BRAKE CERTIFICATION PROCEDURES USED BEFORE THE ACCIDENT

Safety Board investigators, with engineers from McDonnell Douglas and Goral, reviewed the DC-10-30 brake certification and qualification test methods and performance data used before the accident. Federal Aviation Regulations for certification of transport category airplane brakes require that a series of stopping tests be performed on the runway and on the dynamometer.

Runway Tests

Federal Aviation Regulations require that a stop be demonstrated on a hard-surface dry runway, at a speed and weight equivalent to the maximum kinetic energy RTO for which the airplane will be certificated to operate. The regulations allow for the use of new brake assemblies during the demonstration and, historically, the demonstrations have been conducted without the use of thrust reversers.

During the DC-10-30/40 airplane certification on June 13, 1976, a successful demonstration of a maximum kinetic energy RTO was completed using new brakes. The demonstration was conducted from a landing rather than a takeoff and was designed to develop data on stopping distance, not data on brake energy capacity. At touchdown, the airplane was in a takeoff configuration and the speed was greater than the anticipated brake-on speed of

185 KTGS. Power was reduced to forward flight idle (reverse thrust not commanded) and the spoilers were deployed. When the airplane slowed to 185 KTGS, the brake pedals were fully depressed and full braking was achieved about 2.5 seconds later. The total airplane kinetic energy was 888 million foot-pounds, based on a weight of 598,000 pounds and a brake-on speed of 183.1 KTGS. The forward flight idle thrust added an additional 21.2 million foot-pounds of energy while the brakes on the center body gear and main landing gear absorbed a total of about 814 million foot-pounds of energy. The remainder of the energy was dissapated by aerodymanic drag, nose wheel friction, and runway slope. Each main landing gear brake absorbed an average of 87.6 million foot-pounds of energy. The duration of the stop was about 28 seconds, and the measured stopping distance was used as the basis for stopping performance data in the FAA Approved Flight Manual. Using these data, corrected for environmental factors, the airplane was certificated to take off up to a kinetic energy level of 898 million foot-pounds, which corresponds to a maximum gross weight of 590,000 pounds and a V1 speed of 185.4 KTGS.

The brake-absorbed energy levels and energy absorption rates would have been greater during the demonstration if the RTO had been initiated during a takeoff rather than from a landing. If the engines are at idle at brake application, an additional 11.6 million foot-pounds of energy is added to the airplane during the stop. If the engines are at takeoff thrust at brake application, about 74.3 million foot-pounds of energy is added before the engines spool down to idle thrust. The brakes would absorb most of the additional energy. In addition, applying the brakes while the engines are at takeoff power results in a greater time duration at higher speeds and higher energy absorption rates.

The airplane's center of gravity location and elevator deflections used in the demonstration were appropriate for determining data on stopping distance. Other center of gravity locations and elevator deflections, however, could result in greater-than-normal forces on the landing gear, which, in turn, result in greater braking forces and increased brake-absorbed energy and energy absorption rates. Tests have shown that greater brake-absorbed energy levels and energy absorption rates can increase the brake wear and increase the risk of structural failure of the brake and wheel assemblies.

For the DC-10-30/40 airplane, the calculated increase in total brake energy for an actual RTO was about 55 million foot-pounds greater than the brake energy absorbed during the RTO certification demonstration conducted from a landing; this is an increase of 6.0 million foot-pounds for each main landing gear brake. The brakes should have been tested to 93.6 million foot-pounds either on the runway or the dynamometer to assure that new brakes could perform an actual maximum energy RTO consistent with conditions that would produce the maximum brake absorbed energy. The FAA did not require such tests, however, until 1983.

The DC-10-30/40 brake has been demonstrated to 87.6 million foot-pounds on the runway and dynamometer. That is equivalent to an actual RTO at 840 to 860 million foot-pounds airplane kinetic energy (without reverse thrust) although the airplane is currently certified to operate at a maximum kinetic energy of 898 million foot-pounds. However, either the operating weight limit of the airplane would have to be lowered or the brakes would have to be demonstrated to a greater energy capacity to conform with current standards. The Safety Board believes that the FAA should reduce the maximum kinetic

energy takeoff limit to one that is consistent with demonstrated brake energy capacity of worn brakes. Reverse thrust should not be used in establishing the new limits.

Dynamometer Tests

When the DC-10-30 brake assembly was subjected to technical standard order (TSO) qualification dynamometer tests in 1972, the brake manufacturer used test standards provided by the airplane manufacturer. These test standards were the basis of the 1972 FAA-approved certification testing. The airplane manufacturer specified the required brake energy capacity and the runway speeds, which the brake manufacturer simulated by defining the dynamometer flywheel mass and rotational speed. The airplane manufacturer also specified the required brake drag forces and provided the brake manufacturer a test curve for the brake drag force as a function of velocity. The brake drag force specified by the test curve was achieved on the dynamometer test by modulating brake pressure. The magnitude of the brake drag force defined the rate at which the energy is absorbed into the brake.

The brake drag force test curve was based on estimated aerodynamic forces and estimated antiskid braking friction coefficients prior to DC-10-30/40 flight tests. Credit for reverse thrust was not included. In the 1972 test conducted by Loral, the brake-absorbed energy was 87.6 million foot-pounds The test condition corresponded to a runway RTO weight of 555,000 pounds and a brakes-on speed of 186 KTGS. The brake performed in a normal manner.

The total energy to be absorbed by brakes during an RTO is defined by the speed and weight at RTO initiation. The ability of the brake to absorb that energy, however, is greatly affected by the shape of the brake drag force test curve. Brake drag force is limited by either the coefficient of friction attainable between the tire and the runway or the maximum brake torque that can be developed (the wheel retarding friction attainable between the rotating and stationary disks in the brake). The initial limitation to brake drag force on a hard, dry runway is the tire-to-runway friction. The maximum brake torque is great enough that the tire would skid on the runway if the torque were not limited by the antiskid system. Brake drag forces are skid-limited when the maximum torque that can be developed is greater than the torque that would produce a skid.

As the kinetic energy is converted to heat by the braking action, the brake temperatures increase rapidly. Within seconds, the friction material within the brake assembly reaches temperatures wherein the surface of the friction material begins to ablate, reducing the coefficient of friction between the rotating and stationary disks and increasing the rate of wear of the friction material. Consequently, the brake torque attainable by the brake decreases below the level required to produce a skid. The brake drag force is then torque-limited and the drop in brake drag force is called brake fade or brake force sag.

Safety Board investigators concluded that the DC-10-30 brake drag force dynamometer test curve supplied by McDonnell Douglas for the 1972 test did not replicate the actual brake drag forces that could be achieved on the runway and did not provide an adequate test of new or worn brakes. Actual skid-limited brake drag forces were 25 percent greater than the brake drag force dynamometer test curve used in 1972. Although about the same total kinetic

energy was converted to heat during dynamometer and runway testing, the rate of the energy conversion was less on the dynamometer. During an actual RTO, brake friction material absorbed heat more rapidly, and this increased the rate at which the friction material was depleted.

Another brake drag force curve was supplied by McDonnell Douglas in 1976 to fulfill "worn brake" test requirements of the British Civil Aviation Authority (CAA). The low brake force values of the CAA worn brake tests, however, were 46 percent less than the brake drag force achieved on the runway, and this did not generate the higher energy rate and subsequent excessive wear of the friction material noted in later tests. To provide adequate test conditions, the brake drag force test curves used for dynamometer testing should replicate the high energy absorption rate that occurs at the initiation of a maximum kinetic energy rejected takeoff.

DYNAMOMETER TESTS AFTER THE ACCIDENT

New Brake Drag Force Test Curve

In 1988, McDonnell Douglas provided a new brake drag force test curve so that dynamometer-tested brakes would be tested at energy rates that replicate those experienced by brakes during an actual RTO (appendix A). The new brake drag force test curve required that the brake be tested at the skidding limits (maximum braking) unless or until the brake is not capable of generating the skid limit brake force, typically due to high temperatures in the brake. The brake drag force values of the 1988 test curve are 25 percent greater than the TSO brake drag force values of the curve used for the DC-10-30 dynamometer tests in 1972 and are consistent with the forces actually achieved on the runway.

Exception to Policy that Prohibited Credit for Reverse Thrust

Use of reverse thrust lessens the stopping distance and energy absorbed by the brakes. Manufacturers, however, have not proved the reliability of the thrust reverser systems to FAA satisfaction. Therefore, the FAA has not allowed distance and energy credit attributed to reverse thrust when establishing RTO safety margins.

To show that the DC-10-30/40 brakes are adequate to perform a maximum kinetic energy RTO with brakes worn to the service limits, McDonnell Douglas chose to deviate from past FAA-approved brake testing practices by taking credit for reverse thrust, which results in less energy being absorbed by the brakes. In April 1989, the FAA issued a policy paper on the subject (appendix B). They stated in part:

> It should be noted that this use of reverse thrust applies to kinetic energy determination for the purpose of establishing worn brake limits only. The FAA will not consider allowing credit for reverse thrust in the determination of accelerate-stop distances or braking performance.

The FAA also stated:

> As you know, the FAA has been reluctant in the past to grant credit for reverse thrust relating to braking performance or brake kinetic energy determination. We remain unconvinced that reverse thrust credit should be granted in the case of airplane braking performance, because reverse thrust has not been shown to be sufficiently reliable for this purpose. However, we see no good reason to deny the use of reverse thrust in the determination of brake kinetic energy for brake wear limit tests. Reverse thrust will certainly be used in any RTO (if available), and the probability of a high energy, field-length limited RTO combined with an inoperative reverser(s) is sufficiently low to allow relief in this area.

On October 24, 1989, the FAA revised the policy for using reverse thrust credit during worn brake testing (appendix B). In part, the FAA states:

> C. ENERGY LEVEL AND STOPPING REQUIREMENT
>
> It will be acceptable to conduct the dynamometer test with an initial energy value prior to the RTO test that is analogous to that used for the airplane certification flight test of the brake, including, if desired by the applicant, the effect of:
>
> (1) Engine reverse thrust, excluding the one engine presumed to be failed, and
>
> (2) The demonstrated transition time achieved in flight test.

As a result of these changes, braking performance (stopping distance) and brake kinetic energy determination (brake-absorbed energy capacity) requirements for worn brakes are not as demanding as requirements for new brakes. Both factors are equally important to stopping the airplane. Brakes that cannot absorb the required amount of energy will fail to provide braking force needed to achieve the demonstrated stopping distance, and they may structurally fail before the airplane comes to a complete stop. To absorb the additional energy that would be dissipated by reverse thrust (in the worn brake testing), the DC-10-30/40 wear replacement limits would have to be further reduced or the brake would have to be redesigned. The Safety Board believes that the FAA should not allow the use of reverse thrust credit for determining either worn or new brake energy capacity tests.

Summary of Dynamometer Tests

Before the accident of AA70, DC-10-30/40 wheel brake assemblies could contain either short or long cylinder sleeves and matching pistons. Because the brake assembly pistons had over-extended in AA70, subsequent dynamometer tests used only long or extra-long cylinder sleeves; spacers were added to the pistons to provide full piston travel without the pistons extruding from the sleeves. Brake wear was recorded during the tests to determine the onset time and rate of the brake wear during the stop.

A series of dynamometer tests were conducted in 1988. The brakes were applied while the dynamometer flywheel was at about 186 knots and the kinetic energy level was about 87.6 million foot-pounds, consistent with the lower energy levels associated with the use of reverse thrust. Results of the tests follow.

On July 29, 1988, Loral tested a new brake to the 1988 brake drag force test curve that accounted for the initially higher rate of kinetic energy conversion to heat. The brake performed in a normal manner from a brake-on speed of 186 knots to a stop. The wear was about 1.4 inches, about 70 percent greater than the wear measured after the 1972 dynamometer test. The increased wear was consistent with the wear found after the runway RTO test in 1976 and was attributed to using the new brake drag force test curve. The use of the reverse thrust energy credit lessened the amount of brake wear during the test.

On August 1, 1988, Loral tested a brake in which 1.47 inches of friction material had been depleted. The brake failed structurally during deceleration at 60 knots. The brake was only worn to about 73 percent of the wear permissible before replacement (2.0 inches), and piston spacers assured that the pistons would not over-extend the cylinder sleeves as had happened on AA70. The wear rate during the test greatly exceeded that demonstrated with a new brake, and the remaining friction material was worn away in about 5 to 6 seconds and at about 147 knots. With the friction material depleted, steel surfaces on the rotating disks rubbed directly on the steel wear pads on the stationary disks (steel-on-steel) until structural failure occurred at 60 knots.

All subsequent worn brake tests have resulted in a steel-on-steel condition. The steel-on-steel condition has never been tested on the runway and has never been an acknowledged design condition for these types of brakes until these tests that were conducted after the accident. Dynamometer testing does not duplicate many of the forces present during an actual RTO. Runway roughness and dynamic interactions between the airplane, landing gears, tires and brakes are not duplicated. The Safety Board believes that the FAA should require the brake and airplane manufacturers to demonstrate with sufficient additional tests, including runway tests if necessary, the safety of the steel-on-steel condition that develops when the DC-10-30/40 brake friction material is depleted during a maximum kinetic energy RTO with brakes at the wear replacement limit before the start of the RTO. For the demonstration, the runway roughness and dynamic interactions between the airplane, landing gears, tires, and brakes should be simulated.

A 0.71-inch worn brake was tested on August 18, 1988. The worn brake had 2.05 inches of material remaining prior to the test, and long cylinder sleeves plus spacers replaced the original sleeves. Test results showed that the worn brake stopping distance was 340 feet greater than the new brake stopping distance, based on dynamometer distances. The test also showed that the length of the long piston cylinder sleeves was not adequate.

On January 6, 1989, a 1.00-inch worn brake was tested that used newly designed extra-long cylinder sleeves and had about 1.8 inches of remaining friction material. The brake failed from piston over-extension at about 45 knots.

On January 12, 1989, a 0.76-inch worn brake with extra-long cylinder sleeves was tested; the brake was successful in stopping the dynamometer. The brake drag forces during the sag were 20 to 30 percent less than other tests, and the dynamometer stopping distance was about 700 feet greater than the stopping distance achieved with new brakes. The brake drag force data indicated that the airplane stopping distance would increase about 500 feet for worn brakes compared to new brakes. Subsequent tests resulted in greater brake drag forces and shorter stopping distances: 220 feet greater than new brakes. Loral and McDonnell Douglas have attributed the differences in the worn brake stopping distances to the type of automatic brake adjuster mechanisms used in the tests.

To relieve operators from the restrictive wear replacement requirements, McDonnell Douglas and Loral have tested a brake at a 1.04-inch worn condition but at reduced kinetic energies. The lower kinetic energy was based on a maximum airplane brake energy of 680 million foot-pounds, less than the certificated operating limit of 898 million foot-pounds. Results of a test conducted on November 10, 1988, are the basis for the McDonnell Douglas recommendations that would allow a wear limit of 0.75 inch for airplanes operating below 680 million foot-pounds brake kinetic energy and with the long cylinder sleeve. The test showed that the worn brake could stop the dynamometer from an initial kinetic energy of 69.2 million foot-pounds.

On March 28, 1989, a 1.09-inch field-worn brake with extra-long piston cylinder sleeves was successfully tested at the equivalent of 898 million foot-pounds airplane kinetic energy with reverse thrust. The test was the basis for the McDonnell Douglas recommendation of a 0.9-inch wear replacement limit at an airplane kinetic energy limit of 898 million foot-pounds, if the extra-long sleeves and reverse thrust are used.

Factors Contributing to the Excessive Wear of DC-10-30/40 Brakes

The worn DC-10-30/40 brakes exhibited an excessive wear rate in the first few seconds of each dynamometer test, similar to the excessive wear rate present on AA70 at the time of the accident. Based on dynamometer test results, McDonnell Douglas and Safety Board staff believe that a general increase in wear rate results from less heat sink mass available in worn brakes to absorb energy; the lower mass results in elevated brake temperatures. Physical changes in the friction material, such as cracking, may further reduce the thermal efficiency of the brake, and an increase in brake temperature results in more rapid wear of the friction material, particularly if ablation temperatures are reached.

The design of the brake may also be a major factor in the differences in performance between new and worn brakes. The DC-10-30/40 brake is a wear-padded brake: flat steel wear pads are attached flush to the stationary disks with two rivets through each pad. Heat transfers directly through each pad into the disk. The steel wear pads lose mass and undergo a thermal cycle each time the brake is activated. Gradually, the wear pads curl around the attaching rivets and the surface contact with the disk is reduced, reducing the rate at which heat can be transferred through the wear pad away from the friction surfaces. McDonnell Douglas and Safety Board staff believes that during a high energy RTO, the reduced heat flow characteristics result in accelerated heating and ablation of the friction material. In addition, the

curling results in sharp edges on the wear pads and gaps between the wear pads, which may also contribute to accelerating the brake wear during a high energy RTO.

Loral supports the theory that many factors contribute to the accelerated wear rate of field-worn brakes compared to brakes in which the friction material has been machined from an as-new condition to simulate wear. Loral states that "review of DC-10-10 worn brake test data concerning machined versus field worn brakes indicate that the differences in wear rate cannot be contributed solely to wear pad curl."4/ A new brake, evenly machined to a worn dimension, has a higher friction coefficient than does a field-worn brake. Therefore, less piston pressure is required for a new brake during testing to produce a given brake drag force. The wear pad and lining mass of a new machine-worn brake is about 8.5 pounds greater than the respective mass of a field-worn brake of the same thickness. The higher friction coefficient and greater mass of a machine-worn brake contribute to less rapid wear of a machine-worn brake under RTO conditions.

CORRECTIVE ACTIONS TAKEN

As a result of the examination of the brakes from AA70, the Safety Board issued the following safety recommendations on July 11, 1988, the FAA:

A-88-73

Require the McDonnell Douglas Aircraft Corporation to immediately redefine the "maximum brake wear" limits for the DC-10-30 and -40 airplanes to ensure that the brake kinetic energy capacity ratings for wheel brake assemblies that are at the allowable "maximum brake wear" limit are not less than the kinetic energy absorption requirements that result from the critical combination of weight, true airspeed, altitude, temperature, runway slope, and tail wind component for which the airplane is certified.

A-88-74

Issue a telegraphic airworthiness directive for DC-10-30 and -40 airplanes to require that operators comply with redefined brake wear limits.

A-88-75

Revise 14 CFR 25.735(f) to require that the brake kinetic energy capacity ratings for wheel brake assemblies that are at the allowable "maximum brake wear" limit may not be less than the kinetic energy absorption requirements that result from the critical combination of weight, true airspeed, altitude, temperature, runway slope, and tail wind component for which the airplane is certified.

4/ Telecopier message from Loral to the Safety Board, July 13, 1989.

A-88-76

Verify, by conducting tests and data analysis as necessary, that all turbojet transport category airplanes meet the requirement of 14 CFR 25.735(f) for wheel brake assemblies at the "maximum brake wear" limits. (Note: This recommendation is superceded by recommendation A-90-30.)

On July 26, 1988, the FAA issued Airworthiness Directive (AD) 88-16-02 to decrease the allowable brake wear on DC-10-30/40 airplanes from 2.0 inches to 1.5 inches for brakes with short sleeves and 1.75 inches for brakes with long sleeves.

Based on the dynamometer test August 1, 1988, in which a 1.47-inch worn brake structurally failed, McDonnell Douglas sent a COMTWIX DC-10-COM-36/FWM to DC-10-30/40 operators on August 11, 1988, recommending a 0.75-inch wear limit. McDonnell Douglas also recommended using the maximum flap setting, using procedures for an unbalanced field length, and limiting the use of derated thrust to reduce the maximum kinetic energy at the initiation of an RTO and to provide maximum distance for stopping (assuming a V1 RTO). The use of maximum takeoff thrust results in greater obstacle clearances that can be traded for a reduction in the V1 speed.

On September 27, 1988, the FAA issued an amended AD (AD-88-16-02R1) requiring long piston sleeves for DC-10-30/40 brakes and limiting the brake wear to 0.75 inches.

On January 30, 1989, McDonnell Douglas issued COMTWIX DC-10-COM-5/FWM recommending the use of the extra-long piston cylinder sleeves in DC-10-30/40 brakes. On February 16, 1989, Mcdonnell Douglas issued COMTWIX DC-10-COM-7/FWM recommending (1) the use of the extra-long sleeves and a 0.9-inch wear limit when operating at a 898 million foot-pound energy level (then limited by FAA AD to 0.75 inch); (2) a 0.5-inch wear limit with the use of long sleeves when operating at a 898 million foot-pound energy level; and (3) a 0.75-inch wear limit with the use of long sleeves when operating at less than a 680 million foot-pound energy level. Those combinations of sleeve lengths and wear limits have been shown to be adequate to stop the airplane at the specified kinetic energy levels without encountering over-extension of the pistons, provided that reverse thrust is used to absorb some of the energy.

On August 14, 1989, the FAA issued a Notice of Proposed Rulemaking to modify AD 88-16-02R1 to be consistent with COMTWIX DC-10-COM-7/FWM, with the exception of not allowing the use of the long cylinder sleeves at reduced energy levels. AD 88-16-02R2 was adopted on December 27, 1989.

The entire series of postaccident tests and corrective actions were based on the assumption that reverse thrust would be used during an RTO. The Safety Board does not agree with a rationale that accepts test requirements of worn brakes that are less stringent than the test requirements for new brakes originally established as the basis for airplane operational limitations, especially when worn brakes have proven greater wear rates and less capacity to absorb energy.

RTO SAFETY MARGINS

The maximum kinetic energy RTO has been described as one of the most demanding maneuvers in aviation. A runway-limited RTO is even more demanding. Few safety margins are included in the calculations of accelerate-stop distances. Therefore, any substandard performance by the pilots, brakes, or other airplane equipment related to the airplane acceleration or stopping performance will result in the airplane overrunning the end of the runway.

The V1 concept is based on the assumption that the airplane can accelerate to the V1 speed and stop in a predefined distance and that runway length requirements are greater than that distance, thus providing a safety margin. In the event of an engine failure, the RTO must be initiated at or prior to reaching the V1 speed. The initiation is defined as action being taken by the crew to stop the airplane. Data show that the V1 concept was exceeded by 6 knots for the RTO of AA70 based on action being taken to stop the airplane. AA70 was not limited by runway length for the takeoff, however, and the RTO kinetic energy was within the airplane's certification limit. If the brakes had not failed and assuming that the deceleration level had remained consistent with the stopping performance demonstrated with new brakes, the airplane could have been stopped near the end of the runway.

Data on worn brake stopping distance developed after the accident of AA70 show that the DC-10-30 may require a 220-foot to 500-foot increase in stopping distance if worn, rather than new brakes, are used for the stop. This demonstrated increase in stopping distance prompted the Safety Board staff to review the process by which the safety margins for RTOs are established.

Reverse Thrust Safety Margin

The two predominant safety margins available in the RTO are the use of reverse thrust and the inclusion of time delays (for in-service variations of airplane and pilot performance) with the accelerate-stop distances published in the FAA Approved Airplane Flight Manual (AFM). Use of reverse thrust results in a shorter stopping distance but is not factored into the calculations for stopping distance in the AFM. If reverse thrust is used, the shorter stopping distance is considered a safety margin. In addition, the use of reverse thrust results in less energy absorbed by the brakes and, therefore, a greater brake energy capacity safety margin exists during the RTO. For runway-limited, maximum kinetic energy RTOs of the DC-10-30, the reverse thrust from two engines can shorten the stopping distance by about 310 feet with new brakes and 350 feet with worn brakes.

Time Delay Safety Margins for In-Service Variations

During certification RTO tests, pilot reaction times are documented. If a pilot executes an in-service RTO on schedule with the documented reaction times, the demonstrated stopping distance can be achieved. To provide a safety margin, time delays for in-service variations are added to the demonstrated pilot reaction times, which, in effect, increase the calculated stopping distance and provide a distance safety margin.

McDonnell Douglas time delay safety margins.--To incorporate the time delays for in-service variations into the accelerate-stop distance calculations during the original certification, McDonnell Douglas, with approval from the FAA, chose to use a simplified procedure for complying with the certification rule 14 CFR 25.109, effective December 24, 1964. This procedure was simplified by using constant speeds for some calculations and assuming that full braking was present at the start of the deceleration. The accelerate-stop distances were determined by adding the distance traveled to engine failure and the distance traveled from engine failure to V1 to the distance required to stop the airplane from V1 using pilot procedures for stopping the airplane as established by the manufacturer. The stopping distance is determined theoretically from runway braking tests demonstrated from landings. Added to these distances was the calculated distance traveled during pilot reaction time and safety margin time delays 5/ at a constant speed equal to V1. The total was used as the accelerate-stop distance that became the basis for AFM runway performance data.

Although McDonnell Douglas and the FAA considered this simplified procedure sufficient to provide an adequate safety margin over obtainable accelerate-stop performance, the Safety Board believes the procedure is deficient and does not provide a margin intended by the regulation. After the accident of AA70, the Safety Board undertook efforts to determine the actual safety margin in terms of accelerate-stop distance requirements. The Safety Board requested that McDonnell Douglas conduct computer simulation studies based on specific takeoff conditions to determine stopping distances that can be compared to the stopping distances obtainable from the present AFM data for the specific conditions.

For these postaccident calculations, the present AFM stopping distance was also compared to the stopping distance determined using the procedures recommended by the FAA subsequent to the DC-10 certification. FAA Order 8110.8, Engineering Flight Test Guide for Transport Category Airplanes, Change 2, effective 9-17-79, and FAA Advisory Circular (AC) 25-7 described these procedures for determining accelerate-stop distances. Time delays were required to be included for recognition of an engine failure and for the incremental actions required by the pilot to pull the throttles, deploy the spoilers, and apply the brakes. The airplane manufacturer established the sequence of pilot actions to be used during the RTO as they would be included in the AFM.

Demonstrated time delays.--Time delays resulting from pilot reaction had been demonstrated by McDonnell Douglas at the time of the DC-10 certification. The first delay, engine failure recognition, occurs between the instant of engine failure and recognition by the pilot, which was defined by the pilot's initial action to pull the throttle. The speed at recognition is defined as the V1 speed. The DC-10 certification tests showed a 1.1-second delay for engine failure recognition.

5/ The time elapsed for pilot actions to configure the airplane for stopping plus delays for in-service variations.

McDonnell Douglas established a sequence of pilot actions for the RTO: throttle pull, spoiler activation, and brake application. The throttle pull is coincident with the V1 speed. Pilot reaction times were demonstrated for the remaining two actions: 0.6 seconds after V1 to recorded spoiler movement, and 0.5 seconds after spoiler movement to a recorded rise in brake pressure. Reaction time for the latter two actions thus totaled 1.1 seconds after V1.

Pilot reaction and time delays for safety margins.--An agreement between McDonnell Douglas and the FAA dictated that the 1.1-second reaction time between engine failure and throttle pull would be used for determining the AFM data.

In addition, the 1.1-second reaction delay between throttle pull and brake application (as demonstrated by the certification test pilot) would also be used. To provide a safety margin, a 1-second time delay was to be added for each action after throttle pull. 2 additional seconds were thus added to the demonstrated reaction times occurring after V1. The time delay between V1 and the brake application, therefore, totaled 3.1 seconds: 0.6 seconds plus a 1-second safety margin to activate the spoilers, and 0.5 seconds plus a 1-second safety margin to apply the brakes. McDonnell Douglas chose to use a total 3.1-second delay while assuming that the speed remained constant at V1. At the end of the 3.1-second period, full braking capability was assumed to be available.

By assuming that full braking capability was available at the end of the 3.1-second period, the full effect of the 2-second delay was diminished. The stopping distance from V1 was obtained from faired time-speed-distance data curves based on flight test. The method of fairing the data curves eliminated the distance effect attributed to the brake ramp-up time. In effect, the result is based on the assumption that the brakes were providing full braking force at the time of brake application, when, in fact, the time history of brake forces showed that 2.5 seconds were required to achieve full braking force after brake pedal application. The extra distance attributed to the delay in reaching full braking force was not factored into the calculations to determine stopping distance for the AFM.

Distance safety margins attributed to the 2-second time delay.--Using procedures described in AC 25-7, the determination of the accelerate-stop distance should have been based on the following incremental distances: (1) the actual distance traveled to the point at which the takeoff thrust is removed from one engine; (2) the distance for a continued acceleration with two-engine takeoff thrust for 1.1 seconds; (3) the distance traveled during the increment in which the two-engine thrust starts decaying, the spoilers start deploying, up to the point when the brakes are initially depressed, which, including both 1-second safety margins, is a 3.1-second period (1.6 seconds for spoiler activation and 1.5 seconds for brake pedal activation); and (4) the distance to stop the airplane from the point of brake application. The safety margin provided for in-service variations should be about equal to a free roll for 2 seconds, or about 627 feet (the distance traveled in 2 seconds at 185.5 KTGS).

The following comparisons between actual stopping distances and the values derived from the AFM apparently had not been made before the accident of AA70. A maximum certificated takeoff gross weight of 590,000 pounds and a V1 speed of 185.5 KTGS defined the takeoff conditions. The distance traveled during the acceleration portion of the takeoff is assumed to be constant for all the cases discussed. The data in the present AFM for these conditions yielded a stopping distance of 5,197 feet. These data would be used by operators to establish the requirements for takeoff weight and runway length.

A simulation based on the RTO procedures selected during the original certification--throttle pull at V1, spoiler deployment at 0.6 seconds after V1, and brake application at 1.1 seconds after V1 without adding the two 1-second time delay safety margins--resulted in a 5,113-foot stopping distance, only 84 feet less than the AFM stopping distance. This small margin is clearly not consistent with the safety margin intended by certification requirements, and the procedure for establishing the safety margin does not guarantee an adequate safety margin. When a distance safety margin of 627 feet (2 seconds X 185.5 KTGS) is added to the demonstrated distance, the time delay stopping distance is 5,740 feet, or 543 feet greater than the distance resulting from the simplified AFM procedure.

After the original certification of the DC-10, and as a result of overrun accidents, McDonnell Douglas apparently concluded that a more favorable stopping safety margin could be obtained by changing RTO procedures described in the AFM while retaining the original accelerate-stop distance data. As a result of the AA70 investigation, an accelerate-stop simulation was conducted based on current RTO procedures established by McDonnell Douglas: simultaneous throttle pull and brake application at V1 followed by spoiler activation within 0.6 seconds. McDonnell Douglas believes that such procedures are reasonable and compatible with the ability of pilots and the airplane. When the brakes are applied simultaneously at V1 and the throttle pull, the stopping distance is shortened to 4,837 feet, or 360 feet less than the AFM distance that allowed for the originally demonstrated brake application at 1.1 seconds after V1. When McDonnell Douglas applied a 1-second time delay for in-service variations, with the brake application at 1.0 second and the spoiler activation at 1.6 seconds, the simulation achieved a 5,088-foot stopping distance, or 109 feet less than the AFM value. If the 2-second delay factor (2 seconds X V1) were added to the 4,837-foot distance, however, the stopping distance would increase to 5,464 feet. Therefore, even when the procedures change the brake-on time from 1.1 seconds--as demonstrated in certification--to 0.0 seconds, the present AFM data fall short of the intended safety margin by 267 feet.6/

Total safety margin.--The total safety margin provided by McDonnell Douglas calculations is only 670 feet: 310 feet attributed to reverse thrust, and AFM safety margin of 360 feet 7/ attributed to the 2-second time delay if the McDonnell Douglas procedural changes are allowed. Another accepted method of calculating the distance effects of the 2-second delay, however, would increase the value from 360 feet to 627 feet (2 seconds X V1 of 185.5 KTGS). The safety margin would be 937 feet when combined with the use of new brakes and reverse thrust.

6/ 5,464 feet minus 5,197 feet.
7/ 5,197 feet minus 4,837 feet.

The Safety Board is concerned that the DC-10-30/40 AFM data do not provide the intended RTO safety margin for pilot performance, even when the most effective RTO procedures are used. In addition, McDonnell Douglas has stated that the original brake delay of 1.1 seconds was probably planned and required, possibly as a result of antiskid design limitations at the time of certification. Documentation supporting that belief has not been provided to the Safety Board. Consequently, the Safety Board believes that the AFM should reflect a distance safety margin that incorporates a distance correction equivalent to 2 seconds X V1 distance and that any changes to the FAA-demonstrated time delays should be approved by the FAA.

The Safety Board acknowledges that the brake failure resulting from excessive wear is the most relevant factor in the accident of AA70, and that deficiencies in the calculations of accelerate-stop distances are not necessarily relevant because the AA70 takeoff was not field length-limited. The Safety Board believes, however, that the inadequate distance safety margins related to the 2-second time delay and the current procedures followed to calculate the accelerate-stop distances in the AFM must be corrected before accounting for the distance penalties attributed to worn brakes.

Other Factors Affecting the RTO Safety Margin

Runway alignment distance.--Operators, with FAA approval, have improperly determined runway length requirements for RTOs by assuming that the runway length may be equal to the accelerate-stop distance defined by the AFM. This assumption does not allow for the distance used to turn onto and align with the runway. A DC-10 typically requires about 270 feet of runway distance to achieve alignment. For a runway length-limited takeoff, this would reduce the safety margin for DC-10-30/40 airplanes to 400 feet.8/

Brakes worn to the 0.75-inch replacement limit provide less braking force than do new brakes, which results in greater stopping distances for high energy RTOs. The drop in braking force with worn brakes results from the reduction of brake mass, sagging of the brake force earlier in the RTO, and deterioration of the friction material. Even with two-engine reverse thrust, the worn brake stopping distance for the DC-10-30/40, as determined by McDonnell Douglas, is 220 feet to 500 feet greater than that of the same airplane with new brakes. Consequently, in a normal operation with runway alignment, worn brakes, and reverse thrust, the stopping margin on the runway is reduced to 180 feet.9/ With a 1-second delay in brake application, the stopping distance with worn brakes will increase an additional 280 feet, resulting in a 100-foot overrun. If reverse thrust is not available, a worn-brake stop with no delay in braking would result in a 130-foot overrun under conditions that would have resulted in a 360-foot safety margin according to AFM data. A 1-second delay in brake application without reverse thrust would increase the overrun to 410 feet.

8/ 670-foot total margin minus 270-foot alignment distance.
9/ The 400-foot margin after runway alignment minus the 220-foot distance reduction (called a penalty) attributed to worn brakes.

Credit for the availability of reverse thrust.--FAA policy had not allowed credit for the use of reverse thrust when establishing RTO stopping distances. McDonnell Douglas, however, currently is trading the incremental stopping distance attributed to the use of reverse thrust for the incremental stopping distance attributed to worn brakes. McDonnell Douglas and the FAA have stated that the increase in stopping distance resulting from worn brakes will not be addressed in the AFM unless that distance penalty for worn brakes exceeds the safety margin provided by the use of reverse thrust. That position is in direct contrast to the previously stated FAA policy that credit for reverse thrust "should not be granted in the case of airplane braking performance" (appendix B). The FAA notes that trading the stopping distance derived from reverse thrust for that derived from worn brakes is not a factor in an RTO for the DC-10-30/40 except for the remote possibility of an RTO when (1) the airplane is near gross weight, (2) all the brakes are at or near the replacement limit, (3) the RTO is initiated at or near V1, (4) the takeoff is runway length-limited, and (5) the thrust reversers fail.

The Safety Board believes that, for turbojet transport category airplanes, the accelerate-stop distance in the AFM should be consistent with a complete stop on the runway. Full allowances should be made for the runway turn-on and alignment distance, the worn-brake distance penalties, and the 2-second X V1-speed distance safety margin. Because the RTO safety margins are very small, the FAA should not allow the use of the distance credit or energy benefits attributed to reverse thrust.

CONCLUSIONS

Investigation of the AA70 accident revealed that the DC-10-30/40 brake wear limits in effect at the time of the accident were adequate only for normal airplane operations. Brakes at or near the brake wear replacement limit did not have the capacity to stop a DC-10-30/40 airplane during a high energy RTO. Dynamometer test requirements were not stringent enough to establish the brake energy or wear capacity for stopping the airplane during a high energy RTO. RTO tests on the runway were conducted from a landing and used new brakes, both of which reduced the rate of brake wear during the tests. Even though the main landing gear brakes wore an average of 1.55 inches with two brakes wearing more than 2.0 inches, the brake wear replacement limits provided only 0.45 inches to 0.65 inches of material at replacement, about one-third to one-fourth of the demonstrated wear. Clearly, the friction material wear during a high energy RTO would far exceed the material available at the originally specified replacement limits. Dynamometer testing subsequent to the accident has shown that worn brakes will wear at a much greater rate than new brakes during a high energy RTO.

Current Federal regulations do not require setting proper brake wear limits based on the amount of remaining brake friction material necessary to assure continuous brake capability during a maximum energy RTO.

The maximum demonstrated brake energy capacity for new and worn brakes on the DC-10-30 is consistent only with a maximum airplane kinetic energy of 840 to 860 million foot-pounds although the airplane is certified to operate at 898 million foot-pounds.

The stopping distance with worn brakes exceeds the stopping distance with new brakes even when the stop is initiated with adequate braking material to assure functional brakes throughout the RTO. For the DC-10-30 airplane, a maximum kinetic energy RTO with worn brakes may result in a 220- to 490-foot increase in the accelerate-stop distance.

The amount of energy dissipated during the dynamometer testing of DC-10-30/40 brakes after the AA70 accident has been limited by subtracting the energy credit for use of reverse thrust. Therefore, the ability of brakes at the current wear replacement limit to stop the airplane from a maximum kinetic energy RTO without the use of reverse thrust has not been verified. The stopping ability of new brakes under the same conditions are required to be verified without the use of reverse thrust.

The FAA has typically required runway testing of new brake designs. The steel-on-steel condition that develops during RTOs with brakes at the wear replacement limit have not been demonstrated on the runway. Therefore, runway roughness and dynamic interactions between the airplane, landing gears, tires, and brakes have not been demonstrated for the steel-on-steel condition.

RECOMMENDATIONS

As a result of its special investigation, the National Transportation Safety Board recommends that the Federal Aviation Administration:

> Require McDonnell Douglas to demonstrate with sufficient additional tests, including runway tests if necessary, the safety of the steel-on-steel condition that develops when the DC-10-30/40 brake friction material is depleted during a maximum kinetic energy rejected takeoff (RTO) with brakes at the wear replacement limit before the start of the RTO. For the demonstration, simulate runway roughness and dynamic interactions between the airplane, landing gears, tires, and brakes. (Class II, Priority Action)(A-90-25)
>
> Issue an airworthiness directive to reduce the DC-10-30/40 maximum kinetic energy takeoff limit to a limit that is consistent with the brake energy capacity demonstrated for brakes worn to the replacement limits without credit for reverse thrust. (Class II, Priority Action)(A-90-26)
>
> Require McDonnell Douglas to conduct tests and analyses to determine the increase in the stopping distance attributed to the difference between the use of new brakes and the use of brakes worn to the replacement limits for DC-10-30/40 airplanes without credit for the use of reverse thrust. (Class II, Priority Action)(A-90-27)

Require McDonnell Douglas to determine by tests, simulation, and/or analyses the accelerate-stop distances for the DC-10-30/40 airplane as required by 14 CFR 25.109 (pre-amendment 42) using demonstrated certification stopping performance data from worn brakes and current procedures prescribed for rejected takeoffs. Account for demonstrated pilot reaction times and for deceleration device reaction times, such as engine spool-down time and brake force ramp-up time, in the determination of accelerate-stop distances and add a distance safety margin for in-service variations as described in Advisory Circular 25-7 (chapter 2, paragraphs 11.c.12.iv and vii) to be equivalent at least to a distance traveled in 2 seconds at an appropriate brake-on speed or V1 speed. (Class II, Priority Action)(A-90-28)

Require McDonnell Douglas to revise, as appropriate, the accelerate-stop distances in the DC-10-30/40 FAA Approved Airplane Flight Manual to include the increase in stopping distance attributed to worn brakes (determined in accordance with Safety Recommendation A-90-27) and to include the proper application of safety margins for in-service variations (determined in accordance with Safety Recommendation A-90-28). (Class II, Priority Action)(A-90-29)

Require the appropriate airplane and brake manufacturers to verify, by conducting tests and analyses, that all turbojet transport category airplanes meet the maximum energy requirement of 14 CFR 25.735(f) for wheel brake assemblies at the "maximum brake wear" limits; if the requirement is not met, reduce the maximum kinetic energy takeoff limit. In conducting this verification, use dynamometer brake test curves for demonstrating energy capacity that are consistent with runway-demonstrated braking forces during a maximum kinetic energy rejected takeoff. The test curves should replicate the brake's high energy absorption rate that occurs at the initiation of a maximum kinetic energy rejected takeoff. Note: This recommendation supersedes Safety Recommendation A-88-76. (Class III, Longer Term Action)(A-90-30)

Require airplane manufacturers to conduct tests and analyses to determine the increase in the stopping distance for all turbojet transport category airplanes currently in service attributed to the difference between the use of new brakes and the use of brakes worn to the replacement limits without credit for the use of reverse thrust. (Class II, Priority Action)(A-90-31)

Require the appropriate airplane manufacturers to determine by tests, simulation, and/or analyses the accelerate-stop distances for all turbojet transport category airplanes currently in service as required by 14 CFR 25.109 (pre-admendment 42) using demonstrated certification stopping performance data from worn brakes and current procedures prescribed for rejected takeoffs. Account for demonstrated pilot reaction times and for deceleration device reaction times, such as engine spool-down time and brake force ramp-up time, in the determination of accelerate-stop distances and add a distance safety margin for in-service variations as described in Advisory Circular 25-7 (chapter 2, paragraphs 11.c.12.iv and vii) to be equivalent to at least a distance traveled in 2 seconds at an appropriate brake-on speed or V1 speed. (Class II, Priority Action)(A-90-32)

Revise, as appropriate, the accelerate-stop data in the approved flight manuals of all turbojet transport category airplanes currently in service to include the increase in stopping distance attributed to worn brakes (determined in accordance with Safety Recommendation A-90-31) and to include the proper application of safety margins for in-service variations (determined in accordance with Safety Recommendation (A-90-32). (Class II, Priority Action)(A-90-33)

Require that the operators of large turbojet transport category airplanes add the distance required for runway turn-on and takeoff alignment to the field length distances as determined from data in the approved flight manuals. (Class II, Priority Action)(A-90-34)

Revise 14 CFR 25.109 to require that the stopping distance capabilities of brake assemblies at the allowable "maximum brake wear" limit are included in the requirement for determining the accelerate-stop distances for certification of new airplanes without credit for the use of reverse thrust. (Class II, Priority Action)(A-90-35)

Revise certification procedures for new airplanes to require: (1) the airplane manufacturer to determine that the dynamometer brake drag force test curves used for certification are consistent with the brake forces and energy absorption rates that can be developed during a maximum kinetic energy rejected takeoff; (2) the airplane and brake manufacturers to record the brake wear during maximum kinetic energy brake certification tests to determine the onset time and rate of the brake wear during the stop, and then to use these data in the development of in-service brake wear limits; and (3) the airplane and brake manufacturers to consider the variance and distribution of brake wear during a rejected takeoff and to use this factor to develop brake wear replacement limits. (Class II, Priority Action)(A-90-36)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

/s/ JAMES L. KOLSTAD
Chairman

/s/ SUSAN M. COUGHLIN
Acting Vice Chairman

/s/ JOHN K. LAUBER
Member

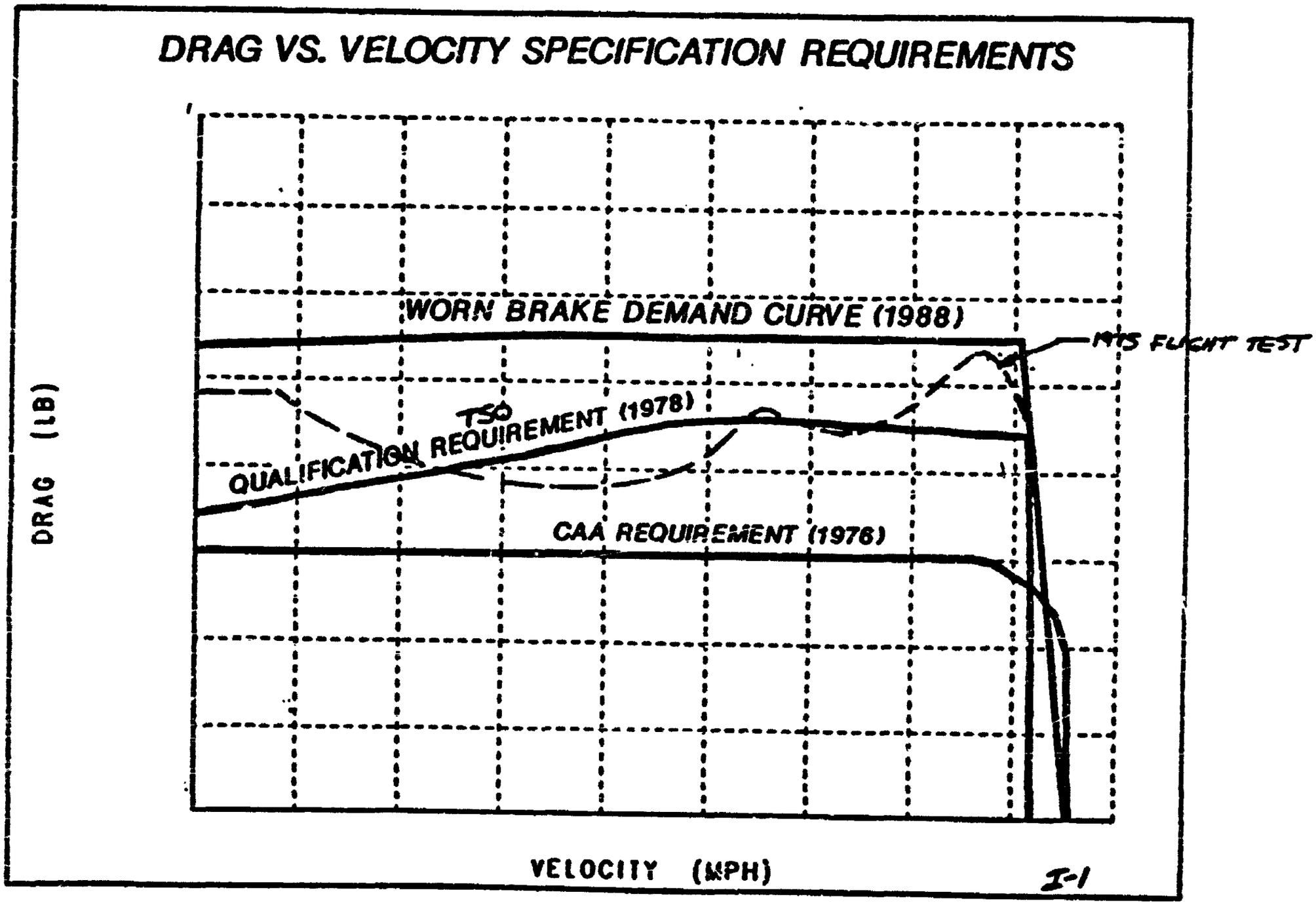
/s/ JIM BURNETT
Member

February 27, 1990

APPENDIX A

LORAL

BRAKE DRAG FORCE TEST CURVES



APPENDIX B

FEDERAL AVIATION ADMINISTRATION POLICY PAPERS

FAA Policy Paper, "Credit for Effect of Reverse Thrust in Worn Brake Kinetic Energy Determination" to FAA Directorates, April 28, 1989, and,

FAA Policy Paper to Aerospace Industries Association of America, October 24, 1989

Credit for Effect of Reverse Thrust
in Worn Brake Kinetic Energy Determination

APR 2 8 1989

Manager, Transport Airplane Directorate,
Aircraft Certification Service, ANM-100

Manager, Engine and Propeller Directorate, ANE-100,
Manager, Small Airplane Directorate, ACE-100,
Manager, Rotorcraft Directorate, ASW-100

On May 21, 1988, an American Airlines DC-10 aborted takeoff at the Dallas/Ft. Worth Airport. Eight of the 10 brakes were worn to their approved wear limits and failed during the attempted stop. As a result, the airplane ran off the end of the runway. This accident has prompted the review of the methodology used in the determination of the allowable wear limits for transport category airplane brakes.

During certification of aircraft brake systems, a demonstration of stopping performance at the maximum takeoff weight and speed expected in service is conducted. This refused takeoff test (RTO) shows that the brake has the capacity to absorb the required kinetic energy, and may limit certain performance information in the Airplane Flight Manual. This test is conducted with new brakes and without reverse thrust or other deceleration means other than spoilers.

The accident with the DC-10 has shown that DC-10-30/40 brake-wear limits and brake design in general are inadequate to provide the required stopping performance at maximum RTO energy levels with worn brakes.

An Adopted Rule AD which reduces allowable brake wear prior to overhaul on the DC-10-30/40 series airplanes has been issued. This AD was based on dynamometer testing, and provides for a brake overhaul interval such that sufficient brake mass remains at overhaul to absorb the certificated RTO energy and allow the airplane to stop on the runway.

The Transport Airplane Directorate is evaluating the criteria to determine if AD action is needed against other transport airplanes because all aircraft brakes, regardless of manufacturer or airplane on which they are used, are designed to meet the same certification requirements and operational environment. It is possible that the brake-wear limits on other transports will also have to be restricted. Any new, restricted brake wear limits would have to be validated by dynamometer testing. Data are still being collected with regard to the impact on brake assemblies utilized on airplanes other than the DC-10-30/40 series airplanes and any additional AD action is pending completion of this review.

The FAA has had meetings with the Aerospace Industries Association (AIA) in order to develop a dynamometer test protocol prior to any testing, so as to minimize costs and delays. A major issue which arose during these meetings is credit for the effects of reverse thrust on the kinetic energy that must be absorbed by the brakes. Because of the way brake energy for the DC-10 dynamometer tests was calculated, the DC-10-30/40 AD includes credit for (N-1) thrust reversers, i.e., 2-engine reverser credit for the 3-engined DC-10. As you know, the FAA has been reluctant in the past to grant credit for reverse thrust relating to braking performance or brake kinetic energy determination. We remain unconvinced that reverse thrust credit should be granted in the case of airplane braking performance, because reverse thrust has not been shown to be sufficiently reliable for this purpose. However, we see no good reason to deny the use of reverse thrust in the determination of brake kinetic energy for brake wear limit tests. Reverse thrust will certainly be used in any RTO (if available), and the probability of a high-energy, field-length-limited RTO combined with an inoperative reverser(s) is sufficiently low to allow relief in this area. It will be acceptable to allow credit for the effects of (N-1) thrust reversers in the determination of allowable wear limits in dynamometer tests discussed above. Other models of the DC-10 will be the first to be affected by this policy, due to work now being concluded in the Los Angeles ACO, but other models will also be affected.

It should be noted that this use of reverse thrust applies to kinetic energy determination for the purpose of establishing worn brake limits only. The FAA will not consider allowing credit for reverse thrust in the determination of accelerate-stop distances or braking performance.

A number of other technical issues remain to be resolved and these are expected to be resolved in meetings with ATA in about 1 month. Once these issues are solved, guidelines will be provided and each cognizant ACO will be responsible for addressing the need and developing an AD for each model for which they are responsible. No schedules have been set, and the exact scope of models has not been determined yet. Any further action is pending FAA-AIA agreement on the parameters used for the dynamometer testing. We will advise all ACO's as soon as this information becomes available. It is likely that the Seattle and Los Angeles ACOs will be most affected by this project, but other offices may be involved, and this memo is forwarded for information.

Original Signed By:
Darrell M. Pederson
Leroy A. Keith

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APPENDIX B

U.S. Department of Transportation
Federal Aviation Administration

Northwest Mountain Region
Colorado Idaho Montana
Oregon Utah Washington
Wyoming

17900 Pacific Highway South
C-68966
Seattle, Washington 98168

OCT 2 4 1989

Mr. Richard E. Macdonald
Director, Aviation Division
Aerospace Industries Association of America, Inc.
1250 Eye Street, N.W.
Washington, D.C. 20005

Dear Mr. Macdonald:

This is in response to your letter dated August 8, 1989, in which you submitted the final version of the AIA Worn Brake Rejected Takeoff (RTO) Dynamometer Test Guidelines, which is recommended by the AIA to be used to validate appropriate wear limits for airplane brakes. This recommended test procedure is the result of a series of meetings between the AIA and FAA, which were held following the May 21, 1988, aborted takeoff of the American Airlines DC-10 at the Dallas/Ft. Worth Airport.

The FAA has determined that the following dynamometer RTO test procedure may be used for the determination of acceptable airplane brake wear limits. These test guidelines may be used to verify or decrement the airplane Flight Manual (AFM) brake performance limits, but not to improve existing limits.

a. ACCEPTABLE TEST BRAKES

(1) Either airplane-worn or mechanically-worn brakes may be used. Mechanically-worn is defined as not being airplane-worn, e.g., machined or dynamometer-worn. If mechanically-worn brakes are used, it must be shown that they can be expected to provide similar results to airplane-worn brakes.

(2) Each test brake shall be subjected to a sufficient number and type of stops to ensure that the brake's performance is representative of in-service use.

b. WEAR STATE OF THE TEST BRAKE

(1) Degree of Wear

The degree of wear of the test brake shall be 100 percent. One hundred percent worn is defined as that degree of wear which the applicant intends to allow before the brake is to be removed for overhaul. At the overhaul limit the brake will not be fully worn out, but will contain sufficient

braking capability to meet the stopping requirements discussed in section c., below. The chosen test brake shall be such that the wear-in conditions produce a brake ready to perform the RTO test at the correct wear setting. If a brake to be tested is worn less than 100 percent, an acceptable method of extrapolation to the fully worn state must be provided prior to test.

(2) Definition of Degree of Wear

The degree of wear shall be defined in terms of the linear, axial direction dimension relating to the allowable wear of the brake as commonly determined by noting wear pin extension.

(3) Distribution of Wear (Applicable only to mechanically-worn brakes)

The proportioning of the wear through the brake for the various friction pairs shall be based on either:

(a) Service experience on the test brake or an appropriate equivalent brake, or

(b) Dynamometer wear test data.

c. ENERGY LEVEL AND STOPPING REQUIREMENT

It will be acceptable to conduct the dynamometer test with an initial energy value prior to the RTO test that is analogous to that used for the airplane certification flight test of that brake, including, if desired by the applicant, the effects of:

(1) Engine reverse thrust, excluding the one engine presumed to be failed, and

(2) The demonstrated transition times achieved in flight test.

d. POWER LEVEL

The test shall be conducted at either of the conditions below, provided that the test is conducted at the condition which more closely represents the actual braking conditions obtainable on the airplane. The intent of these procedures is to simulate actual airplane conditions as closely as possible:

(1) The maximum brake pressure, or

(2) The maximum tire drag or brake torque consistent with the airplane's hydraulic system and any antiskid and/or torque limiter pressure limitations that would occur on the airplane during an equivalent RTO operation.

e. FINAL CONDITION DEFINITION

(1) A full stop demonstration is not required for the worn brake RTO test. The test brake pressure may be released at a dynamometer speed of

up to 20 knots to facilitate a detailed post-test inspection of the brake. The dynamometer test may be started at a slightly higher speed so that the test may be terminated at 20 knots or less, provided that the data submitted for each test show that the energy absorbed by the brake during a test that is terminated at 20 knots or less, is equal to the energy that would have been absorbed if the test had been started at the proper speed and continued to zero ground speed.

(2) There shall be no wheel burst as a result of this test.

f. DATA REQUIREMENTS

(1) As a minimum, the following technical data shall be obtained for each dynamometer test conducted:

Brake torque (or force)
Brake pressure
Time
Road wheel speed
Road wheel distance
Dynamometer inertia equivalent

(2) The absorbed dynamometer kinetic energy and resultant braking force shall be computed based on measured data. Additional data may also be obtained to aid in interpolating and extrapolating test results.

(3) A test report shall be prepared which, as a minimum, shall include:

(a) A detailed description of the test article (e.g., component part numbers, individual disk measurements, wear pin measurements, etc.).

(b) The test procedures, and

(c) the test results.

g. INTERPRETATION OF DATA

Any adjustment of energy levels, resultant braking force, or allowable wear from the dynamometer test shall be based on a review of the test data, inspection of brake hardware after test, and subsequent analysis.

(1) An extrapolation of wear data, energy, and resultant braking force data up to 5 percent of the test values shall be permissible.

(2) An interpolation of data up to 20 percent of the test values shall be permissible to establish energy and performance levels from multiple dynamometer tests which are within this range from the target condition.

h. ACCEPTANCE OF PRIOR TESTS

Worn brake RTO tests which have been conducted successfully prior to the adoption of this procedure may be acceptable. These tests need not be repeated solely to gather test data specified here.

These worn brake dynamometer test guidelines are a recommended test procedure, and, as such, represent one means, but not necessarily the only means, of determining acceptable maximum brake wear. It is possible that a situation unique to a given brake design, installation, or application may require different test procedures, and this test plan should not be considered to be the only acceptable means. The FAA would consider deviations from these guidelines if it can be shown that the proposed procedure is appropriate and would produce equivalent results.

Sincerely,

Leroy A. Keith
Manager, Transport Airplane Directorate
Aircraft Certification Service

APPENDIX C

RECOMMENDED BRAKE WEAR LIMITS

Source of wear limit and airplane kinetic energy (million foot-pounds)	Sleeve length	Wear limit (inches)
McDonnell Douglas:		
898	long	0.50
898	extra-long	.90
680[a]	long	.75
Federal Aviation Administration Airworthiness Directive:		
898	extra-long	.90

[a] To be further reduced if thrust reverser is inoperative.

*U.S.GOVERNMENT PRINTING OFFICE:1990-261-991:00047

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