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National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

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In reply refer to: A-94-42 through -60

Honorable David R. Hinson
Administrator
Federal Aviation Administration
Washington, DC 20591

Since December 1992, there have been five accidents and incidents in which an airplane on approach to landing encountered the wake vortex of a preceding Boeing 757 (B-757). Thirteen occupants died in two of the accidents. The encounters, which occurred during visual conditions, were severe enough to create an unrecoverable loss of control for a Cessna Citation, a Cessna 182, and an Israel Aircraft Industries Westwind. Additionally, there were significant, but recoverable losses of control for a McDonnell Douglas MD-88 and a B-737 (both required immediate and aggressive flight control deflections by their flightcrews).

Safety Board data show that between 1983 and 1993, there were at least 51 accidents and incidents in the United States, including the 5 mentioned above, that resulted from probable encounters with wake vortices. In these 51 encounters, 27 occupants were killed, 8 were seriously injured, and 40 airplanes were substantially damaged or destroyed.

The Safety Board conducted a special investigation to examine in detail the circumstances surrounding the five recent accidents and incidents to determine what improvements may be needed in existing procedures to reduce the likelihood of wake vortex encounters.[1] A brief description of the five recent encounters follows.

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[1] National Transportation Safety Board. 1994. Safety issues related to wake vortex encounters during visual approach to landing. Special Investigation Report NTSB/SIR-94/01. Washington, DC.

Billings, Montana.—On December 18, 1992, a Cessna Citation 550, N6887Y, operating under Part 91, Title 14 of the Code of Federal Regulations (14 CFR 91), crashed while on a visual approach to runway 27R at the Billings Logan International Airport, Billings, Montana.[2] The two crewmembers and six passengers were killed. Witnesses reported that the airplane suddenly and rapidly rolled left and then contacted the ground while in a near-vertical dive. Recorded air traffic control (ATC) radar data show that at the point of upset, the Citation was about 2.78 nautical miles (nm) (about 74 seconds) behind a B-757 and on a flight path that was about 300 feet below the flight path of the B-757. The flight path angle of the Citation was 3°, and the flight path angle of the B-757 was 4.7°.

The B-757, at a takeoff weight of 255,000 pounds, and the Citation, at a takeoff weight of 13,000, are both classified as large airplanes. Standard instrument flight rules (IFR) radar separation (greater than 3 nm) was provided to the pilot of the Citation until the pilot requested and was cleared for a visual approach behind the B-757. The clearance was issued to the pilot about 4.5 minutes prior to the accident while following the B-757 at a distance of 4.2 nm. After the visual approach clearance was acknowledged, the speed of the Citation increased while the speed of the B-757 decreased in preparation for landing. The controller informed the pilot of the Citation that the B-757 was slowing and advised the pilot that a right turn could be executed to increase separation. Although the pilot never asked the controller about his distance from the B-757, a statement recorded on the cockpit voice recorder (CVR) indicates that the pilot recognized the separation had decreased because he stated, "Almost ran over a seven fifty-seven," about 40 seconds prior to the upset.

The Citation's rapid and extreme departure from controlled flight occurred when the airplane was about 2.78 nm (about 74 seconds) behind the B-757. Calculations indicate that an additional 0.22 nm (about 6 seconds) would have provided the required 3 nm of longitudinal IFR separation had the pilot not requested the visual approach clearance. However, available data show that under the existing atmospheric conditions, a vortex would not likely have diminished an appreciable amount in the next 6 seconds. Consequently, this accident indicates that lighter weight airplanes in the large category, such as the Cessna Citation, require a separation distance greater than 3 nm when following heavier airplanes in the large category, such as a B-757.

Although radar data indicate that, at any instant, the Citation was at least 600 feet higher than the leading B-757 during the last 4 miles of the approach, the flight path of the Citation was actually at least 300 feet below that of the B-757.

The only cue available to the Citation pilot to determine his flight path relative to the flight path of the B-757 would have been the Citation pilot's visual alignment of the B-757 and objects on the ground. For example, assuming that the B-757 was

[2] NTSB accident SEA 93-G-A041.

on a relatively constant flight path, the Citation flight path would have been similar to that of the B-757 if the Citation pilot had observed that the B-757 was aligned with the runway touchdown zone. If the B-757 were aligned with the far end of the runway, the flight path of the Citation would have been lower than the flight path of the B-757. If the B-757 were aligned with the approach lights, the flight path of the Citation would have been above the flight path of the B-757.

The failure of the Citation pilot to prevent the decrease in separation distance strongly suggests that the pilot failed to realize that he was placing the airplane in a dangerous position relative to the wake of the B-757. Although the Airman's Information Manual (AIM) suggests that the pilot of the following airplane should remain above the flight path of the preceding airplane, the Safety Board is not aware of existing training material that discusses techniques for determining the relative flight paths of airplanes on approach to landing.

Orlando, Florida.—On March 1, 1993, a Delta Airlines McDonnell Douglas MD-88, operating under 14 CFR 121, was executing a visual approach to runway 18R at Orlando International Airport, Orlando, Florida, while following a B-757 to the airport.[3] The crew of the MD-88 reported that the airplane suddenly rolled right about 15°, and the pilot rapidly deflected both the wheel and rudder pedal to correct the uncommanded roll. Data from the digital flight data recorder (DFDR) indicate that at about 110 feet above ground level (AGL), the roll angle reached 13° right wing down and the ailerons and rudder were deflected about one-half of full travel, 10° and 23°, respectively. The crew regained control and the approach was continued to an uneventful landing. Recorded radar data show that at the point of upset, the MD-88 was about 2.5 nm (65 seconds) behind a Delta B-757 while the flight path of the MD-88 was slightly below that of the B-757. The flight path angle of both airplanes was 3°.

The MD-88 flightcrew was issued a visual approach clearance when the airplane was 4.5 nm from the leading B-757. However, the separation quickly reduced to 2.5 nm. Had the MD-88 flightcrew not accepted the visual approach, the required IFR separation distance of 3 nm would have provided an additional 13 seconds of separation. The MD-88 flightcrew told investigators that they thought they had a 4 nm separation at the time of the encounter.

Denver, Colorado.—On April 24, 1993, the flightcrew of a United Airlines B-737 reported a wake vortex encounter while executing a visual approach to runway 26L at Stapleton International Airport, Denver, Colorado.[4] The flightcrew reported that about 1,000 feet AGL the airplane rolled left violently with no yaw, the pitch decreased 5°, and the airplane lost 200 feet altitude. To correct the uncommanded

[3] NTSB incident DCA 93-I-A021.

[4] NTSB incident DEN 93-I-A044.

roll, the pilot rapidly deflected the wheel and rudder about 60° and 7°, respectively, according to the DFDR. A go-around was initiated, and the airplane landed without further incident. The DFDR data also indicate that at the point of upset, the B-737 was about 900 feet AGL; in 2 seconds, its roll angle reached 23° left wing down. Recorded radar data show that at the point of upset, the flight path of the B-737 was about 100 feet below the flight path of a B-757 that was landing on runway 26R. The B-737 was about 32 seconds and 1.35 nm behind the B-757. The wind was from the north at about 10 knots gusting to 16 knots. The flight path angle of both airplanes was about 3°.

Runway 26L is parallel to and displaced 900 feet south of runway 26R. The threshold of runway 26L is offset about 1,300 feet to the east of the threshold of runway 26R, resulting in a flight path to 26R that is about 70 feet higher than the flight path to 26L. Under the existing wind conditions, a wake vortex from the B-757 would descend and move to the south, toward a standard flight path to runway 26L.

Air traffic controllers are required to provide standard separation to IFR airplanes that are approaching 26L and 26R because the runways are separated by less than 2,500 feet. If the flightcrew of the B-737 had not accepted a visual approach, the controller would have been required to provide 3 nm separation. During the early portions of the approach, ATC provided vectors to the B-737, which resulted in S-turns for spacing. Subsequently, the B-737 and B-757 were on converging courses within 12 nm of the runway. Upon completion of the S-turns, the actual separation between the airplanes was about 4.6 nm. However, the separation was predominately lateral, not in-trail or longitudinal. The lateral component of the separation was about 4.55 nm, and the longitudinal component was only about 0.65 nm along the intended approach path. The B-757 was 1.6 nm to the right of its final approach path, and the B-737 was 2.8 nm to the left of its final approach path. The final approach paths were separated by 0.15 nm. Radar data show that the B-757 was on a 15° intercept from the right side to align for the approach to runway 26R. The B-737 was on an 8° intercept from the left side to align with the approach to runway 26L. Both airplanes converged to their respective runway alignments, which resulted in a 900-foot lateral (left-right) separation. The longitudinal component of the separation increased from about 0.65 nm to an in-trail separation of about 1.35 nm. The controller should have recognized that the relative spacing, in conjunction with the converging courses, would result in less than a 3-nm separation when the B-737 was in-trail behind the B-757. To maintain a 3-nm separation after the acceptance of a visual approach clearance, the pilot of the B-737 would have had to continue to execute S-turns.

Salt Lake City, Utah.—On November 10, 1993, the pilot of a Cessna 182, N9652X, operating under 14 CFR 91, was executing a visual flight rules (VFR) approach to runway 32 at Salt Lake City International Airport, Utah.[5] The pilot

[5] NTSB accident SEA 94-G-A024.

reported that he was instructed by ATC to proceed "direct to the numbers" of runway 32 and pass behind a "Boeing" that was on final approach to runway 35. There is no evidence to suggest that the pilot was advised that the airplane was a B-757.[6] The Cessna pilot reported that while on final approach, the airplane experienced a "burble," and then the nose pitched up and the airplane suddenly rolled 90° to the right. The pilot immediately put in full-left deflection of rudder and aileron and full-down elevator in an attempt to level the airplane and to get the nose down. As the airplane began to respond to the correct attitude, the pilot realized that he was near the ground and pulled the yoke back into his lap. The airplane crashed short of the threshold of runway 32, veered to the northeast, and came to rest on the approach end of runway 35. The pilot and the two passengers suffered minor injuries, and the airplane was destroyed. The wind was 5 knots from the south.

The approach ends of runways 32 and 35 are about 560 feet apart. Radar data show that the Cessna was at an altitude of less than 100 feet AGL when it crossed the flight path of the B-757. The B-757 had passed the crossing position about 38 seconds prior to the Cessna 182. Trends in the recorded radar data suggest that the flight path of the Cessna was slightly above the flight path of the B-757 at the point of crossing. The exact position of the upset has not been determined. However, wake vortices tend to remain above the ground while in ground effect and translate outward at a speed of 3 to 5 knots plus the wind component. In ground effect, the left vortex from the B-757 typically would have translated 200 to 300 feet to the west. The vortex core may have been located about 75 feet above the ground, although researchers have said the vortex has the potential to "bounce" twice as high as the steady state height. In addition, the diameter of the vortex's flow field is usually about equal to the wing span of the generating airplane. Thus, the Cessna 182 could have been affected by the vortex at any altitude between ground level and 200 feet AGL. Although the Cessna's flight path was above that of the B-757, the pilot did not adequately compensate for the height of the vortex.

Santa Ana, California.—On December 15, 1993, an Israel Aircraft Industries Westwind, operating under 14 CFR 135 at night, crashed while on a visual approach to runway 19R at the John Wayne Airport, Santa Ana, California.[7] The two crewmembers and three passengers were killed. Witnesses reported that the airplane rolled, and CVR data indicate that the onset of the event was sudden. The airplane pitch attitude was about 45° nose down at ground contact. Recorded radar data show that at the point of upset, the Westwind was about 1,200 feet mean sea level (MSL) and 3.5 nm from the end of runway 19R. The Westwind was about 2.1 nm

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[6] At the time of the accident, there was no requirement for such an advisory. On December 22, 1993, the FAA issued a General Notice (GENOT) requiring wake turbulence advisories to airplanes operating behind B-757 airplanes. The FAA also issued a pilot bulletin cautioning pilots about the possibility of wake vortex encounters, especially when following a B-757. However, the separation distances were not changed.

[7] NTSB accident LAX 94-F-A073.

(60 seconds) behind a B-757 and on a flight path that was about 400 feet below the flight path of the B-757. The flight path angle of the Westwind was 3°, and the flight path angle of the B-757 was 5.6°. CVR data indicate that the Westwind pilots were aware they were close to a Boeing airplane and that the airplane appeared high. They anticipated encountering a little wake and intended to fly one dot high on the glide slope (about 3.1° instead of 3.0°). There is no evidence that the crew were advised specifically that they were following a B-757.

While receiving radar vectors to the airport, the crews of both airplanes were flying generally toward the east and would have to make right turns to land to the south. Radar data and ATC voice transcripts show that the Westwind was 3.8 nm northeast of the B-757 when cleared for a visual approach. The Westwind started its right turn from a ground track of 120° while the B-757 ground track remained at about 90°. The resultant closure angles started at 30° and became greater as the Westwind continued its turn. About 23 seconds later, the B-757 was cleared for the visual approach. The average ground speeds of the Westwind and B-757 were about 200 and 150 knots, respectively. The Westwind was established on course 37 seconds prior to the B-757. Although the combination of the closure angle and the faster speed of the Westwind reduced the separation distance from about 3.8 nm to about 2.1 nm in 46 seconds, the primary factor in the decreased separation was the converging ground tracks. The only way the pilot of the Westwind could have maintained adequate separation was to execute significant maneuvers.

Based on radar data, at the time the visual approach clearance was issued, the separation distance was rapidly approaching the 3 nm required for IFR separation. To prevent compromise of the separation requirement, the controller would have had to take positive action to change the Westwind's track, or to issue the visual approach clearance and receive confirmation that the pilot accepted the visual approach within 29 seconds.

The investigation disclosed that the company for which the crew were flying had not provided specific training regarding wake vortex movement and avoidance techniques. According to Safety Board investigators, the company's director of operations stated that any such training would have been included in the required windshear training. However, wake vortex avoidance was not discussed in the company's windshear training. Further, the Safety Board is unaware of any such training for Part 121 and 135 pilots.

Discussion

The Safety Board's investigations of the preceding cases initially focused on why the B-757 appeared to be involved in a disproportionate number of wake vortex encounters. Several reports indicated that the B-757 generated wake vortices that were more severe than would be expected for an airplane of its weight. However, as a result of a thorough study and analysis of the issue, the Safety Board found little technical evidence to support the notion that the wake vortex of a B-757 is significantly stronger than indicated by its weight. The calculated initial vortex strength is closely related to the weight of the airplane. Of note, the B-757 is the heaviest airplane in its weight category, and there are no other airplanes of similar weight.

The Safety Board's investigations, therefore, raised concerns about the adequacy of: (1) the current aircraft weight classification scheme to establish separation criteria to avoid wake vortex encounters; (2) air traffic control procedures related to visual approaches and VFR operations behind heavier airplanes; and (3) pilot knowledge related to the avoidance of wake vortices. Resolution of these concerns would address any concerns that were believed to have been specific to the B-757.

Aircraft Separation Criteria Based on Weight.—The wake vortex characteristics of transport category airplanes are not required to be determined at the time of airplane certification; airplane separation distances to avoid wake vortex encounters are based solely on weight. For example, not until 1992 did the National Oceanic and Atmospheric Administration (NOAA) and FAA conduct tower fly-by tests to determine the characteristics of wake vortices produced by the B-757; yet the airplane entered service in 1982, and there are 574 airplanes now in service. The testing has shown that the B-757 generated the highest vortex tangential velocity,[8] 326 feet per second, of any tested airplane, including heavy category B-747, B-767, and C-5A airplanes.[9] The vortex core radius was about 3 inches. Various theories have been offered as to why the tangential velocity was higher than previously measured. Although not proven, a number of researchers and engineers believe that the B-757 wing flap design is an important factor. Most of the larger transport category airplanes have gaps between the trailing edge flaps that disrupt the uniform development of the vortex. The B-757 flaps are continuous from the fuselage to the ailerons, a design that is believed to be more conducive to uniform development of the wake vortex.

More importantly, however, the high core velocity (within the small core radius) is not considered the primary factor in defining the risk associated with encountering the vortex. Researchers and engineers generally believe that the vortex

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[8] A vortex, a mass of rotating air, consists of a core and a flow field about the core. Lift is created by a pressure differential between the upper and lower surface of the wing. This pressure differential results in a rollup of the airflow aft of the wing, thus creating a vortex. The tangential velocities of the core are proportional to the distance from the center of the core whereas the tangential velocities in the flow field are generally inversely proportional to the square of the distance from the core.

[9] National Oceanic and Atmospheric Administration Technical Memorandum ERL ARL-199, January 1993.

circulation[10] is a more significant factor in the risk of a wake vortex encounter. The circulation theory has been verified and accepted for many years. The *initial strength* of a vortex can be accurately calculated and the fly-by test results have shown that the circulation of the B-757's wake is typical for its weight. The B-757's circulation was greater than that of a B-727 and less than that of a B-767. In addition, the data to date suggest that the longevity of the B-757 vortices is consistent with its wing span.

The January 1993 NOAA report did not recommend an increase in the separation distances behind the B-757, citing insufficient testing to determine the persistence of a B-757 vortex. The report did recommend additional testing to determine the persistence of and the effects of atmospheric conditions on B-757 vortices. The Safety Board concurs in this recommendation. However, the Board also believes, as discussed in more detail, that the accident at Billings, Montana, provides sufficient evidence to warrant increasing the separation distance behind the B-757.

The Safety Board is concerned that the design of future airplanes could result in wake vortices that are unusually strong or persistent for the weight of the airplane. Flight testing would provide data about the vortex decay, transport, residual strength, effects of atmospheric conditions, and unusual or unique characteristics of the airplane's vortex. Accordingly, the Board believes that the FAA should require manufacturers of turbojet, transport category airplanes to determine, by flight test or other suitable means, the characteristics of the airplanes' wake vortices during certification.

Until the FAA has developed the knowledge and systems that will permit a significant reduction in the probability of wake vortex encounters, there will be a need to visually determine adequate separation distances. Further, the five vortex encounters described earlier and data on wake vortex encounters from the Civil Aviation Authority of Great Britain (CAA) demonstrate the need to increase the IFR separation distances for small and large airplanes on approach and in-trail behind the B-757 and other airplanes of similar weight if they are introduced into service. The accident at Billings and the incident at Orlando show that an encounter with a B-757 vortex at 3 nm can be dangerous to most large airplanes. In addition, greater ATC separation standards may have reduced or prevented the excessive closures noted in the other three encounters.

The FAA requires less radar separation for wake vortex considerations for IFR airplanes under positive air traffic control than that recommended by the International Civil Aviation Organization (ICAO) and required by the CAA. A Citation or Westwind following an airplane such as a B-757 would require a 5-nm

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[10] Circulation is a measure of the angular momentum of the air in the flow field and defines the strength of a vortex. The size and strength of the flow field determine the risk of upset posed to a following airplane.

separation based on ICAO recommendations and a 6-nm separation based on CAA standards, rather than the 3-nm separation required by the FAA.

One method to achieve increased separation behind a B-757 would be to reclassify the B-757 as a heavy airplane.[11] Large airplanes would benefit from a 5-nm separation and small airplanes would benefit from a 6-nm separation when executing an instrument approach in-trail behind a B-757. However, the reclassification would reduce the required radar separation of a B-757 in-trail behind a B-747 (maximum gross weight of 820,000 pounds) from 5 nm to 4 nm, increasing the risk of a wake vortex upset for the B-757. The FAA and Boeing have expressed concern about increasing the risk of a wake vortex encounter if a B-757 followed a heavy airplane more closely.

The characteristics of certain airplane pairs were examined to determine the relative risks of upset by wake vortex encounters. The relative risk of wake vortex upsets is a function of the strength of a vortex generated by the leading airplane and the roll moment inertia of the trailing airplane. The vortex strength is generally defined as a function of weight divided by velocity and span. The roll moments of inertia are generally proportional to the weight of the airplane.[12]

Safety Board staff used the maximum landing weights to represent the roll inertia of B-757s and Citations. The vortex strengths of B-747s and B-757s were calculated also using maximum landing weights. The combination of the B-747 vortex strength and the B-757 landing weight was compared to the combination of the B-757 vortex strength and the Citation landing weight. The comparisons show that, at equal separation distances, the risk of loss of control when a Citation encounters the wake vortex of an airplane similar in weight to a B-757 is 8 times greater than the risk associated with a B-757 encountering the wake vortex of a B-747. In practice, however, the B-757/B-747 pair would be separated by 4 nm if both were classified as heavy airplanes, thus lessening the risk for that pair (because 3 nm was used in the risk calculations). Therefore, the relative risk of the two pairs is greater than a factor of 8. In addition, the determination of the relative risk does not reflect the CAA data, which suggest that the wake vortex of a B-757 may last longer than would be expected for its weight. Clearly, therefore, if the risk associated with reclassifying the B-757 as a heavy category airplane is unacceptable, the current risk to a Citation at 3 nm behind a B-757 is also unacceptable.

The Safety Board shares the concern of the FAA and Boeing about reclassifying airplanes such as the B-757 as heavy airplanes. The Safety Board believes it would be preferrable to maintain the current separation distance of 5 nm when such

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[11] Canada has reclassified the B-757 as a heavy airplane when it is the leading airplane.

[12] Roskam, Jan. 1982. *Airplane flight dynamics and automatic flight controls.* Ottawa, KS: Roskam Aviation and Engineering Corporation. (p. 19).

airplanes are following a heavy airplane and to increase the separation distances for other airplanes when they are following a B-757 or other airplanes of similar weight. The accident in Billings, Montana, for example, clearly demonstrates that lighter weight airplanes in the large airplane category require a separation distance greater than 3 nm when following a B-757. Further, the CAA wake vortex incident data raise concern about airplanes of the size of B-737s following only 3 nm behind airplanes of the size of the B-757. Accordingly, the Board believes that the FAA should immediately establish the following interim wake vortex separation requirements for IFR airplanes following a Boeing 757 and other airplanes of similar weight: 4 nm for airplanes such as the B-737, MD-80, and DC-9; 5 nm for airplanes such as the Westwind or Citation; and 6 nm for small airplanes. The current separation requirement of 5 nm when a B-757 or other airplane of a similar weight is following a heavy category airplane should be maintained.

The relative risk comparisons also indicate that the lighter weight airplanes in the large airplane category are at high risk of upset from the vortices generated from airplanes in the heavy category. Consequently, the Safety Board is concerned that the current separation requirements for IFR airplanes such as the Westwind and Citation when following heavy category airplanes are also inadequate.

The most significant problem related to establishing adequate separation standards is the great range of weights (12,500 to 300,000 pounds) in the large airplane category. Because of the large weight differences between the high and low end of the large airplane category, lighter weight airplanes are at high risk of upset from the vortices generated by the heavier weight airplanes. One possible means to minimize the risk of wake vortex encounters is simply to divide the large airplane category into two separate categories (for example, 12,500 to 150,000 pounds and 150,000 to 300,000 pounds), accompanied with increased separations between the newly created categories. However, a preferrable approach would be to create four weight categories in which the ratios of the high and low weights in each category would be similar. For example: heavy (greater than 300,000 pounds), large (between 100,000 and 300,000 pounds), medium (between 30,000 and 100,000 pounds), and small (less than 30,000 pounds). The maximum ratio of weights within each category is about 3.

Appropriate separation distances, based on such a revised weight classification scheme, consistent with the separation distances discussed above, could be the following: for airplanes following a heavy category airplane, the separation distance should be 4 nm (heavy), 5 nm (large), 6 nm (medium), and 7 nm (small). For airplanes following a large category airplane, the separation distances should be 4 nm (large), 5 nm (medium), and 6 nm (small). Current data suggest that a separation distance of 3 nm may be adequate for a medium category airplane following another medium category airplane and for all airplanes following a small airplane. Such an approach would provide more separation because of the increased number of categories and would also reduce the weight disparity of the high and low weights within each category. Therefore, the Safety Board believes that the FAA should revise the airplane weight classification scheme to reduce the weight disparity of high and low weights within each category and to establish separation distances between the various weight categories, consistent with the separation distances discussed above (for airplanes trailing airplanes such as the B-757).

Air Traffic Control Procedures Related to Visual Approaches and VFR Operations Behind Heavier Airplanes.—The Safety Board believes that one common element to the five wake vortex encounters described earlier is that a combination of ATC procedures and pilot actions resulted in separation distances that were too small for the airplane trailing behind a B-757 while on a visual approach to landing. Currently, controllers are required to ensure that airplanes have the proper radar separation prior to the issuance of a visual approach clearance. However, the incident at Denver and the accident at Santa Ana illustrate that controllers sometimes issue visual approach clearances when the separation distance and closure rate preclude the pilot from maintaining a safe separation distance without excessive maneuvering. During peak traffic periods, controllers rely on the use of visual approaches to increase traffic capacity and to reduce delays. Pilots may try to accommodate the controller by accepting a visual approach even though they may be unable to maintain adequate separation from the preceding traffic without excessive maneuvering, excessive reconfiguration of the airplanes, or drastic reduction of their airspeed. When this situation occurs, a compression effect can be created, increasing the exposure of each successive arrival to a wake turbulence encounter.

The Safety Board believes that the FAA should amend handbook 7110.65H, Air Traffic Control, to prohibit controllers from issuing a visual approach clearance to an IFR airplane operating behind a heavier airplane (in the large or heavy airplane category) until the controller has determined that the in-trail airplane should not have to execute S-turns, make abrupt configuration changes, or make excessive speed changes while maintaining a separation distance that would be required for IFR approaches. If the airplane is in-trail or on a converging course at the time the visual clearance is issued, closure rate should be consistent with the required separation distance. That is, if the separation distance is slightly greater than the required separation distance, the closure rate should be minimal. However, if the separation distance is large, a greater closure rate may be tolerated. The controller should set up the in-trail situation in a manner in which both airplanes can continue the approach in a reasonable manner.

In addition, although controllers receive initial training in these areas, the Safety Board believes that controllers should be provided annual refresher training related to wake turbulence separation and advisory criteria. The training should emphasize the need for controllers to avoid using phrases or terminology that would encourage pilots of VFR or IFR airplanes to reduce separation to less than that required during IFR operation, thereby increasing the chance for a wake turbulence encounter when operating behind a turbojet airplane.[13]

The Safety Board is especially concerned that the GENOT and pilot bulletin issued on December 22, 1993, by the FAA are not likely to be effective in reducing wake turbulence encounters of pilots who accept a visual approach clearance or who follow closely behind a B-757 while on approach to the airport. The GENOT and pilot bulletin, in essence, reiterate past practices. The only change, albeit a good one, is the requirement that wake turbulence cautionary advisories be issued to airplanes following a B-757. Pilots are not provided any additional guidance on how to adhere to the procedures defined in the AIM. Specifically, pilots are still not provided sufficient information to determine that adequate separation distances are being maintained or to determine that their flight path remains above the flight path of the preceding airplane.

Knowledge of the manufacturer and model would help the pilot determine a safe separation distance. For example, in the Salt Lake City and Santa Ana accidents, the pilots knew they would be operating behind a turbojet airplane. The controller, in each situation, had ample opportunity to advise the pilot, specifically, that he would be operating behind a B-757. In addition, a pilot, if provided with a wake turbulence cautionary advisory and other information relevant to the avoidance of wake turbulence, such as separation distance and the existence of an overtaking situation, would be better able to maintain an adequate separation distance. Thus, the Safety Board believes that controllers should be required to provide this information, as a minimum, to pilots prior to allowing visual operations behind or in-trail of heavier, turbojet airplanes. Several of the 46 accidents and incidents from 1983 to 1993 that resulted from probable encounters with wake vortices occurred during phases of operation other than the approach phase. Had the pilots involved in these accidents and incidents known the manufacturer and model of the other aircraft, they might have been able to maintain adequate separation distances. Therefore, the Safety Board believes that the FAA should amend handbook 7110.65H, Air Traffic Control, to require that controllers issue both the manufacturer and model of airplane when issuing information about air carrier traffic.

The Safety Board recognizes that the proposed changes will be an additional burden for air traffic controllers. However, until more reliable systems are in place to predict and detect wake votices, these measures should further reduce the likelihood of wake vortex encounters.

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[13] A review of ATC transcripts from some of the accidents and incidents which resulted from probable encounters with wake vortices revealed terminology used by controllers that would encourage pilots to violate separation requirements, such "keep a tight pattern and follow the large airplane." In one instance, the controller requested a short approach but also cautioned about wake turbulence; in that instance the pilot encountered turbulence at 50 feet and crashed, sustaining serious injuries.

Pilot Knowledge Related to the Avoidance of Wake Vortices.—The accident and incident data suggest that a combination of pilots' lack of understanding of the hazards of wake vortices and the difficulty of knowing the movements of wake vortices are major contributors to wake vortex encounters. A pilot's visual estimate of range is not sufficiently accurate to ensure safe separation. It is especially difficult to estimate separation distances at night. In addition, Safety Board accident and incident data show that student pilots and pilots operating under 14 CFR 91 rules continue to encounter wake vortices at an unacceptable rate. The Safety Board notes that many pilots involved in accidents and incidents had instrument ratings, had been given wake vortex precautions, and yet continued on, either ignoring the caution, or mistakenly believing that they were above the vortex. To help pilots avoid wake vortex encounters, the Board urges the FAA to develop comprehensive training programs related to wake turbulence avoidance and to publish the information in the AIM[14] and other training materials. This information should include techniques for determining relative flight paths and separation distances. The accident at Billings, Montana, for example, clearly demonstrated the need for techniques to help pilots maintain a flight path that is higher than that of the leading airplane. In that accident, the flight path of the Citation was at least 300 feet below that of the B-757.

Further, the information should define the vertical movement of wake vortices in ground effect. In the accident at Salt Lake City, Utah, the Cessna 182 could have been affected by the vortex of the B-757 at any altitude between ground level and 200 feet AGL. Although the Cessna's flight path was above that of the B-757, the pilot did not adequately compensate for the height of the vortex. Knowledge of or training specifically related to the height of wake vortices in ground effect likely would have prompted the Cessna pilot involved in the Salt Lake City accident to remain several hundred feet above the B-757 flight path. However, the Safety Board is not aware of any training related to wake vortex avoidance that is provided to pilots after they initially receive their pilot's license. Consequently, the Safety Board believes that the FAA should require 14 CFR 121 and 14 CFR 135 operators to implement training specifically related to the movement and avoidance of wake vortices and techniques to determine relative flight paths and separation distances. In addition, the FAA should revise the practical test standards for commercial, air transport pilot, and additional type ratings to place emphasis on wake turbulence avoidance.

Finally, the B-757 has the capability to fly steeper approaches at slower speeds than most other turbojet transport category airplanes at similar weights. The steeper approaches may be conducted for fuel conservation, noise abatement policies, or simply because the performance of the B-757 allows such approaches. As a result,

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[14] The Airman's Information Manual provides information on wake vortices and instructs pilots to maintain a flight path that is higher than that of the leading airplane. The manual, however, does not provide guidance on how to avoid wake vortices or to maintain the proper flight path.

smaller airplanes, while conducting a normal approach, may be faster and on lower flight paths than a B-757, thus increasing the risk of an encounter with the vortex of the B-757. The Safety Board believes that the FAA should establish air traffic control and operational procedures for the B-757 and other heavier large category airplanes or heavy category airplanes that would result in approaches being conducted in accordance with flight path guidance, when available, or on a standard flight path angle of about 3° when such airplanes are established on course to the runway and other airplanes are in-trail. In addition, the FAA should inform operators of the B-757 and other heavier large category airplanes or heavy category airplanes to instruct pilots of the importance (because of the potential for a strong wake) on approach to landing of maintaining a flight path in accordance with guidance, when available, or on a standard flight path angle of about 3°.

Use of Traffic Collision and Avoidance Systems.—As discussed above, the investigations show that pilots typically do not possess the skills to accurately determine the flight paths of airplanes they are following nor can they accurately estimate the distance to those airplanes. The Safety Board believes that training can improve those skills but cannot eliminate the problem. One possible remedy would be to develop technology to help the pilots determine their position relative to a preceding airplane. Currently, ground-based radar is the only operational tool designed for that purpose. With radar, air traffic controllers can determine separation but cannot easily determine relative flight paths. However, radar separation requires the constant attention of the controller and the controller's communication with the following airplane.

Another possibility would be to use Traffic Collision and Avoidance Systems (TCAS) to provide range information to a pilot following another airplane. Although TCAS was designed only for warning of pending collisions, certain models provide position data of other airplanes. The Safety Board understands that some pilots are currently using the range information provided by TCAS to corroborate range information provided by ATC. In addition, the FAA and some airlines are currently evaluating the feasibility of using TCAS to provide separation information over the Atlantic Ocean when radar coverage is not available. According to the FAA, TCAS manufacturers have determined that the systems are sufficiently accurate for use over the Atlantic when the range is within 10 to 15 miles.

However, various concerns have been raised about the use of TCAS for separation during a visual operation in the terminal environment. Among these concerns are: that TCAS was not designed to provide separation information; the pilot's attention may be diverted into the cockpit; the pilot will have more tasks to perform; the display of some TCAS systems are not adequate for use as a separation aid; and the systems have had problems with reliability and false alarms. Also, the smaller general aviation and corporate airplanes that would benefit the most from accurate range information are less likely to have TCAS installed.

TCAS II is required to be installed on Part 121 airplanes, and TCAS I will be required to be installed on Part 135 airplanes by February 1995, although the FAA estimates that the compliance date will be extended by 1 or 2 years. Currently, more than 1,000 corporate airplanes have TCAS II installed. TCAS is now being installed during the manufacture of some corporate airplanes such as the Grumman Gulfstream IV and the Cessna Citation.

The Safety Board believes that TCAS may have the potential of providing useful range information to the pilot who has accepted a visual approach clearance while in trail behind another airplane. Therefore, the Safety Board believes that the FAA, in conjunction with industry, should determine whether TCAS is appropriate for providing pilots with the separation distance to the preceding airplane during visual landing approaches. If appropriate procedures can be developed, the use of TCAS for establishing safe separation should be encouraged for the pilot of airplanes so equipped.

Research on Wake Vortex Detection and Prediction.—The National Aeronautics and Space Administration (NASA), in conjunction with the FAA, is conducting an aggressive wake vortex research program related to the Terminal Area Productivity Program. According to the director of the NASA program, the purpose of the program is to increase airport capacity by accurately predicting safe separation distances using real-time data of atmospheric conditions and data specific to the airplane model. NASA envisions that the system would be backed up by real-time monitoring of wake vortex movements. The structure of the program is to parallel the highly successful windshear research program conducted by NASA several years ago. The multidisciplined program will address training, risk characterization (of airplane pairs), defining atmospheric effects of wake transport and decay, and airborne or ground-based wake vortex detection systems. Once the positions of wake vortices can be accurately predicted and detected, NASA research reportedly will focus on developing systems for controllers that will enable airplanes to be safely spaced at smaller separation distances.

NASA has had recent success using a ground-based LIDAR radar to track wake vortices at Stapleton International Airport; NASA plans to continue the project, testing LIDAR radar at Memphis this summer. In addition, NASA plans to install LIDAR radar on its B-737 to study the feasibility of using the radar for airborne detection of wake vortices. A highly instrumented OV-10,[15] with variable roll inertia, will be flown in the wake of other airplanes. NASA has conducted wind tunnel tests using a model to create wake vortices and used another remote control model to fly in the test wake. NASA plans additional tests in the NASA Ames 80-foot by 120-foot wind tunnel, using a large size B-747 wind tunnel model. The Safety Board is encouraged that new technology being developed may find application in future

[15] The Rockwell OV-10 is a twin-engine turboprop airplane with a 40-foot wing span and a 9,900-pound gross weight.

airborne and ground-based systems to monitor wake vortex movements and believes that the FAA should continue funding research in these areas.

Data on Wake Vortex Encounters.—Data are not available to analyze the wake vortex incident history in the United States because the FAA does not require pilots to report wake vortex encounters. The only existing U.S. data on wake vortex encounters of which the Safety Board is aware are the Board's own accident and incident reports and reports filed through the Aviation Safety Reporting System (ASRS). Despite the limitations of the ASRS data,[16] the report narratives provide insight into specific safety issues, such as wake vortex encounters. Although the airplane models are not identified in the ASRS data base, on the basis of ASRS reporting categories, it can be inferred that most pilot reports defining a large (LRG) airplane (150,000 to 300,000 pounds) were referring to a B-757.

Unlike the FAA, the CAA, in 1972, established a voluntary reporting system to gather data on wake vortex encounters. In 1982, using data from the reporting system, the CAA changed from a three-group airplane weight category to a four-group weight category.

The CAA continues to gather data on wake vortex encounters. An analysis of CAA wake vortex incidents reported between 1972 and 1990 found:

> ...the B-747 and B-757 airplanes appear to produce significantly higher incident rates than the other airplanes considered, indicating prima facie that they produce stronger and more persistent vortices than the other aircraft in their respective weight categories....The fact that the B-747 is by far the heaviest in the 'heavy' wake vortex class (maximum take-off weight 371,000 Kg) is a likely explanation for its higher incident rates. However, the cause of the higher B-757 incident rates is uncertain.[17]

The B-737 was cited as being most involved as the following airplane. Of note, the CAA requires a 3-nm separation when a B-737 is following a B-757, and the B-757 is the largest airplane in its category.

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[16] Because all ASRS reports are voluntarily submitted, they cannot be considered a measured random sample of the full population of like events. Moreover, not all pilots, controllers, air carriers, or other participants in the aviation system are equally aware of the ASRS or equally willing to report. Consequently, the data reflect reporting biases.

[17] Proceedings of the Aircraft Wake Vortices Conference, October 29, 1991, DOT/FAA/SD-92/1 1, p.8.2.

The CAA Wake Vortex Reporting Programme was transferred to the Air Traffic Control Evaluation Unit (ATCEU) in 1989.[18] The ATCEU collects data from various parties on each wake vortex encounter and enters the data into the wake vortex data base. The notification usually comes from the affected airplane crew or ATC. Formal procedures for the reporting of wake vortex incidents by ATC are in operation only at London City and Heathrow airports. Additional data are collected from the pilot of the airplane causing the vortices, the Meteorological Office, London Air Traffic Control Center (for recorded radar data provided to ATCEU by data link), and from the airlines (flight data recorder data). One airline has agreed to extract FDR data for all reported wake vortex incidents. The data are analyzed to determine if the cause of the reported incident is, in fact, an encounter with a wake vortex. A total of 86 incidents were reported in 1990, and 87 incidents were reported in 1991.[19]

The Safety Board believes that the FAA should also require reporting of wake vortex encounters and establish a system to collect and analyze pertinent information, such as recorded radar data (including wind and temperature data recorded on many of the newer airplanes), atmospheric data, and operational information, including selected flight data recorder data. The Safety Board acknowledges the difficulty in developing clearly usable definitions and suggests that the CAA program could be an excellent source in developing this reporting system. Because pilots may be reluctant to report wake vortex encounters as a result of concerns of enforcement actions, the FAA will need to address the issue of enforcement when developing the reporting procedures.

Therefore, as a result of this special investigation, the National Transportation Safety Board recommends that the Federal Aviation Administration:

> Establish the following interim wake vortex separation requirements for instrument flight rules airplanes following a Boeing 757 and other airplanes of similar weight: 4 nautical miles (nm) for airplanes such as the B-737, MD-80, and DC-9; 5 nm for airplanes such as the Westwind and Citation; and 6 nm for small airplanes. Maintain the current separation requirement of 5 nm when a B-757 or other airplane of a similar weight is following a heavy category airplane. (Class I, Urgent Action) (A-94-42)
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> Revise the airplane weight classification scheme to reduce the weight disparity of high and low weights within each category and to establish separation distances between the various weight categories, consistent with the interim separation distances outlined in Safety Recommendation A-94-42. (Class II, Priority Action) (A-94-43)

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[18] National Air Traffic Services. Civil Aviation Authority, ATCEU Memorandum No. 177.

[19] ATCEU Memorandum No. 184.

Establish air traffic control and operational procedures for the Boeing 757 (B-757) and other heavier large category airplanes or heavy category airplanes that would result in approaches being conducted in accordance with flight path guidance, when available, or on a standard flight path angle of about 3° when such airplanes are established on course to the runway and other airplanes are in-trail. (Class II, Priority Action) (A-94-44)

Inform operators of the Boeing 757 (B-757) and other heavier large category airplanes or heavy category airplanes to instruct pilots of the importance (because of the potential for a strong wake) on approach to landing of maintaining a flight path in accordance with guidance, when available, or on a standard flight path angle of about 3°. (Class II, Priority Action) (A-94-45)

Amend FAA Handbook 7110.65H, Air Traffic Control, to prohibit the issuance of a visual approach clearance to an instrument flight rules airplane operating behind a heavier airplane (in the large or heavy airplane category) until the airplane is in-trail and the closure rate is such that the pilot can maintain the minimum IFR separation without excessive maneuvering. (Class II, Priority Action) (A-94-46)

Amend FAA Handbook 7110.65H, Air Traffic Control, to require that instrument flight rules airplanes cleared for a visual approach behind a heavier turbojet airplane be advised of the airplane manufacturer and model, be provided a wake turbulence cautionary advisory, and be provided other information relevant to the avoidance of wake turbulence, such as separation distance and the existence of an overtaking situation. (Class II, Priority Action) (A-94-47)

Amend FAA Handbook 7110.65H, Air Traffic Control, to require that arriving visual flight rules airplanes that have been sequenced for approach behind a heavier turbojet airplane be advised of the airplane manufacturer and model, be provided a wake turbulence cautionary advisory, and be provided other information relevant to the avoidance of wake turbulence, such as separation distance and the existence of an overtaking situation. (Class II, Priority Action) (A-94-48)

Amend FAA Handbook 7110.65H, Air Traffic Control, to require that controllers issue both the manufacturer and model of airplane when issuing information about air carrier traffic. (Class II, Priority Action) (A-94-49)

Develop annual refresher training for air traffic controllers regarding wake turbulence separation and advisory criteria. The training should emphasize the need for controllers to avoid using phrases or terminology that would encourage pilots of visual flight rules or instrument flight rules (IFR) airplanes to reduce separation to less than that required during IFR operation, thereby increasing the chance for a wake turbulence encounter when operating behind a turbojet airplane. (Class II, Priority Action) (A-94-50)

Expand the current guidance in the Airman's Information Manual and develop other training material to help pilots to determine that their flight path remains above the flight path of the leading airplane and that their separation distance remains consistent with that required for instrument flight rules operations. (Class II, Priority Action) (A-94-51)

Expand the information in the Airman's Information Manual and other training material to define the vertical movement of wake vortices in ground effect, such as vortex core height, upper and lower limits of the vortex flow field, and the potential to "bounce" twice as high as the steady state height. (Class II, Priority Action) (A-94-52)

Require 14 CFR 121 and 14 CFR 135 operators to provide training specifically related to the movement and avoidance of wake vortices and techniques to determine relative flight paths and separation distances. (Class II, Priority Action) (A-94-53)

Revise the practical test standards for commercial, air transport pilot, and additional type ratings to place emphasis on wake turbulence avoidance. (Class II, Priority Action) (A-94-54)

Conduct additional tests of the Boeing 757 to determine the persistence and strength of its wake vortex and the effects of atmospheric conditions on B-757 vortices. (Class II, Priority Action) (A-94-55)

Require manufacturers of turbojet, transport category airplanes to determine, by flight test or other suitable means, the characteristics of the airplanes' wake vortices during certification. (Class III, Longer Term Action) (A-94-56)

Require reporting of wake vortex encounters and establish a system to collect and analyze pertinent information, such as recorded radar data, atmospheric data, and operational information, including selected flight data recorder data. (Class III, Longer Term Action) (A-94-57)

Continue to sponsor research and development projects that may lead to technological or procedural solutions to reduce the hazards posed by wake vortices. (Class III, Longer Term Action) (A-94-58)

Determine if the Traffic Collision and Avoidance System (TCAS) is appropriate for providing pilots with the separation distance to the preceding airplane during visual approaches to landing. If appropriate, develop procedures to allow the use of TCAS for that purpose. (Class II, *Priority Action*) (A-94-59)

Encourage operators of smaller general aviation and corporate airplanes to install and use the Traffic Collision and Avoidance System (TCAS), if procedures to allow the use of TCAS to confirm separation distances during visual approaches are developed. (*Class II, Priority Action*) (A-94-60)

Chairman VOGT, Vice Chairman COUGHLIN, and Members LAUBER, HAMMERSCHMIDT, and HALL concurred in these recommendations.

By: Carl W. Vogt
Chairman