NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Washington, D.C. 20594

September 26, 2011

Aircraft Performance Study

A. INCIDENT: DCA11IA047

Location:	Chicago, Illinois
Date:	April 26, 2011
Time:	Approximately 18:33 GMT
Airplane:	Boeing 737-700, registration number N799SW

B. GROUP IDENTIFICATION:

The Vehicle Performance group members were:

Chairman: Marie Moler
National Transportation Safety Board
Washington, DC

Member: A. Tom Stephens
Boeing Commercial Aircraft
Everett, WA

Member: Brian Gleason
Southwest Airlines
Dallas, TX

C. SUMMARY

On April 26, 2011, at about 13:33 Central Daylight Time (CDT), a Boeing 737-7Q8, registration N799SW, operated by Southwest Airlines as Flight 1919, exited the left side near the end of runway 13C after landing at Chicago Midway International Airport, Chicago IL (MDW). The flight was a regularly scheduled passenger flight from the Denver International Airport, operating under the provisions of 14 CFR Part 121. The airplane had minor damage and there were no injuries.

D. DETAILS OF INVESTIGATION

FDR Summary

Flight data recorder (FDR) data were available for the incident aircraft. Greenwich Mean Time (GMT) was recorded by the FDR. Time in this study will be reported in GMT, which was 5 hours ahead of the local CDT. Figure 1 shows the pitch, roll, and heading of the aircraft from one minute prior to touchdown until the aircraft came to a stop. Touchdown is identified by the weight on wheels reading (Figure 5) and the steadying of pitch and roll at 18:33:05 GMT. Before touchdown, the aircraft was experiencing ±5° of roll. The Meteorological Group Chairman Report (Reference 1) states the ASOS 2-minute-average data reported winds at the time of landing as 218° at 12 knots with gusts to 16 knots and at 18:28 the 1-hour precipitation amount was 0.11 inches. Pitch remained at about -1° throughout the landing roll until the aircraft left the pavement. As stated in the incident summary, the aircraft exited the left edge of runway 13C, which is consistent with the aircraft heading.

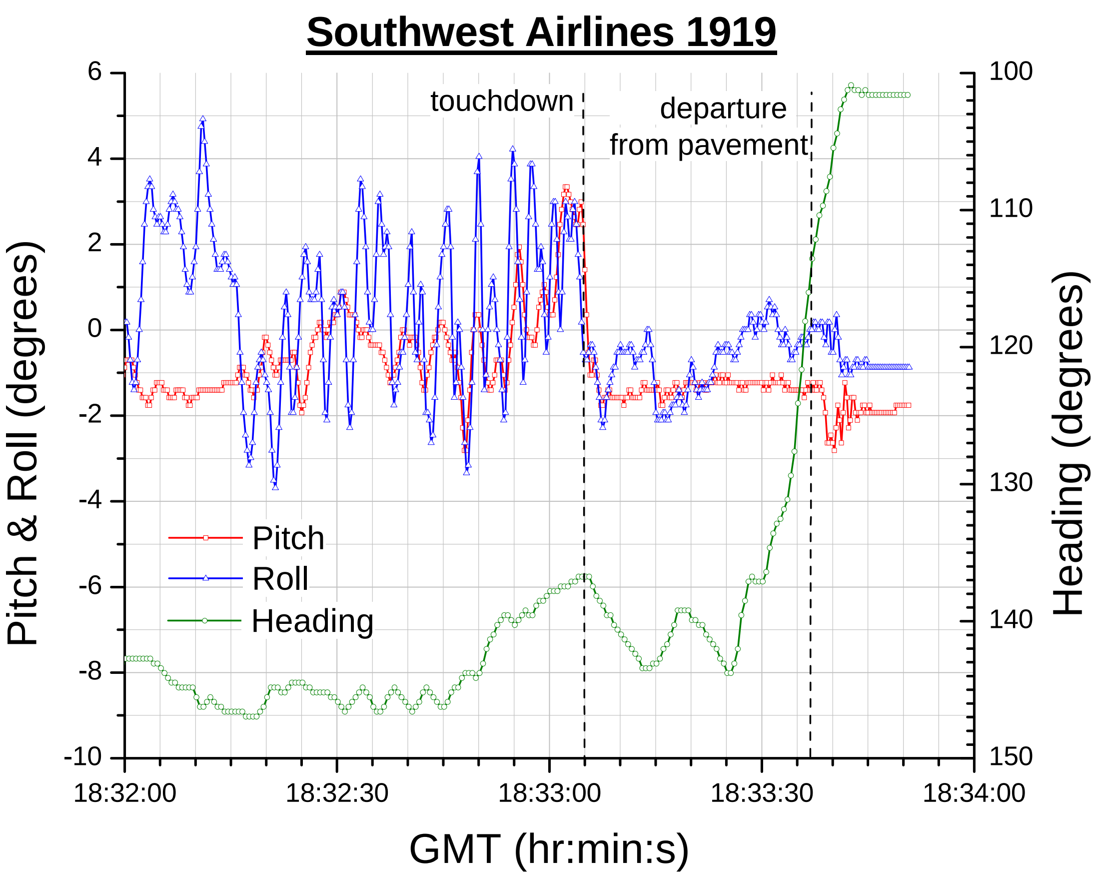

Figure 1. Pitch, Roll, and Heading

The longitudinal, lateral, and vertical load factors are shown in Figure 2. The longitudinal load factor shows greater deceleration late in the rollout, consistent with the time of the thrust reverser and speedbrake deployment that will be discussed later. The negative lateral load factor during the second half of the touchdown roll is also consistent with the aircraft's left turn. Vertical load factors throughout the period reflect the changes in pitch attitude and indicate about 1.4 g's at touchdown. The increase in the amplitude of the oscillations of the normal load factor near the end of the period is consistent with the departure of the airplane from the paved surface.

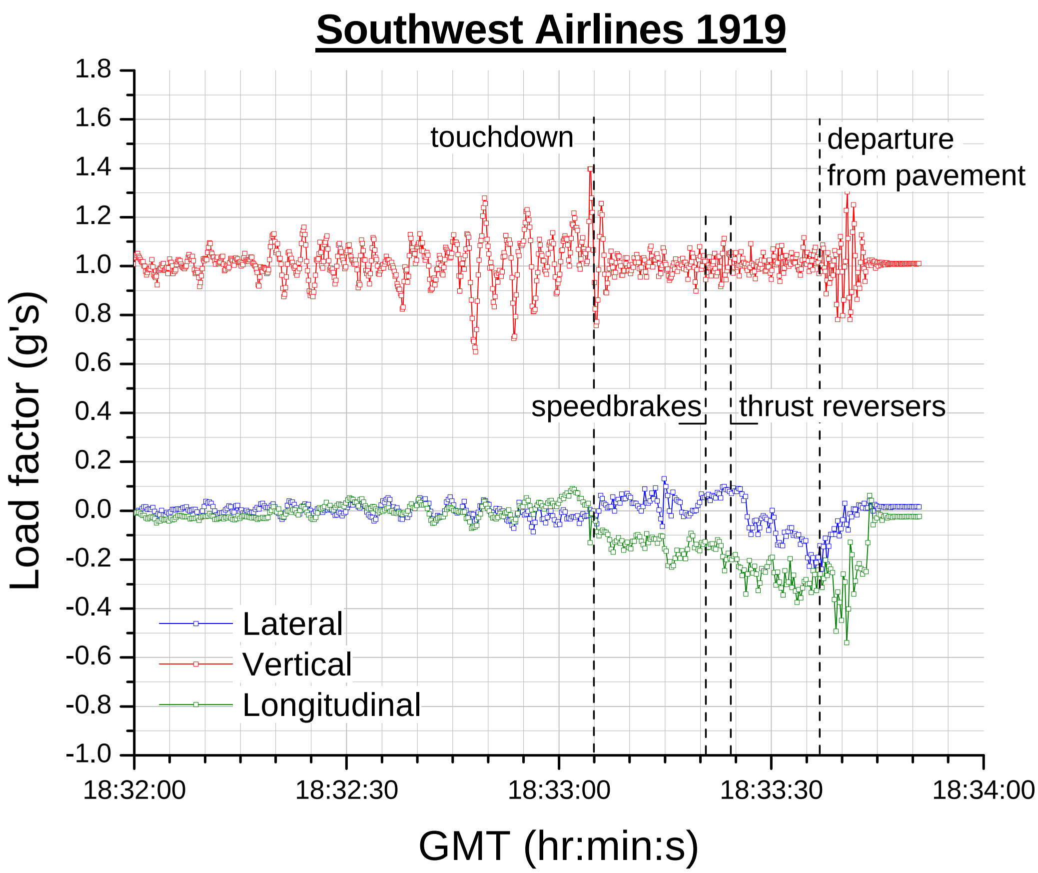

Figure 2. Longitudinal, lateral, and vertical load factors.

Flight Path Integration

The FDR accelerations were integrated to obtain a time history of the position of the aircraft during touchdown and landing. The integration program requires the time histories of the three directional load factors (N_x, N_y, and N_z), the three Euler angles (pitch, yaw, and roll) and their rate of change, ground speed, drift angle, altitude, static air pressure, and static air density. Figure 3 and Figure 4 show the integrated flight path matched to the FDR data.

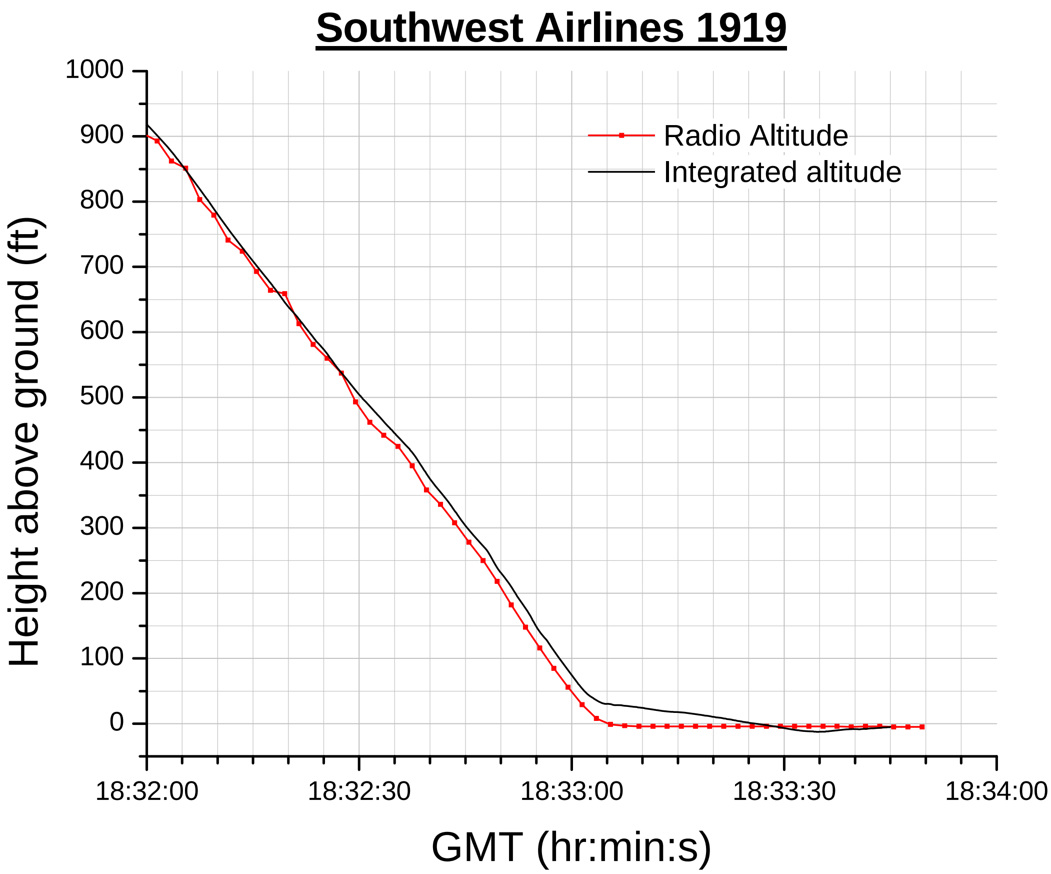

Figure 3. Altitude match.

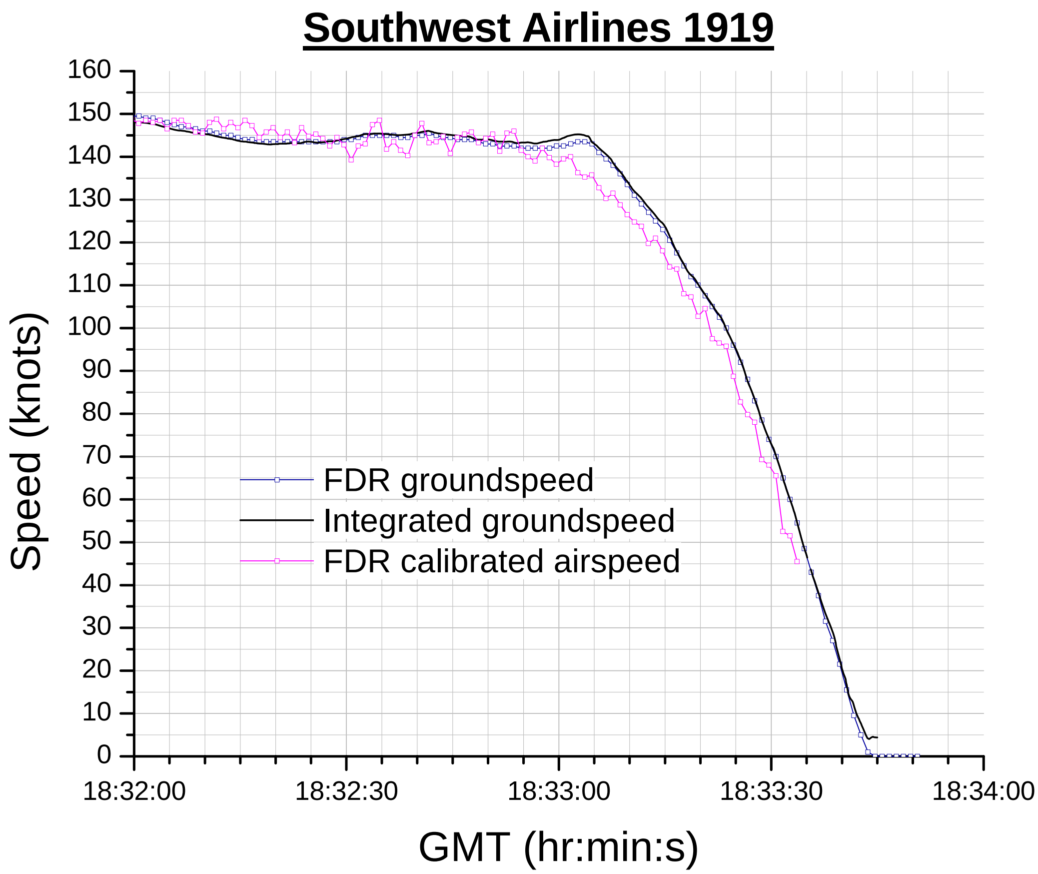

Figure 4. Ground speed match.

Figure 6 shows a profile view of the aircraft's approach and landing. The aircraft's approach glide path was approximately 3 degrees, consistent with the ILS glide slope angle. The aircraft initially touched down at 18:33:05 GMT at an airspeed of 136 knots and a ground speed of 143 knots, shown in Figure 5. Runway 13C is 6059 feet long and 150 feet wide. The aircraft came to rest approximately 180 feet beyond the end of the paved runway overrun at 18:33:44 GMT. Integration of the FDR data shows that the aircraft landed within 500 feet of the runway threshold as shown in Figure 6 and Figure 7. Consequently at touchdown, the aircraft had at least 5500 feet of pavement ahead of it.

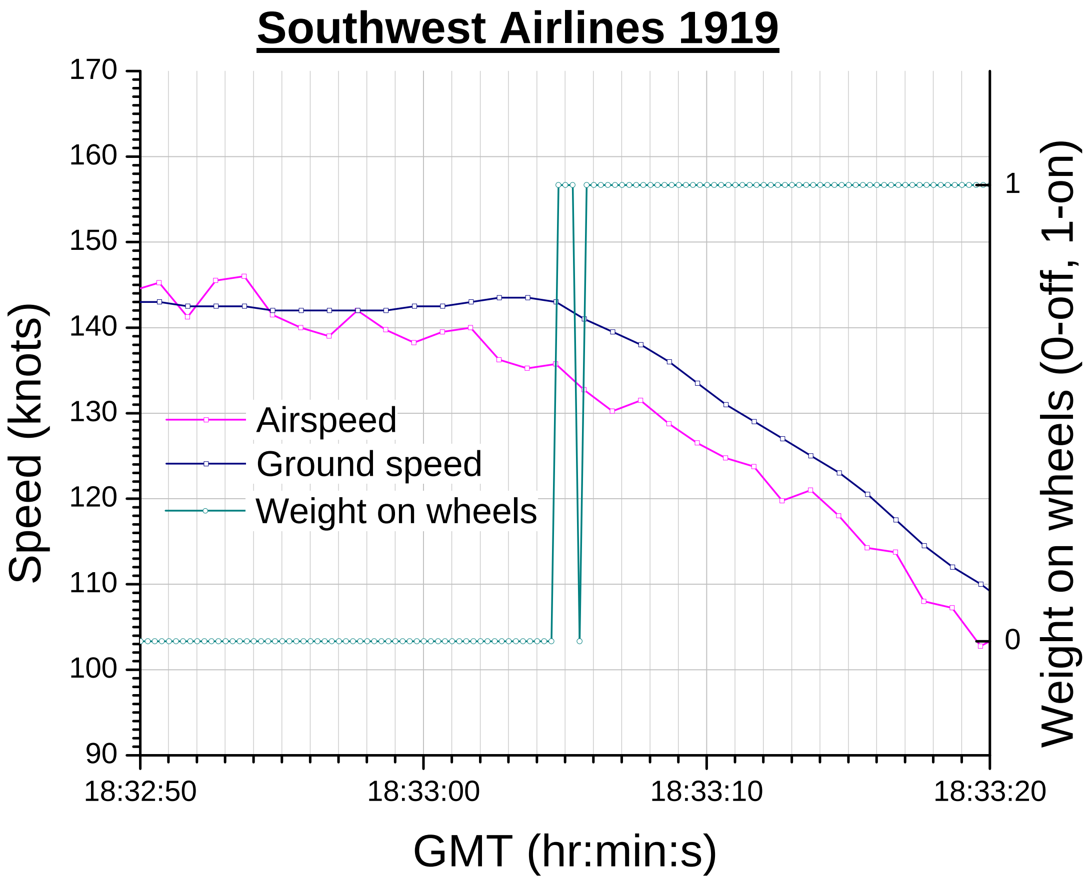

Figure 5. Airspeed and weight on wheels.

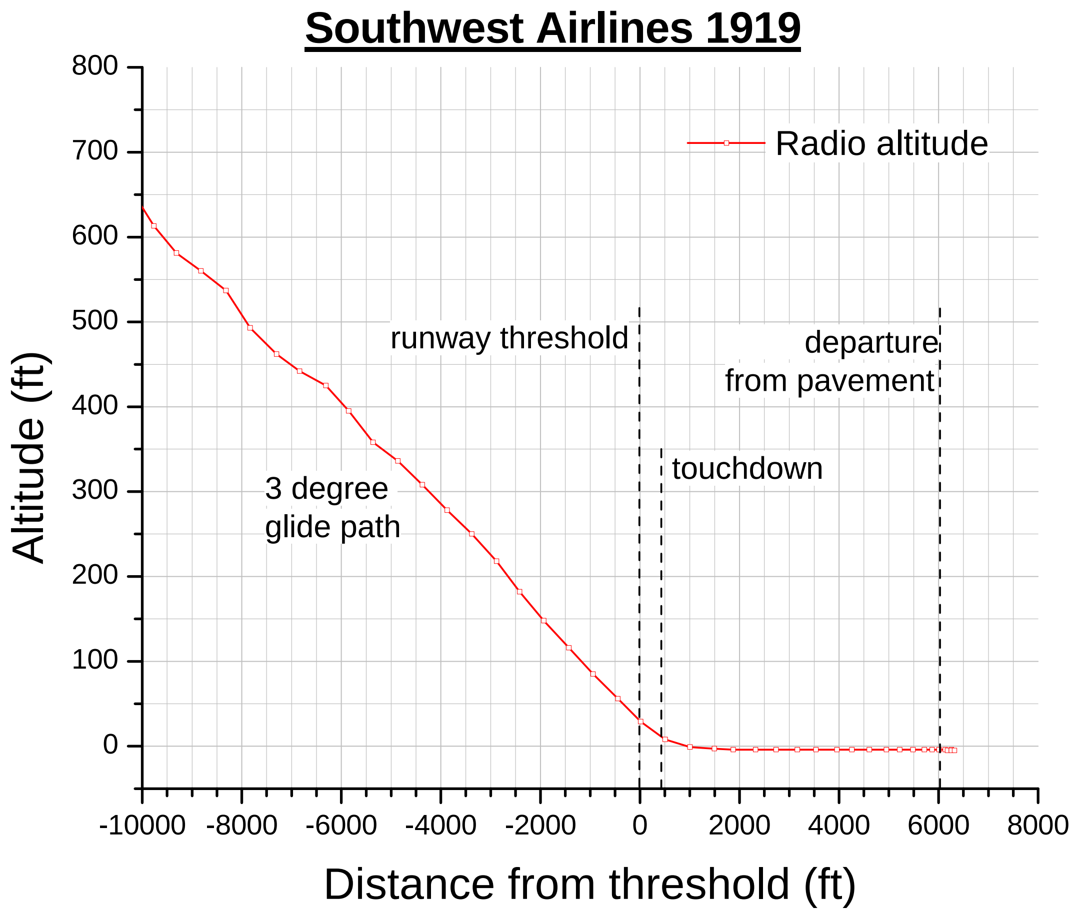

Figure 6. Altitude profile.

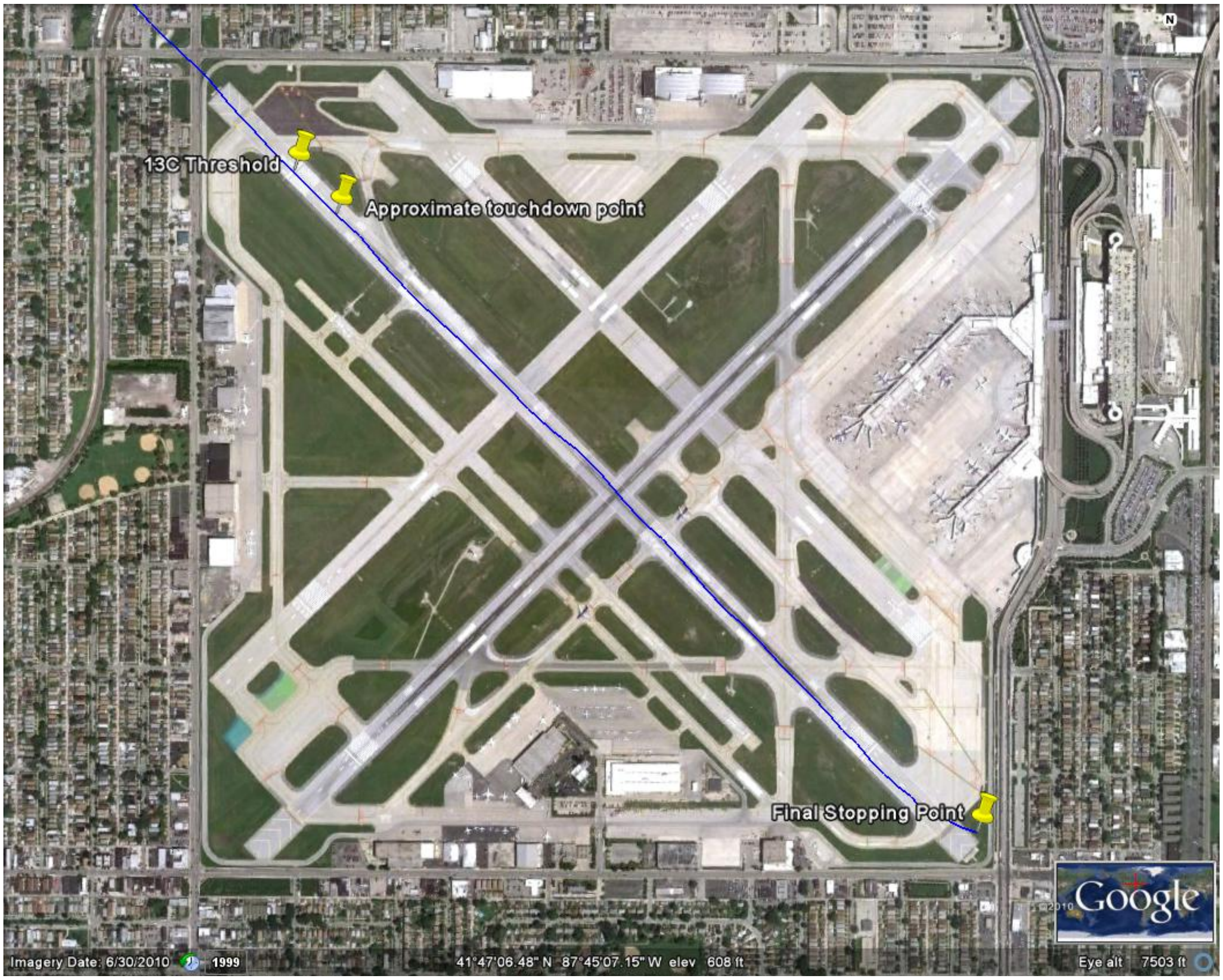

Figure 7. Landing and rollout.

Brakes were engaged upon landing as indicated by the increase in brake pressure shown in Figure 8, but both the thrust reversers and speedbrakes began to deploy 16 seconds after touchdown, as shown in Figure 9. Speedbrakes, when armed prior to landing, deploy automatically upon touchdown and thrust reversers are to be deployed within 2 seconds after touchdown according to Southwest Airlines' Flight Operations Manual as referenced in the Operations Group Chairman Report (Reference 2). The Systems Group Chairman Report (Reference 3) states that15 to 16 seconds after touchdown, the reverse thrust levers were positioned in a way that satisfied the logic to command the speedbrakes and thrust reversers began to deploy. The speedbrake panels reached their fully deployed positions about 2 seconds after the required control logic was satisfied. The thrust reversers required 5 seconds to fully deploy and their effectiveness was further delayed by the time it took for the engine power to increase.[1] Figure 10 indicates where on the runway speedbrakes and thrust reversers were engaged. Speedbrakes began to deploy at 18:33:21 GMT, 16 seconds and 4600 feet past the threshold. Deploying speedbrakes reduces lift and transfers the airplane weight onto the landing

[1] Reference 1 states that the engines had transitioned from flight idle to the lower ground idle and required a longer amount of time to spool back up to the required power for the thrust reverser function.

gear, increasing the effectiveness of the brakes. Thrust reversers began to deploy at 18:33:24 GMT, 19 seconds and 4800 feet past the threshold and the engine speed (N1) for engines 1 and 2 did not reach peak performance until 18:33:34 which is 5800 feet past the threshold.

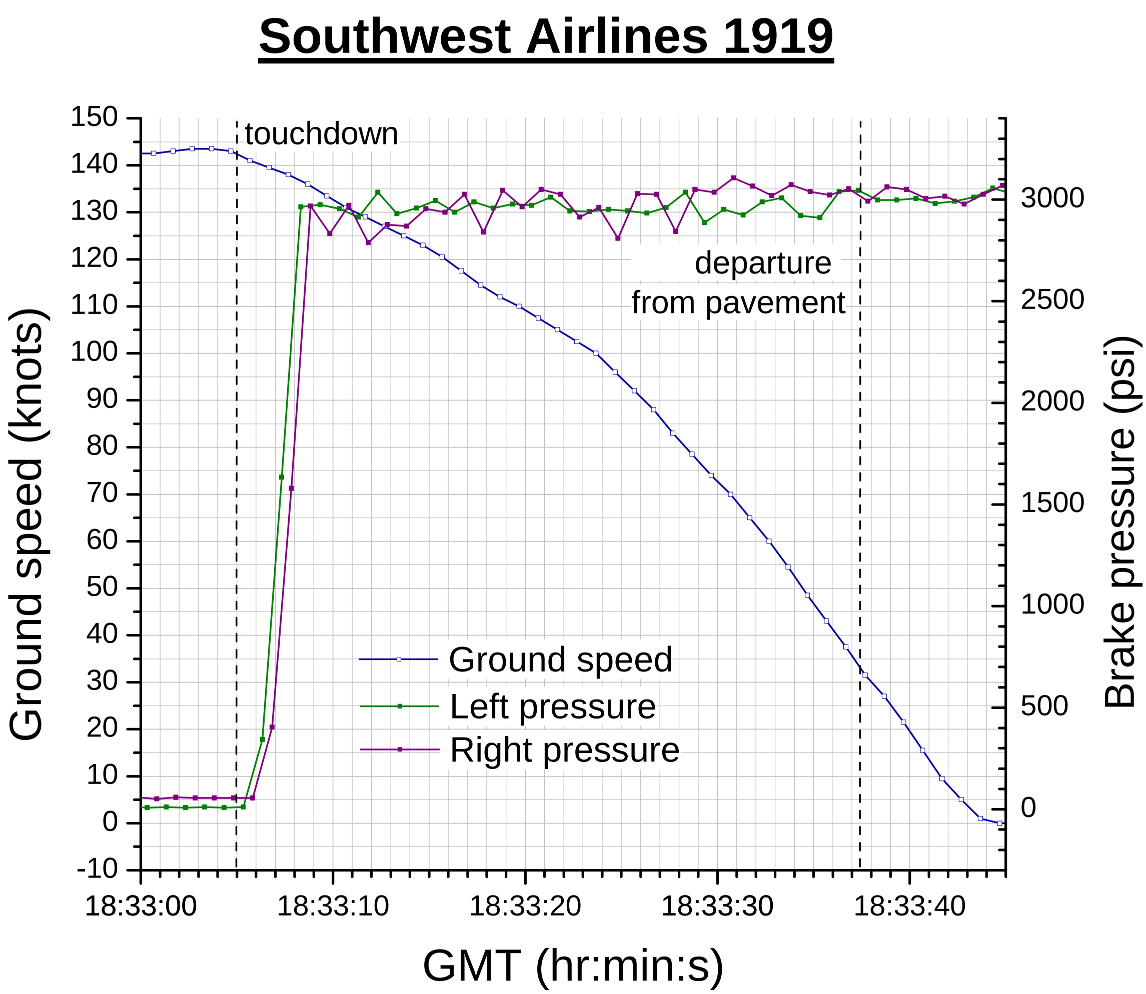

Figure 8. Ground speed and brake pressure versus time.

Figure 9 and Figure 10 display the aircraft ground speed and speedbrake handle position versus time and distance respectively. The ground speed of the aircraft when the thrust reversers were deployed was 92 knots, down from 143 knots groundspeed at touchdown. The engine speed did not reach a maximum until the aircraft had slowed to 60 knots and had less than 300 feet of pavement remaining. Thrust reversers are most effective at higher speeds. In Figure 9 and Figure 10 the aircraft shows greater deceleration (as indicated by the steeper negative slope of the speed and the longitudinal load factor shown in Figure 2) after the speedbrakes and thrust reversers are deployed.

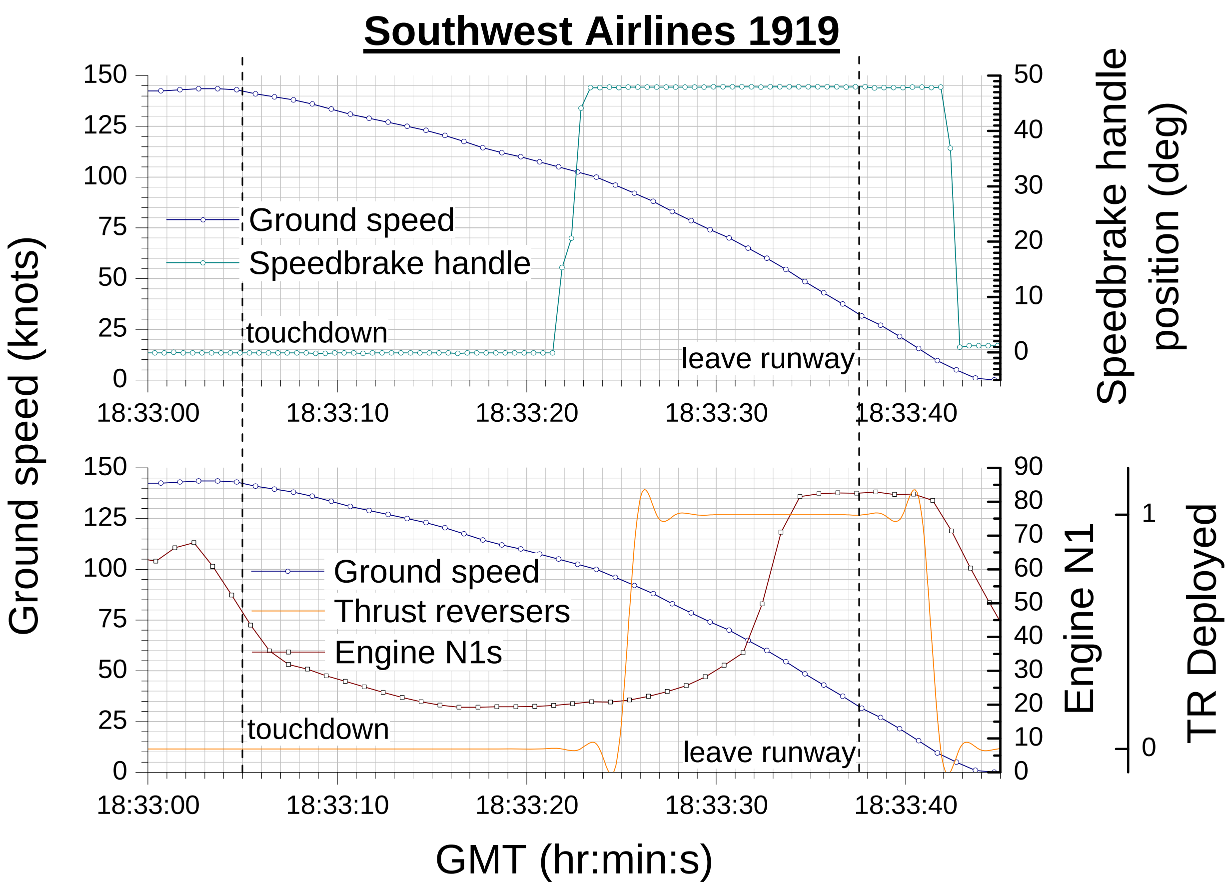

Figure 9. Speed, thrust reversers, and speedbrake handle versus time. Only the right engine N1 is shown for plot clarity; the left engine N1 was similar.

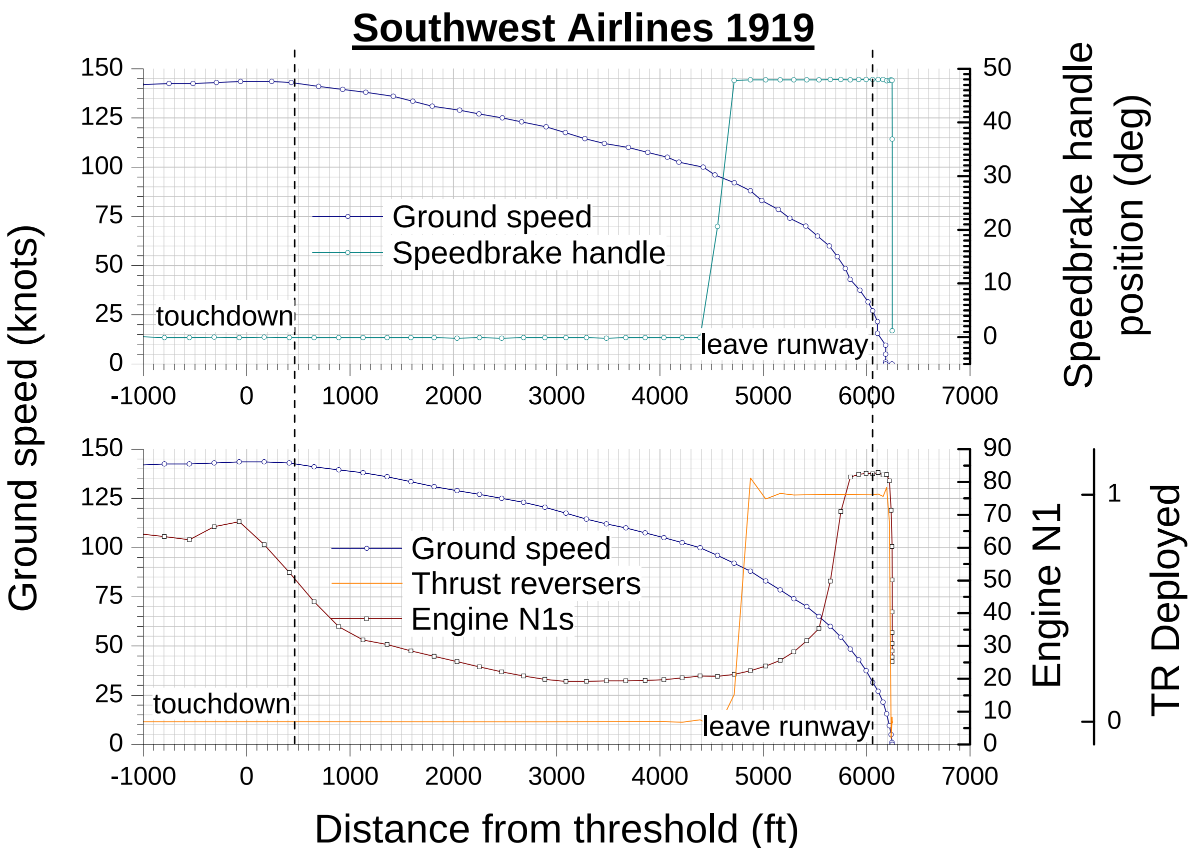

Figure 10. Speed, thrust reversers, and speedbrake handle versus distance. Only the right engine N1 is shown for plot clarity; the left engine N1 was similar.

<u>Boeing Performance Simulation</u>

At the NTSB's request, the Air Safety Investigation group at Boeing completed a series of simulations of the stopping performance using the 737-700 with winglets desktop simulation tool. The simulation uses a six-degree-of-freedom non-linear coefficient buildup model and can be driven using FDR data or a mathematical pilot model. Boeing analyzed the aircraft's performance while on the ground, and initial conditions at touchdown were matched to the incident flight. The simulation was driven with the FDR stabilizer position, column position, control wheel position, brake pressures, speed brake handle, and throttle resolver angles (TRA).

Using the FDR data, Boeing calculated the airplane braking coefficient during the incident, shown by the navy trace at the top plot of Figure 11, which fluctuates between 0 and 0.4. Normal forces, aerodynamic drag, and thrust force are determined using the FDR data and simulation tool and are used to calculate the airplane braking coefficient. The airplane braking coefficient is the ratio of the frictional retarding force on the tires (including rolling friction on the nose gear) to the total weight borne by the main and nose gear tires.[2] The airplane braking coefficient is dependent on runway conditions and the efficiency of the braking system's anti-

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[2] The weight borne by the tires depends on both the total airplane weight and the lift developed by the wings. As lift is reduced, more of the airplane weight is shifted to the tires, thereby increasing the frictional forces on the tires.

skid function. The airplane braking coefficient is a measure of the “slipperiness” of the runway and the anti-skid system effectiveness, and is independent of the use of speedbrakes and thrust reversers.

Another measure of the friction between the tires and the runway is the wheel braking coefficient, which is the ratio of the frictional retarding force on the main gear tires alone to the weight borne by the main gear tires alone. The wheel braking coefficient differs from the airplane braking coefficient in that it does not include the rolling friction on the nose gear or the weight borne by the nose gear. For a given frictional retarding force on the main gear and (relatively small) rolling friction force on the nose gear, the airplane braking coefficient is usually less than the wheel braking coefficient, since the sum of the frictional forces on both the main and nose gear divided by the sum of the weight borne by both the main and nose gear is usually less than the frictional force on the main gear alone divided by the weight borne by the main gear alone. The results of research into runway friction is usually presented in terms of the wheel braking coefficient, but the Boeing simulator study (and this aircraft performance study) present results in terms of the airplane braking coefficient.

To simulate the combination of runway friction and anti-skid system effectiveness that best matched the airplane stopping performance observed during the incident landing, Boeing created a curve defining the wheel braking coefficient as a function of ground speed. Boeing created this curve by taking the NASA Convair 880 Standing Water curve and adding 60% of the difference between the it and the FAR 25.109 Wet Smooth Runway curve (0% corresponds to NASA Convair 880 and 100% corresponds to FAR 25.109 Wet, Smooth). The resulting simulation airplane braking coefficient is representative of the average levels of the airplane braking coefficient calculated from the FDR data, as shown in the top plot of Figure 11. Furthermore, the resulting simulation ground speed agrees with the incident deceleration as shown in the bottom plot of Figure 11. Use of the braking coefficient curve ensures consistency in the simulated runway conditions between the incident and alternative landing scenarios.

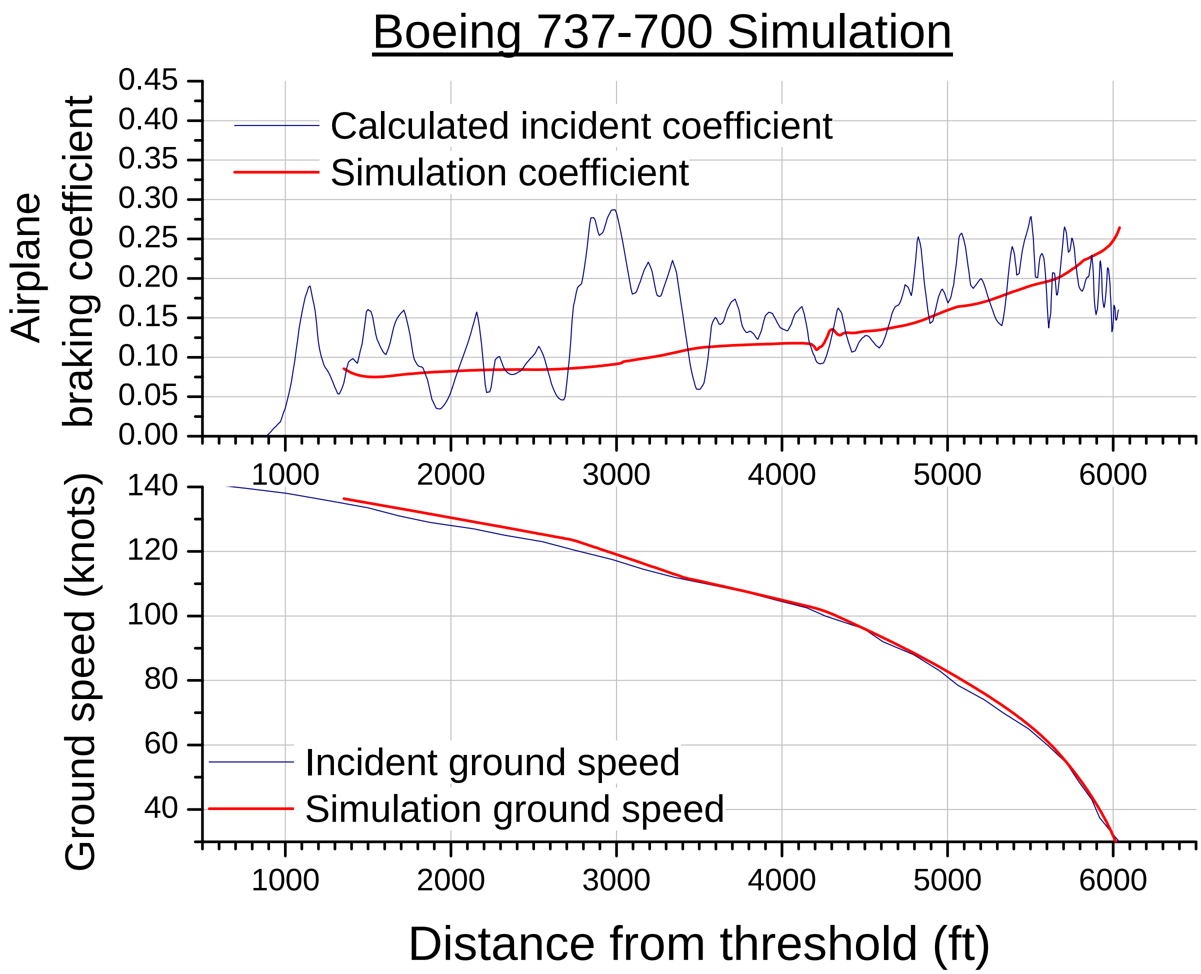

Figure 11. Boeing simulation match of the incident landing.

The coefficient curve was then used to calculate the stopping distance of the aircraft on the runway if speedbrakes and thrust reversers had been deployed upon touchdown per Southwest Airlines' operational procedures. The landing distance results are shown in Figure 12 for the incident landing (speedbrakes and thrust reversers 16 and 19 seconds after touchdown), the aircraft landing with speedbrakes and thrust reversers per procedure, and landing with just speedbrakes per procedure (no thrust reversers at all). The alternative configuration simulations were driven using max autobrake settings and TRAs for maximum reverse (for the case using reverse thrust as well as on-time spoiler deployment). The incident landing simulation was driven with FDR data.

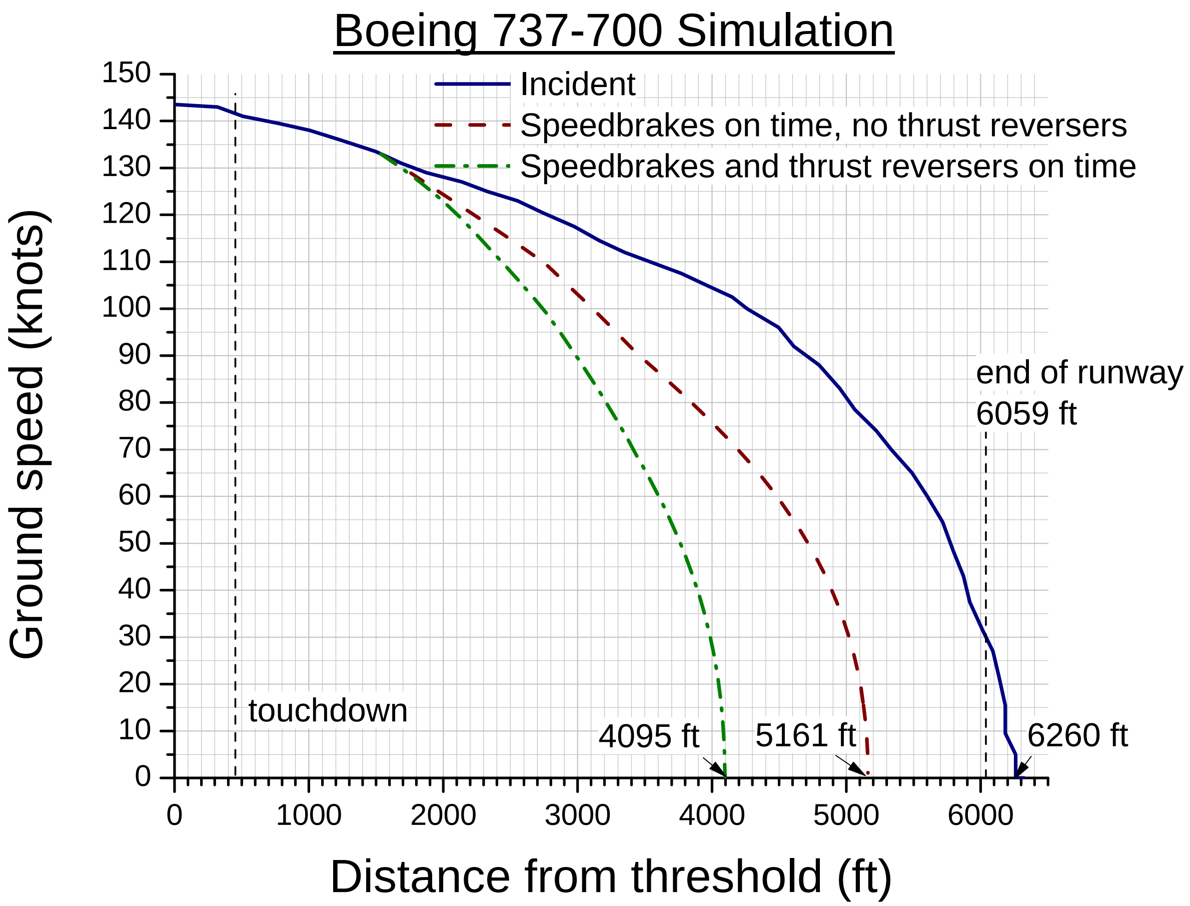

Figure 12. Boeing simulations of alternate landing scenarios.

The incident simulation has the aircraft coming to a stop 201 feet past the end of the runway, which is roughly consistent with the aircraft's path into the grass. If the speedbrakes were applied on time (but with no reverse thrust), the simulation predicts that the aircraft would have stopped 898 feet before the end of the runway and if both speedbrakes and thrust reversers were applied on time the aircraft would have stopped 1964 feet before the end of the runway.

Southwest Airlines Onboard Performance Computer

Southwest Airlines aircraft are equipped with an onboard performance computer (OPC) to determine landing performance. The NTSB used a copy of Southwest Airlines' OPC to determine what stopping distance the crew would have anticipated on approach to landing. For this landing, the crew had entered the information for N799SW, runway 13C at MDW, the reported weather, and reported runway conditions. The input conditions and resulting calculations as known by the crew are shown below in Figure 13.

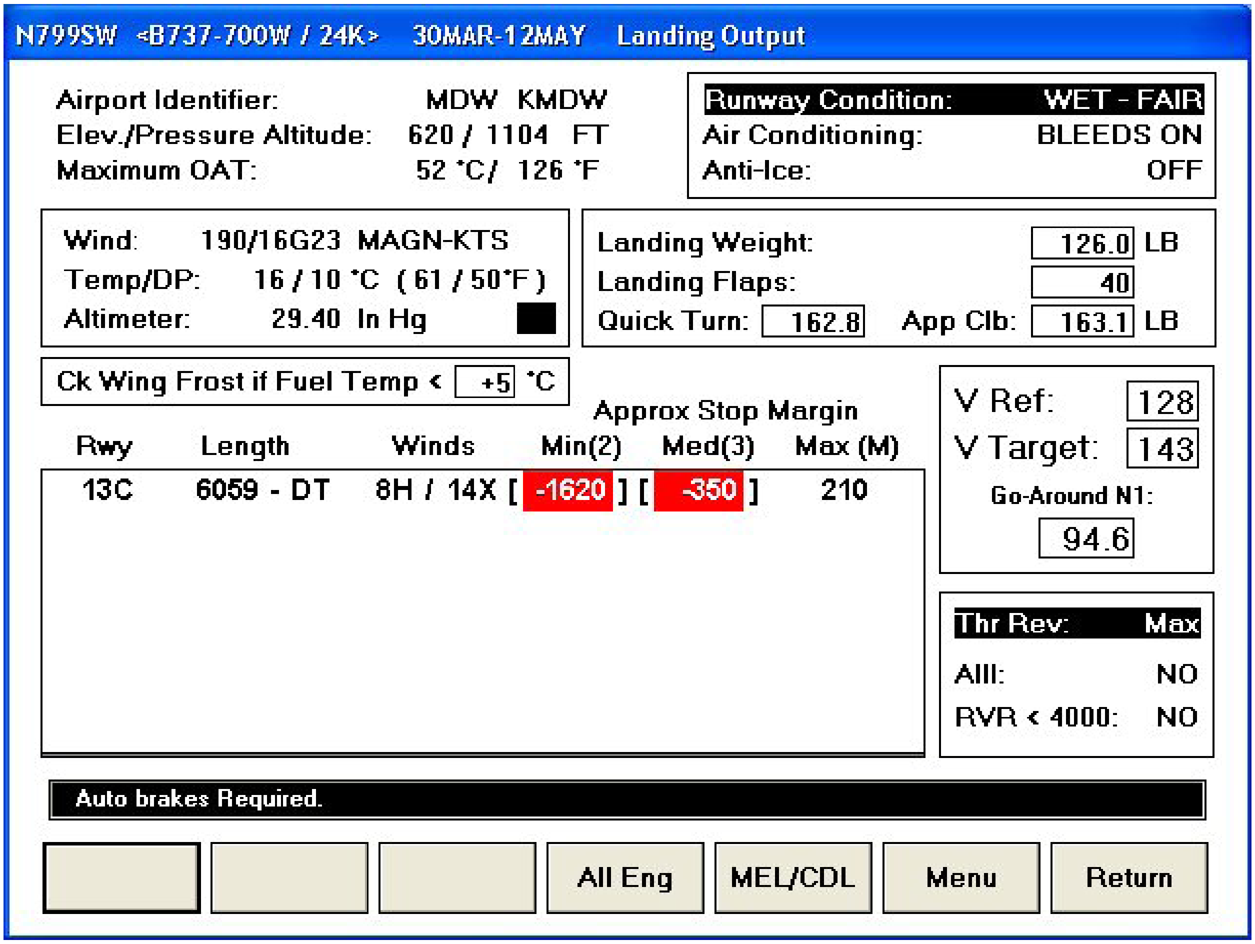

Figure 13. SWA Onboard Performance Computer display for the incident event.

The landing performance results are shown as "Approx Stop Margin" and are calculated using the deceleration rates for auto brakes settings Min(2), Med(3), and MAX(M). Stopping distances are calculated using a reverse thrust level of detent 2, but the policy is that for braking action when runway conditions are less than good (for example, wet-fair, as highlighted in Figure 13) the OPC calls for maximum thrust reversers (lower right of Figure 13, highlighted in black). For the case shown in Figure 13 the aircraft should stop 210 feet before the end of the runway using maximum auto brakes. The OPC assumes touchdown 1500 feet from the runway threshold and adds a 15% margin of safety to the total landing distance. Using these assumptions

$$stopping\ margin = runway\ length - 1.15 \times (air\ distance + ground\ roll\ distance)$$

$$210\ ft = 6059\ ft - 1.15 \times (1500\ ft + ground\ roll\ distance)$$

The actual SWA OPC calculated stopping distance for fair runway conditions is 3586 feet after touchdown. Adding back in the 1500 air distance, the aircraft was expected to stop 5086 feet past the runway threshold, 973 feet before the end of the pavement.

The NTSB also input the weather data at the time of touchdown into the SWA OPC to determine how the landing distance prediction would change. In Figure 14, the winds have been changed to 220º at 12 knots with gusts to 16 knots and the weight of the aircraft is the post-incident reported 124520 lbs (the OPC requires wind direction inputs to be in multiples of 10, e.g., 200, 210, 220).

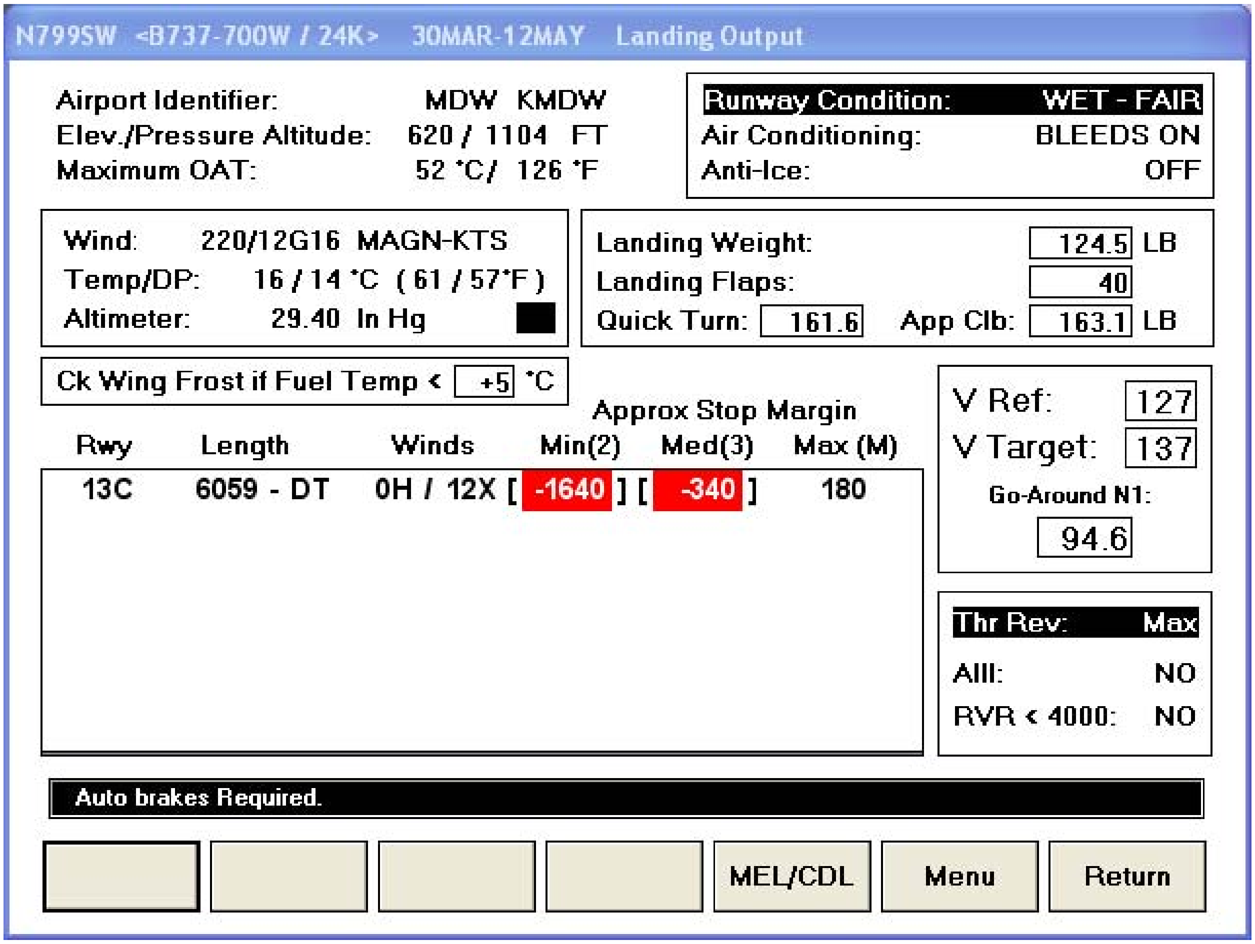

Figure 14. SWA Onboard Performance Computer display using the actual weather and weight at touchdown.

The landing distance has increased slightly due to the 30° change in the wind direction, but the aircraft is still predicted to stop before the end of the runway if maximum braking is used. Using the previous equation and removing the 15% safety margin, the aircraft should have stopped 5112 feet past the runway threshold or 3612 feet after the assumed touchdown location.

The SWA OPC distances, while comparable, do not match the Boeing simulation data due to differences in the airplane braking coefficients and aircraft configuration. The ground roll distances are shown in Table 1, below. The Boeing simulation used a lower airplane braking coefficient which approximated the incident conditions, but a higher thrust reverser setting than the OPC calculations. When thrust reversers and speedbrakes are deployed at touchdown, the Boeing simulation and SWA OPC calculations result in the aircraft stopping 2000 feet earlier.

Table 1. Ground roll distances for SWA 1919, the Boeing simulation, and SWA OPC calculations

	Ground roll distance	Comments
Incident, SWA 1919	5739 feet	Final 180 feet of travel in grass
Boeing simulation: thrust reversers, speed brakes	3625 feet	Maximum reverse thrust
SWA OPC calculation: pre-landing	3586 feet	Detent 2 thrust reversers
SWA OPC calculation: winds at landing	3612 feet	Detent 2 thrust reversers

E. Conclusions

The aircraft came in at a 3 degree slope and touched down at a calibrated airspeed of 136 knots with 5400 feet of runway remaining. The air speed at touchdown was at VREF + 7 knots for that flap setting and gross weight. The thrust reversers and speedbrakes were not deployed according to Southwest Airlines' procedures. Speedbrakes were fully deployed 16 seconds after touchdown and the thrust reversers were deployed 19 seconds after touchdown which resulted in insufficient deceleration during the initial portion of the ground roll for the aircraft to stop before the end of the runway. Simulations by Boeing and calculations using Southwest Airlines onboard performance computer indicate that if the speedbrakes and thrust reversers had been deployed when expected, the airplane would have had sufficient margin to stop on the runway.

Marie C. Moler
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Vehicle Performance Division

F. References

1. Meteorology Group Chairman Factual Report, DCA11IA047, National Transportation Safety Board, July 21, 2011.
2. Operations/Human Performance Group Chairman Factual Report, DCA11IA047, National Transportation Safety Board, July 31, 2011.
3. Systems Group Chairman Factual Report, DCA11IA047, National Transportation Safety Board, July 28, 2011.