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

September 29, 2006

Aircraft Performance Group Study Addendum #2

I. ACCIDENT

NTSB Number:	DCA06MA009
Description:	Runway Overrun
Location:	Chicago Midway Airport, Chicago, Illinois
Date:	December 8, 2005
Time:	1914 CST
Aircraft:	Boeing 737-7H4, N471WN
Operator:	Southwest Airlines Co.

II. GROUP

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1.0 INTRODUCTION

On December 8, 2005, 1914 Central Standard Time, Southwest Airlines (SWA) flight 1248, a Boeing B-737-7H4 registered as N471WN, overran runway 31C at Chicago Midway International Airport (MDW) in Chicago, Illinois, during the landing rollout. The airplane departed the end of the runway, rolled through a blast fence, a perimeter fence, and onto a roadway. The airplane came to a stop after impacting one automobile. Instrument meteorological conditions (IMC) prevailed at the time. The airplane was substantially damaged. The flight was conducted under 14 CFR Part 121 and had departed from the Baltimore/Washington International Thurgood Marshall Airport, Maryland.

The aircraft performance group reconvened in Renton, Washington on May 19, 2006 to review Boeing flight test data used to validate the airplane braking coefficient extraction methodology, discuss parameters to include in a landing distance sensitivity study, and define the matrix of airplane deceleration scenarios and environmental conditions to analyze. The Boeing PSIM engineering simulator, Low Speed Performance System (LSPS), and B737-700W Quick Reference Handbook (QRH) data were used to perform the engineering study. Airplane braking coefficient extraction[1] results for one additional flight test data validation case are included in Section 3.1. Landing distance sensitivity study results are discussed in Section 3.2. Engineering simulation and landing distance performance results for the scenario matrix are presented in Section 3.3.

1.1 Nomenclature

AFM	Airplane Flight Manual, document that shows FAR Part 25 compliance
AFM-DPI	Airplane Flight Manual – Digital Performance Information, 737NG AFM performance data in software form, rather than charts/graphs
BLM	Boeing Landing Module, SCAP module that uses “1st principles” landing performance methodology
EEC	Electronic Engine Controller
FCTM	Flight Crew Training Manual, contains Boeing recommended training and procedures
FPPM	Boeing Flight Planning and Performance Manual
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LSPS	Low Speed Performance System, Boeing engineering software that computes aerodynamic performance using “1st principles” methods
MAC	Mean Aerodynamic Chord
MLW	Maximum Landing Weight
PSI	Pounds per Square Inch
PSIM	Parallel SIMulation system, the Boeing engineering simulator
QRH	Quick Reference Handbook, contains Chapter PI, Performance Inflight
SCAP	Standard Computerized Airplane Performance, an IATA software interface standard for computing airplane performance
SCAP module	SCAP-compliant software module used to compute airplane performance
V_{BRAKE}	Speed at which wheel braking begins
V_{REF}	Reference landing speed f(weight, flap)
737NG	Boeing 737-600/700/800/900 airplane models

[1] See the Aircraft Performance Group Study for a description of the airplane braking coefficient extraction methodology and results for the balance of Boeing flight test data validation cases.

2.0 METHOD

The data sources and methods used in the study are outlined in this section.

2.1 Flight Test Data Validation (Method A)

A detailed description of the time varying airplane braking coefficient extraction method (Method A) is documented in the Aircraft Performance Group Study, Section 2.5, pages 8-11, dated May 26, 2006. Method A was further validated against existing flight test data by computing the airplane braking coefficient time history for a B737-900 flight test airplane landing on a wet, grooved runway. The runway condition, airplane configuration, and calculated airplane braking coefficient for this case are presented in Section 3.1.

2.2 Sensitivity Study

An engineering simulation study was conducted to quantify the sensitivity of calculated landing distance to a known parameter variation. Aircraft initial conditions (weight, center of gravity); configuration (time delay to reverse thrust command); environment (wind, airplane braking coefficient magnitude); and performance (lift coefficient, drag coefficient, peak reverse thrust) parameters were varied one at a time with respect to a reference scenario. Two variations each of these eight parameters resulted in simulation cases 21-28, as defined in Table 2.2. Cases 21 through 28 each contain two subparts to account for the respective effects of the minimum and maximum parameter variation. Case 29 models the effect of reducing thrust to forward idle at 30 knots as opposed to reverse idle at 30 knots, assuming thrust reversers were deployed per Boeing Flight Crew Training Manual (FCTM) normal procedures and the intent was to bring the airplane to a complete stop on the runway.

Reference case 31 models the event landing, case 32 models the event landing with zero wind, and case 54 models the event landing with reverse thrust procedures per the Boeing FCTM, assuming the intent was to bring the airplane to a complete stop on the runway.

Table 2.2: Sensitivity study cases

CASE #	PARAMETER	MINIMUM VARIATION	MAXIMUM VARIATION	UNITS	REFERENCE CASE VALUE	REFERENCE CASE[2]
21	PEAK REVERSE THRUST	-10	10	PERCENT (POUNDS)	8,965	54
22	CENTER OF GRAVITY	-5	5	%MAC	21	31
23	AIRCRAFT[3] WEIGHT	-5,000	5,000	POUNDS	118,240	31
24	AIRPLANE BRAKING COEFFICIENT	-0.02	0.02	NONDIMEN.	0.08	31
25	LIFT COEFFICIENT	-0.1	+0.1	NONDIMEN.	-0.1	31

[2] See Section 2.3 for more detailed reference case definitions.
[3] The modeled weight variation assumed a constant reference case ground speed (i.e., did not account for normal reference speed adjustments).

Table 2.2 (Continued): Sensitivity study cases

CASE #	PARAMETER	MINIMUM VARIATION	MAXIMUM VARIATION	UNITS	REFERENCE CASE VALUE	REFERENCE CASE[4]
26	DRAG COEFFICIENT	-10	+10	PERCENT	0.22	31
27	WIND	-5	+5	KNOTS	0	32
28	THRUST REVERSER COMMAND DELAY	+2	+4	SECONDS	NOMINAL	54
29	THROTTLE SETTING AT 30 KNOTS	-	FORWARD IDLE	NONDIMEN.	NOMINAL	54

2.3 Simulation Scenarios

An engineering simulation study was conducted to calculate the time varying airplane braking coefficient required to decelerate flight 1248 and 4 prior SWA flights; determine an equivalent simulation braking coefficient that would replicate the flight 1248 groundspeed and runway deceleration performance; and quantify the effects of different winds, ground spoiler deployment schedules, and reverse thrust throttle setting and stowage schedules on the flight 1248 stopping performance. In addition, the PSIM engineering simulator results were compared[5] to LSPS and QRH data for a matrix of runway conditions and wheel braking schedules.

A B737-700W airplane equipped with CFM56-7B24 engines and category A brakes was used for all simulation scenarios. The airplane was configured at flaps 40, gear down and trimmed on the ground (i.e., assumed main and nose wheel touchdown occurred prior to the simulation start). Remaining airplane initial conditions are identified as needed. The assumptions stipulated in the Aircraft Performance Group Study, Section 2.5.1, page 8, first paragraph, apply to simulation data in this study.

For each scenario in the simulation matrix, the total simulation ground distance was calculated for the specified reverse thrust schedule (i.e., engine mode, deployment time, engine throttle setting, and stowage speed/time schedule), wheel braking configuration, airplane braking coefficient, ground spoiler schedule, and winds. The total simulation ground distance was compared to the runway 31C ground distance remaining after touchdown or the LSPS and QRH ground distances, as appropriate. The airplane datum for the simulation runway distance remaining calculation is the position of the center of gravity (i.e., about 4 feet forward of the main landing gear for a center of gravity location of 21 percent MAC). The B737-700W nose gear are located approximately 41 feet forward of the main gear.

2.3.1 Reverse Thrust Procedures

Reverse thrust deployment and stowage procedures were documented to facilitate the engineering study and differentiate procedures required to accomplish a full stop on the runway from normal procedures used to transition to a taxiway without stopping. Boeing and

[4] See Section 2.3 for reference case definitions.
[5] The Boeing LSPS and PSIM tools are both validated with flight test data.

Southwest Airlines procedures regarding commanded deployment cues and settings (e.g., detent 2 or maximum reverse) and commanded stowage schedules (e.g., speeds, idle throttle setting) are defined separately.

2.3.1.1 Boeing Reverse Thrust Procedures

Boeing reverse thrust procedures are published in the 737NG FCTM and embedded in the methodology used to generate QRH/FPPM/LSPS/BLM landing performance data. An excerpt of the Boeing 737NG FCTM reverse thrust procedures is included in Attachment 1. Boeing provided the following comments to clarify information found in the FCTM:

> *Starting at 60 knots, the throttles are moved from the reverse thrust position (e.g. detent 2 or max) to the reverse idle position by taxi speed. Taxi speed is 20 knots or less. The throttle movement should be a function of speed, "a rate commensurate with the deceleration rate of the airplane." Therefore, with a dry runway and high deceleration, the throttle movement will be over a short period of time. With a poor contaminated runway and low deceleration, the throttle movement will be over a long period of time.*
>
> *If the intent is to stop on the runway, then the throttles should be left in reverse idle. If the intent is to exit the runway and/or taxi (normal operations) then at taxi speed forward idle should be selected.*

The B737-700W QRH/FPPM/LSPS/BLM[6] calculations are consistent with the FCTM methodology with respect to thrust reverser deployment and stowage. Detent 2 reverse thrust is assumed selected 2 seconds after touchdown and reversers deploy and spinup begins 4 seconds after touchdown. At 60 knots, the reverse thrust decreases as a function of speed to reverse idle by 30 knots. The throttles are left in reverse idle until stop, consistent with the default assumption that the airplane will be brought to a complete stop on the runway.

2.3.1.2 Southwest Airlines Reverse Thrust Procedures

At the time of the accident, the Southwest Airlines reverse thrust procedures for normal operations were contained in the Flight Operations Manual (FOM), as documented in the Operations Group Factual Report, Attachment 4. An excerpt of the FOM that defines reverse thrust procedures for “Landings under Braking Advisories Less than Good” is provided in Attachment 2. The Southwest Airlines reverse thrust procedures differed in part from Boeing procedures in that targeted reverse thrust levels were described in terms of percent engine N1, rather than reverser detent position.

At the time of the accident, the normal Southwest Airlines procedure for thrust reverser stowage after landing was to begin reducing the level of thrust at 80 knots (per FOM page 3.22.3) and to smoothly move the levers to reach idle reverse at 60 knots, then stow the reversers at 60 knots. Idle forward thrust would normally be achieved by taxi speed.

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[6] LSPS and BLM use the same data to calculate landing distance. When using manual braking, LSPS and BLM will provide results that are very close to each other since they use the same assumptions and schedules for wheel brakes, thrust, and speedbrakes. When autobrakes are selected, LSPS will model the transition sequence of events more accurately than BLM. The differences between LSPS and BLM autobrake landing distances will be most pronounced on slippery runways when using reverse thrust. BLM will be more conservative because the onset of reverse thrust is delayed several seconds. The basic assumptions and schedules for wheel brakes and speedbrakes are similar, with minor modeling differences.

2.3.2 B737-700 Reverse Thrust Modeling and Validation

The B737-700 thrust data used in the Boeing aerodynamics performance programs (e.g., LSPS/AFM-DPI/BLM) and the PSIM simulation engine model were obtained from the same source. The engine cycle deck defines the engine performance throughout the flight envelope as a function of altitude, Mach number, ambient temperature, and compressor airbleed offtake effects. The engine cycle deck began with an initial definition based on scaled model test data, was subsequently updated with full scale test stand performance and loads data, and was ultimately validated against a matrix of demonstrated steady state and transient flight test conditions.

Full scale test stand[7] performance and loads tests were performed on the actual engine with engine thrusts that varied from idle to maximum for both the forward and reverse thrust configuration. The simulation propulsion model includes modeling of the throttles, Electronic Engine Controller (EEC), and the timing and sequencing of events that occur on the actual airplane. The simulation model including throttle commands and engine spool-up/down transitions were validated using flight test data.

For the landing condition, the simulation model was flight validated down to 60 knots for reverse thrust and 0 knots for forward idle. For reverse thrust between the speeds of 60 and 0 knots, the simulation model represents the thrust from the engine test stand data. Any abnormal effects to reverse engine thrust in the speed region between 60 and 0 knots that are present on the actual airplane, due for example to re-ingestion, and not captured in the full scale test stand test, are not accounted for in the engine model.

2.3.3 Airplane Braking Coefficient Extraction (Cases 30A-C and Cases 34-37, Yellow)

Cases 30B and 34-37 represent the time varying airplane braking coefficient calculation previously documented in the Airplane Performance Group Study, Section 2.5, pages 8-11 and 18-19) for the event landing and four preceding Southwest Airlines B737-700W airplane arrivals. Cases 30A and 30C were designed to calculate the constant equivalent airplane braking coefficient and constant equivalent simulation braking coefficient, respectively, required to match the event FDR ground speed and calculated ground distance. That is, the time varying airplane braking coefficient extraction corresponding to Case 30B was mapped to a constant equivalent airplane braking coefficient value in Case 30A (small variation in simulation distributed braking coefficient on braked wheels as a function of time) and a constant equivalent simulation braking coefficient value in Case 30C (small variation in airplane braking coefficient as a function of time).

Initial conditions for cases 30B and 34-37 were defined on a per aircraft basis. Backdriven parameters included FDR control column, control wheel, horizontal stabilizer, brake pressures, and speedbrake handle. Throttle resolver angle was set to match the FDR engine N1. The total ground distance calculated in cases 30A-C reflects a 220 feet additive to account for distance traveled during the 1 second between touchdown and simulation start.

2.3.4 Wind Effects (Cases 31-33, Gray)

Cases 31-33 compare the effects of wind on the total ground distance, assuming the event airplane performed an unobstructed rollout and came to a complete stop. These 3 cases

[7] A full scale test performed by Boeing and the engine manufacturer in a controlled environment.

used the constant simulation equivalent airplane braking coefficient determined in Case 30C and differed only in their respective modeling of event winds, zero wind, and winds opposite the event.

The initial conditions[8] for cases 31-33 were: weight 118,240 lb, airspeed 124 knots, center of gravity 21 percent MAC, barometer 30.06 inches Hg, pressure altitude 492 feet, temperature –3 Celcius, 9 knot tailwind, A/C bleeds on. The control column and control wheel were backdriven with FDR data until time 6373.7[9] and thereafter held constant at the neutral position. Backdriven parameters included horizontal stabilizer, brake pressures, and speedbrake handle. Throttle resolver angle was set to match the event FDR engine N1. The constant simulation equivalent airplane braking coefficient value determined in Case 30C was prescribed. The total ground distance calculated in cases 31-33 reflects a 220 feet additive to account for distance traveled during the 1 second between touchdown and simulation start.

2.3.5 Ground Spoiler Effects (Cases 41-46, Orange)

Cases 41-43 model the effects of auto, manual, and no spoiler deployment, respectively, on the total ground distance assuming thrust reversers were stowed and the airplane accomplished an unobstructed rollout and came to a complete stop..

Cases 44-46 compare the effects of thrust reverser deployment using event thrust, the nominal Boeing detent 2/60/30/reverse idle stowage procedure, and an emergency detent 2/no stowage procedure, respectively. In each case, ground spoilers remained stowed until reverse thrust was commanded. [10]

The initial conditions for cases 41-46 were: weight 118,240 lb, airspeed 124 knots, center of gravity 21 percent MAC, barometer 30.06 inches Hg, pressure altitude 492 feet, temperature –3 Celcius, 9 knot tailwind, A/C bleeds on. The control column and control wheel were backdriven with FDR data until time 6373.7 and thereafter held constant at the neutral position. Backdriven parameters included horizontal stabilizer and brake pressures. The constant simulation equivalent airplane braking coefficient value determined in Case 30C was prescribed. The total ground distance calculated in cases 41-46 reflects a 220 feet additive to account for distance traveled during the 1 second between touchdown and simulation start.

2.3.6 Reverse Thrust Throttle and Stowage Schedules (Cases 51-60, Green)

Cases 51-60 model the effects of 5 different thrust reverser stowage schedules and two different reverse thrust throttle settings. In each case the reverse thrust command was initiated 2 seconds after touchdown with the engines producing approach idle thrust. Cases

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[8] For Cases 31-60 and 101-408, only LSPS data account for engine anti-ice on. Boeing stated that the engine anti-ice bleeds for the reverse thrust condition should not significantly affect the overall thrust. The QRH data do not account for A/C bleeds on. The LSPS and QRH data account for a 0.07 percent downhill runway slope effect that was not modeled in PSIM.

[9] Flight 1248 touchdown occurred at 6351.5 seconds and the simulation start time for Cases 30-60 was 6352.5 seconds. The FDR control column position was airplane nose down shortly after touchdown, but gradually returned to the neutral position by 6373.7 seconds.

[10] The 737NG reverse thrust system is designed to deploy speedbrakes if they were not previously deployed by either auto-spoiler or manual command.

51-55 model the detent 2 reverse thrust throttle setting while Cases 56-60 model the detent max throttle setting. In all other respects, Cases 51-55 can be sequentially mapped to Cases 56-60.

Case 51 assumes reverse thrust is held at the detent 2 level until an airspeed of 80 knots, at which time throttle is linearly ramped to forward idle over a period of 3 seconds and remains at forward idle until the airplane comes to a stop. Case 52 assumes reverse thrust is held at the detent 2 level until an airspeed of 60 knots, at which time throttle is linearly ramped to forward idle over a period of 3 seconds and remains at forward idle until the airplane comes to a stop.

Case 53 (Southwest Airlines reverse thrust stowage procedure for normal conditions) assumes reverse thrust is held at the detent 2 level until an airspeed of 80 knots, at which time throttle is smoothly ramped to forward idle by an airspeed of 60 knots and remains at forward idle until the airplane comes to a stop.

Case 54 (Boeing recommended reverse thrust stowage procedure for normal conditions) assumes reverse thrust is held at the detent 2 level until an airspeed of 60 knots, at which time throttle is smoothly ramped to reverse idle by an airspeed of 30 knots and remains at reverse idle until the airplane comes to a stop.

Case 55 (emergency reverse thrust stowage procedure) assumes reverse thrust is held at the detent 2 level until the airplane comes to a stop.

The initial conditions for cases 51-60 were: weight 118,240 lb, airspeed 124 knots, center of gravity 21 percent MAC, barometer 30.06 inches Hg, pressure altitude 492 feet, temperature –3 Celcius, 9 knot tailwind, A/C bleeds on. The control column and control wheel were backdriven with FDR data until time 6373.7 and thereafter held constant at the neutral position. Backdriven parameters included horizontal stabilizer, brake pressures, and speedbrake handle. The constant simulation equivalent airplane braking coefficient value determined in Case 30C was prescribed. The total ground distance calculated in cases 51-60 reflects a 220 feet additive to account for distance traveled during the 1 second between touchdown and simulation start.

2.3.7 Low Speed Performance Tool Comparison (Cases 61-64, Purple)

Cases 61-64 compare the simulation ground distance to the LSPS and QRH low speed performance methods. These 4 cases were specifically included to represent conditions similar to the flight test conditions used to update the LSPS software, which uses first principles methods to compute landing performance. The QRH normal configuration tabular data provide adjustments to a reference landing distance as a function of engine type, flap setting, brake type, reported braking action, wheel braking configuration, weight, pressure altitude, temperature, winds, runway slope, speed relative to V_{REF}, and reverse thrust. The Boeing 737-700 QRH data incorporate a 1,000 feet air distance component which must be removed for comparison to total simulation ground distance.

Cases 61-64 use auto-spoiler and maximum manual braking. Case 61 corresponds to the demonstrated (unfactored) dry runway, maximum manual braking, no reverse thrust landing performance documented in the AFM. Case 62 adds the nominal Boeing reverse thrust detent 2/60/30/reverse idle stowage schedule to the Case 61 dry runway condition.

Cases 63 and 64 model Boeing "good reported braking action" and Boeing "poor reported braking action" by varying the airplane braking coefficient used in Case 62 from a value of approximately 0.41 to values of 0.20 and 0.05, respectively.

The initial conditions for cases 61-64 were: weight 128,000 lb (MLW), V_{Brake} 126.7 knots, center of gravity 9 percent MAC, sea level, standard day, barometer 29.92 in. Hg, temperature 15 Celcius, zero wind, zero runway slope. The control column and control wheel were held constant at the neutral position. The total ground distance calculated in cases 61-64 reflects a 215 feet additive to account for distance traveled during the 1 second between touchdown and simulation start.

2.3.8 Braking Configuration Effects (Cases 101-408, Blue)

Cases 101-408 also compare the simulation ground distance to the LSPS and QRH low speed performance methods for a matrix of reported braking action, reverse thrust, and wheel braking configuration conditions. Cases 101-408 are subdivided into 4 wheel braking configuration groups, corresponding to maximum manual braking, maximum autobrake, autobrake 3, and autobrake 2, respectively. Each group consists of 2 subgroups, corresponding to thrust reversers deployed (dark blue) and stowed (light blue), respectively. Each subgroup consists of 4 cases, corresponding to airplane braking coefficient values of 0.41, 0.20, 0.10, and 0.05, respectively. Thrust reverser scheduling for Cases 101-408, as applicable, was consistent with Case 54 (Boeing recommended reverse thrust stowage procedure for normal conditions).

Cases 101-108 model maximum manual braking, with and without reverse thrust, for Boeing reported braking actions of dry, good, medium, and poor, per Table 3 of the Aircraft Performance Group Study, page 14. Cases 201-208, 301-308, and 401-408 map to cases 101-108, except the maximum manual braking configuration is replaced by maximum autobrake, autobrake 3, and autobrake 2 wheel braking configurations, respectively

The initial conditions for cases 101-408 were: weight 118,240 lb, airspeed 124 knots, center of gravity 21 percent MAC, barometer 30.06 inches Hg, pressure altitude 492 feet, temperature –3 Celcius, 9 knot tailwind, A/C bleeds on. The control column and control wheel were held constant at the neutral position. The total ground distance calculated in cases 101-408 reflects a zero feet additive to simulation ground distance because the simulation began at the touchdown point.

3.0 RESULTS

3.1 Time Varying Airplane Braking Coefficient Extraction (Method A)

The wet, grooved runway flight test data validation result[11] using the time varying airplane braking coefficient extraction method (Method A) is presented in Table 3.1. The calculated airplane braking coefficient varies between about 0.30 and 0.35, which is somewhat worse than the bare and dry runway value (increased from 0.38 to 0.43), but measurably better than the wet, smooth runway value (increased from 0.05 to 0.30 as ground speed decreased) documented in Table 1 of the Aircraft Performance Group Study.

[11] The flight test time history data are Boeing Proprietary information, so the Method A validation result was summarized.

Table 3.1: B737-900 airplane braking coefficient flight test validation case

CASE #	RUNWAY CONDITION	BRAKING	SPEEDBRAKES	THRUST REVERSER	CALCULATED AIRPLANE BRAKING COEFFICIENT
6	WET GROOVED	MAXIMUM MANUAL	DEPLOYED	STOWED	VARIES ON AVERAGE BETWEEN 0.30 AND 0.35

3.2 Sensitivity Study

The sensitivity study results presented in Table 3.2 indicate that the calculated ground roll distance is most sensitive to the airplane braking coefficient magnitude, winds, and time delay to commanded reverse thrust, given a constant equivalent airplane braking coefficient reference value of 0.08. An airplane braking coefficient change of +/-0.01 about the reference value results in a ground roll distance of about –250/+300 feet. A 5 knot tailwind increases the ground roll distance by about 400 feet compared to the zero wind reference case. Each 1 second delay within the first 4 seconds of the nominal reverse thrust deployment command results in a ground roll distance increase of about 100 feet.

The calculated ground roll distance is a weak function of center of gravity location and aircraft weight (assuming a constant touchdown airspeed). Small variations between the simulator and the actual airplane peak reverse thrust, lift coefficient, and drag coefficient yield relatively small adjustments to the calculated ground roll distance. Selection of forward idle thrust as opposed to reverse idle thrust at 30 knots as the thrust reversers are stowed causes a 260 foot increase in stopping distance for the reference airplane braking coefficient, assuming that pilot intent is to bring the airplane to a complete stop on the runway.

Table 3.2: Sensitivity study results

CASE #	PARAMETER	MINIMUM VARIATION	MAXIMUM VARIATION	UNITS	MIN. DELTA DISTANCE (FT)	MAX. DELTA DISTANCE (FT)
21	PEAK REVERSE THRUST	-10	10	PERCENT (POUNDS)	(79)	91
22	CENTER OF GRAVITY	-5	5	%MAC	23	(23)
23	AIRCRAFT WEIGHT	-5,000	5,000	POUNDS	(80)	77
24	AIRPLANE BRAKING COEFFICIENT	-0.02	0.02	NONDIMEN.	576	(484)
25	LIFT COEFFICIENT	-0.1	+0.1	NONDIMEN.	(47)	48
26	DRAG COEFFICIENT	-10	+10	PERCENT	144	(133)
27	WIND	-5	+5	KNOTS	384	(363)
28	THRUST REVERSER COMMAND DELAY	+2	+4	SECONDS	178	391
29	THROTTLE SETTING AT 30 KNOTS	-	FORWARD IDLE	NONDIMEN.	-	259

The landing distance sensitivity to variations in airplane braking coefficient, winds, or different deceleration device schedules is dependent on the reference airplane braking coefficient value. The landing distance would be less sensitive to similar parameter variations on a dry or wet runway than those calculated for the accident conditions.

3.3 Simulation Scenarios

The simulation, LSPS, and QRH results for cases 30-408 are presented in tabular form in Attachment 3. The time varying airplane braking coefficient results (Cases 30B, 34-37), constant equivalent airplane braking coefficient results (Case 30A), and constant equivalent simulation braking coefficient results (Case 30C) are shaded yellow. Wind scenarios (Cases 31-33), ground spoiler deployment scenarios (Cases 41-46), and reverse thrust setting/stowage schedule scenarios (Cases 51-60) are color coded gray, orange, and green, respectively. Flight test validation scenarios (Cases 61-64) and reported braking action/reverse thrust/wheel braking scenarios (Cases 101-408) are color coded purple and blue, respectively.

The time varying simulation matches for Cases 30A-C and 34-37 are plotted in Attachments 4 and 5, respectively. Flight data recorder data are identified by symbols and simulation data are depicted with dashed lines. The simulation match plots present airspeed, ground speed, longitudinal acceleration, calculated total airplane braking coefficient, radio altitude, air/ground switch, speed brake handle position, engine N1, throttle resolver angle, brake metered pressure, simulation estimated brake pressure at the wheels, and control column deflection.

3.3.1 Time Varying Airplane Braking Coefficient

As stated in the Aircraft Performance Group Study, Section 2.5, page 8, the airplane braking coefficient is not equivalent to the tire-to-ground friction coefficient. The estimated airplane braking coefficient is an all inclusive term that incorporates effects due to the runway surface, contaminants, and airplane braking system (e.g., antiskid efficiency, brake wear). The maximum airplane braking coefficient will result if the commanded brake pressure meets or exceeds the brake pressure threshold governed by the antiskid valve. When this occurs the brakes are in a friction limited condition and the airplane braking coefficient is representative of the runway friction characteristics. If the commanded brake pressure is less than the brake pressure governed by the antiskid valve, the airplane braking coefficient will be a function of the level of the commanded brake pressure.

Estimated simulation brake pressure at the wheels provides an order of magnitude indication of the brake pressure expected downstream of the antiskid valve. The simulation estimated brake pressure at the wheels is based on a calculation of brake pressure for a given deceleration force, where the deceleration force is defined by the lesser of the friction limited condition or the applied brake metered pressure. The simulation brake pressure estimate represents average airplane characteristics and variability from airplane to airplane (e.g., due to brake wear or brake temperature) is not modeled.

The time varying simulation match plots in Attachments 4 and 5 include annotations (color coded red) that denote regions where the calculated airplane braking coefficient was considered valid and representative of runway limiting characteristics. These regions were defined by using engineering judgment to compare the applied brake pressure (FDR brake metered pressure) to the general level of the simulation estimated brake pressure at the wheels. The airplane was subject to a friction limited condition when the applied brake pressure was significantly higher than the simulation brake pressure estimate. The airplane was at or near a friction limited condition when the applied brake pressure was near the simulation brake pressure estimate.

The time varying airplane braking coefficient extraction data are summarized in Table 3.3. The simulation data indicate that all five landings were subject to friction limited regions during the ground rollout. Further, the estimated simulation brake pressure at the wheels ranged between 300 and 500 PSI for all landings with friction limited regions. Based on the sensitivity study results for peak thrust, aerodynamic lift, and aerodynamic drag, the uncertainty for the time varying airplane braking coefficient extraction data (Cases 30B and 34-37) is about +/- 0.01.

Table 3.3: Calculated total airplane braking coefficients for 5 SWA B737-700W landings

Aircraft Number/ Case	Flight Number	Landing Weight (LB)	Ground Speed at T.D. (KT)	RWY 31C Exit	T.D. Time	Total Airplane Braking Coefficient	Plot Page	Comments
N795SW (Case 37)	2920	114,560	139.5	B&N T/W	18:52:41	0.12	A5.5	Detent 2 to detent max reverse thrust, max. wheel braking, and differential wheel braking commanded; FDR acceleration data invalid.
N213WN (Case 36)	321	103,320	121.5	end	19:00:39	0.11	A5.4	Detent 2 reverse thrust and symmetric wheel braking commanded.
N482WN (Case 35)	2947	110,320	132.5	end	19:02:28	0.08	A5.3	Detent max reverse thrust and differential wheel braking commanded.
N788SA (Case 34)	1830	105,520	126.5	end	19:04:07	0.10*	A5.2	Detent max reverse thrust, max. wheel braking, and differential wheel braking commanded.
N471WN (Case 30B)	**1248**	**118,280**	**131.5**	**overran**	**19:13:07**	**0.08**	**A4.2**	**Approach idle to ground idle to detent max reverse thrust, autobrake max to max. manual wheel braking, and symmetric wheel braking commanded.**
Case 30A	-	118,280	131.5	-	-	0.08	A4.3	N471WN conditions, except constant equivalent airplane braking coefficient.
Case 30C	-	118,280	131.5	-	-	0.08	A4.4	N471WN conditions except constant equivalent simulation braking coefficient.

*Average braking coefficient increases from 0.09 to 0.11 during the time history
Time varying airplane braking coefficient except as noted.
Blue – denotes the accident flight

3.3.2 Wind Effects (Cases 31-33, Gray)

The simulation results indicate that flight 1248 would have required an additional 750 feet of runway to rollout unobstructed under identical airplane configuration schedules and event conditions. With zero winds, the airplane could have stopped with the main gear and nose gear on the paved blast pad. Opposite winds could have provided a 580-foot stopping margin, assuming that once deployed, detent max reverse thrust was maintained until the airplane came to a complete stop.

3.3.3 Ground Spoiler Effects (Cases 41-46, Orange)

No reverse thrust under the event conditions would have required an additional 2,100 to 2,300 feet of runway if nominal auto or manual ground spoiler deployment occurred, respectively. No reverse thrust and no ground spoiler deployment would have required an additional 5,200 feet of runway. Cases 44-46 indicate the progressive reduction in ground roll distance with use of reverse thrust due to the combination of reverse thrust and ground spoiler deployment. Ground spoiler deployment increases aerodynamic drag, decreases aerodynamic lift, and distributes more aircraft weight on braked wheels.

3.3.4 Reverse Thrust Throttle and Stowage Schedules (Cases 51-60, Green)

The reverse thrust throttle and stowage schedule analysis indicates that under event conditions, the airplane could have stopped on the runway if detent max reverse thrust was selected within 2 seconds after touchdown and maintained until the airplane came to a complete stop (Case 60). The main gear could have stopped on the runway if detent 2 reverse thrust was selected within 2 seconds after touchdown and maintained until the airplane came to a complete stop (Case 55). In this case the nose gear would have stopped on the paved blast pad about 7 feet beyond the end of the runway.

The Case 53 results indicate that if detent 2 reverse thrust was selected within 2 seconds after touchdown and maintained until an airspeed of 80 knots, followed by a smooth throttle ramp to forward idle thrust by an airspeed of 60 knots, an additional 1,400 feet of runway would have been required assuming the pilot intent was to stop on the runway. The Case 54 results indicate that use of normal Boeing FCTM reverse thrust procedures would have required an additional 500 feet of runway, again assuming the pilot intent was to stop on the runway.

3.3.5 Low Speed Performance Tool Comparison (Cases 61-64, Purple)

The flight test validation data ground roll distance comparison indicates that the LSPS and QRH data are nearly equivalent for Cases 61-64. When not equivalent, the QRH data are slightly more conservative than the LSPS data, as expected. The simulation ground distance results were nearly identical to the LSPS results for the dry and “good reported braking action” conditions, but slightly conservative for the “poor reported braking action” scenario.

3.3.6 Braking Configuration Effects (Cases 101-408, Blue)

The wheel braking/reverse thrust/reported braking action results generally indicate that the LSPS and QRH data are more conservative than the simulation results throughout the scenario matrix, except as noted below. In addition, the QRH data are generally more conservative than the LSPS data, except as noted below. Ground roll distance differences less than order 100 feet are considered negligible for comparison purposes.

3.3.6.1 Maximum Manual versus Autobrake Max

The wheel braking results (Cases 101-108 and 201-208) indicate that maximum manual braking does not consistently provide equivalent or shorter stopping distances than maximum autobrake, with or without the use of reverse thrust. The landing distance can be larger for the maximum manual versus the maximum auto brake cases. The maximum manual braking calculation assumes a 1 second delay from touchdown to brake application whereas autobrake cases assume brake application begins at the touchdown point.

3.3.6.2 Simulation versus LSPS

The LSPS data for Boeing "poor reported braking action" thrust reversers deployed (Cases 104, 204, 304, 404) are less conservative than the simulation data due to differences in the engine model implementation. The LSPS thrust model applies more forward thrust in the touchdown-to-wheel-brakes-ON landing segment and more net reverse thrust from wheel-brakes-ON to thrust-reversers-full-deployed-until-stowed segment than the simulation. The cumulative effect is that the LSPS thrust model has more reverse thrust applied earlier in the landing than the simulation, resulting in shorter LSPS calculated stopping distances as airplane braking coefficient decreases.

The LSPS and PSIM thrust data are from the same engine cycle deck, which provides net thrust and ram drag for the given engine N1 and atmospheric conditions. While the thrust modeling and implementation (i.e., timing, spool-up, spin-down) differ between LSPS and PSIM, both programs have been validated with flight test data. The LSPS thrust modeling has been certified and the PSIM modeling meets the International Civil Aviation Organization (ICAO) simulator qualification[12] requirements.

3.3.6.3 QRH versus LSPS

The QRH advisory data for Boeing "poor reported braking action" thrust reverser stowed (Cases 108, 208, 308, 408) are less conservative than the LSPS data. The LSPS data correspond to a point solution, whereas the QRH data represent a generalized solution. As a result, the QRH data can be conservative for some cases and non-conservative for others.

Specifically, the reference basis for QRH data incorporate 2 engine reverse thrust. A point adjustment for zero thrust reversers was calculated only at the reference weight, slope, wind, approach speed, altitude and temperature. Other QRH adjustments, including altitude, wind, slope, temperature and approach speed were calculated based on a variety of weights and conditions to determine a more general adjustment.

3.3.7 Stopping Energy and Longitudinal Acceleration

The simulation data from Cases 31, 54, 55, and 61-64 were used to calculate the respective aerodynamic drag, wheel braking, and reverse thrust contributions to stopping energy. The stopping energy comparison chart included in Attachment 6 shows that on a bare and dry runway at maximum landing weight (Case 62), reverse thrust (black) supplies about 4 percent of the required stopping energy. Aerodynamic drag (blue) and wheel braking (green) provide 12 and 84 percent of the required stopping energy, respectively. Each case on page A6.2 can be considered a maximum wheel braking scenario.

As the runway condition deteriorates from a bare and dry condition to a Boeing "poor reported braking action condition" (Case 64), reverse thrust provides 27 percent of the required stopping energy and aerodynamic drag supplies 38 percent. Wheel braking at this condition contributes only 35 percent of the required stopping energy. The total energy required to bring the airplane to a complete stop for a given case is dependent on the initial

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[12] According to the ICAO Manual of Criteria for the Qualification of Flight Simulators, Second Edition, dated 2003, the acceptable tolerance on landing distance for wet or icy runway conditions using wheel brakes is +/-10 percent of the distance or 200 feet.

conditions, deceleration devices and schedules, and runway surface condition. Alternatively, the total energy required to stop the airplane is dependent on the initial conditions and the distance over which the deceleration forces act.

Wheel braking contributes an almost constant -0.095g component to total longitudinal acceleration as a function of ground speed for Cases 31, 54, and 55. Aerodynamic drag contributes a constant quadratic component to total longitudinal acceleration as a function of ground speed for Cases 31, 54, and 55. The aerodynamic drag contribution to longitudinal acceleration is –0.13g at 130 knots and falls to 0.00g when the airplane comes to a stop. Thus the initial longitudinal deceleration due to aerodynamic drag exceeds the longitudinal deceleration due to wheel braking. Application of detent 2 reverse thrust contributes an additional –0.05 to –0.08g increment to longitudinal acceleration for ground speeds between 70 and 105 knots. For reference, on a bare and dry runway with maximum manual braking ground spoilers deployed, and no reverse thrust, the longitudinal acceleration varied in the range of –0.4 to –0.5g.

4.0 SUMMARY

The Aircraft Performance Group Study and this addendum evaluated a total of 6 flight test cases to validate the time varying airplane braking coefficient extraction method used to calculate the airplane braking coefficient for flight 1248 and 4 preceding B737-700W flights. Flight test data from 4 dry runway conditions, 1 wet, smooth runway condition, and 1 wet, grooved runway condition were analyzed. No “worse than wet” 737NG flight test data were available.

The sensitivity study of calculated landing distance to a known parameter variation about the flight 1248 constant equivalent airplane braking coefficient reference value of 0.08 showed that the calculated ground roll distance was most sensitive to the airplane braking coefficient magnitude, winds, and time delay to commanded reverse thrust. However, the landing distance would be less sensitive to similar parameter variations on a dry or wet runway than those calculated for the accident conditions. The sensitivity study results for peak thrust, aerodynamic lift, and aerodynamic drag, indicated that the uncertainty for the time varying airplane braking coefficient extraction data is about +/- 0.01.

The validated time varying airplane braking coefficient extraction method was used to calculate the airplane braking coefficient required to decelerate flight 1248 and 4 prior SWA flights. A comparison of the estimated simulation brake pressure at the wheels to the FDR commanded brake pressure showed that all 5 airplanes analyzed were subject to runway friction limited conditions during portions of their respective landing rollouts.

An equivalent simulation braking coefficient was calculated for flight 1248 and used to quantify the effects of different winds, ground spoiler deployment schedules, and reverse thrust throttle setting and stowage schedules on the flight 1248 stopping performance. In addition, the PSIM engineering simulator results were compared[13] to LSPS and QRH data for a matrix of runway conditions and wheel braking schedules.

Based on the engineering simulation study, flight 1248 could have been safely stopped on the runway if (1) the winds had been from the opposite direction (or a small headwind had

[13] The Boeing LSPS and PSIM tools are both validated with flight test data.

existed), (2) detent max reverse thrust was selected within 2 seconds after touchdown and maintained until the airplane came to a complete stop, or (3) detent 2 reverse thrust was selected within 2 seconds after touchdown and maintained until the airplane came to a complete stop. In the last scenario, the main gear would have come to a stop on the runway with the nose gear located on the paved blast pad approximately 7 feet beyond the runway end. The balance of landing simulation scenarios based on the flight 1248 initial conditions and equivalent simulation airplane braking coefficient resulted in a runway overrun.

Boeing QRH data were found to be generally more conservative than the simulation data. Boeing LSPS data were also generally more conservative than the simulation data, except at “poor reported braking action” conditions with thrust reversers deployed, due primarily to differences in the simulation and LSPS engine model implementation.

Attachment 1: Boeing 737-700 Reverse Thrust Procedures

The Boeing 737NG FCTM contains the following information with respect to reverse thrust:

737NG FCTM
Section 6 Landing - Landing Roll
Factors Affecting Landing Distance
Advisory information for normal and non-normal configuration landing distances is contained in the PI section of the QRH. Actual stopping distances for a maximum effort stop are approximately 60% of the dry runway field length requirement. Factors that affect stopping distance include: height and speed over the threshold, glide slope angle, landing flare, lowering the nose to the runway, use of reverse thrust, speedbrakes, wheel brakes and surface conditions of the runway.

Note: *Reverse thrust and speedbrake drag are most effective during the high speed portion of the landing. Deploy the speedbrake lever and activate reverse thrust with as little time delay as possible.*

Reverse Thrust Operation
Awareness of the position of the forward and reverse thrust levers must be maintained during the landing phase. Improper seat position as well as long sleeved apparel may cause inadvertent advancement of the forward thrust levers, preventing movement of the reverse thrust levers.

The position of the hand should be comfortable, permit easy access to the autothrottle disconnect switch, and allow control of all thrust levers, forward and reverse, through full range of motion.

Note: *Reverse thrust always reduces the "brake only" stopping distance, brake and tire wear. Reverse thrust is most effective at high speeds.*

After touchdown, with the thrust levers at idle, rapidly raise the reverse thrust levers up and aft to the interlock position, then to the number 2 reverse thrust detent. Conditions permitting, limit reverse thrust to the number 2 detent. The PM should monitor engine operating limits and call out any engine operational limits being approached or exceeded, any thrust reverser failure, or any other abnormalities.

Maintain reverse thrust as required, up to maximum, until the airspeed approaches 60 knots. At this point start reducing the reverse thrust so that the reverse thrust levers are moving down at a rate commensurate with the deceleration rate of the airplane. The thrust levers should be positioned to reverse idle by taxi speed, then to full down after the engines have decelerated to idle. The PM should call out 60 knots to assist the PF in scheduling the reverse thrust. The PM should also call out any inadvertent selection of forward thrust as reverse thrust is cancelled. If an engine surges during reverse thrust operation, quickly select reverse idle on all engines.

Directional Control and Braking during Landing Roll

If the nose wheels are not promptly lowered to the runway, braking and steering capabilities are significantly degraded and no drag benefit is gained. Rudder control is effective to approximately 60 knots. Rudder pedal steering is sufficient for maintaining directional control during the rollout. Do not use the nose wheel steering wheel until reaching taxi speed. In a crosswind, displace the control wheel into the wind to maintain wings level which aids directional control. Perform the landing roll procedure immediately after touchdown. Any delay markedly increases the stopping distance.

Stopping distance varies with wind conditions and any deviation from recommended approach speeds.

Factors Affecting Landing Distance

Advisory information for normal and non-normal configuration landing distances is contained in the PI section of the QRH. Actual stopping distances for a maximum effort stop are approximately 60% of the dry runway field length requirement. Factors that affect stopping distance include: height and speed over the threshold, glide slope angle, landing flare, lowering the nose to the runway, use of reverse thrust, speedbrakes, wheel brakes and surface conditions of the runway.

Note: Reverse thrust and speedbrake drag are most effective during the high speed portion of the landing. Deploy the speedbrake lever and activate reverse thrust with as little time delay as possible.

Note: Speedbrakes fully deployed, in conjunction with maximum reverse thrust and maximum manual anti-skid braking provides the minimum stopping distance.

Floating above the runway before touchdown must be avoided because it uses a large portion of the available runway. The airplane should be landed as near the normal touchdown point as possible. Deceleration rate on the runway is approximately three times greater than in the air.

Height of the airplane over the runway threshold also has a significant effect on total landing distance. For example, on a 3° glide path, passing over the runway threshold at 100 feet altitude rather than 50 feet could increase the total landing distance by approximately 950 feet. This is due to the length of runway used up before the airplane actually touches down.

Glide path angle also affects total landing distance. As the approach path becomes flatter, even while maintaining proper height over the end of the runway, total landing distance is increased.

Slippery Runway Landing Performance

When landing on slippery runways contaminated with ice, snow, slush or standing water, the reported braking action must be considered. Advisory information for reported braking actions of good, medium and poor is contained in the PI section of the QRH. The performance level associated with good is representative of a wet runway. The performance level associated with poor is representative of a wet ice covered runway. Also provided in the QRH are stopping distances for the various autobrake settings and for non-normal configurations. Pilots should use extreme caution to ensure adequate runway length is available when poor braking action is reported.

Pilots should keep in mind slippery/contaminated runway advisory information is based on an assumption of uniform conditions over the entire runway. This means a uniform depth for slush/standing water for a contaminated runway or a fixed braking coefficient for a slippery runway. The data cannot cover all possible slippery/contaminated runway combinations and does not consider factors such as rubber deposits or heavily painted surfaces near the end of most runways. With these caveats in mind, it is up to the airline to determine operating policies based on the training and operating experience of their flight crews.

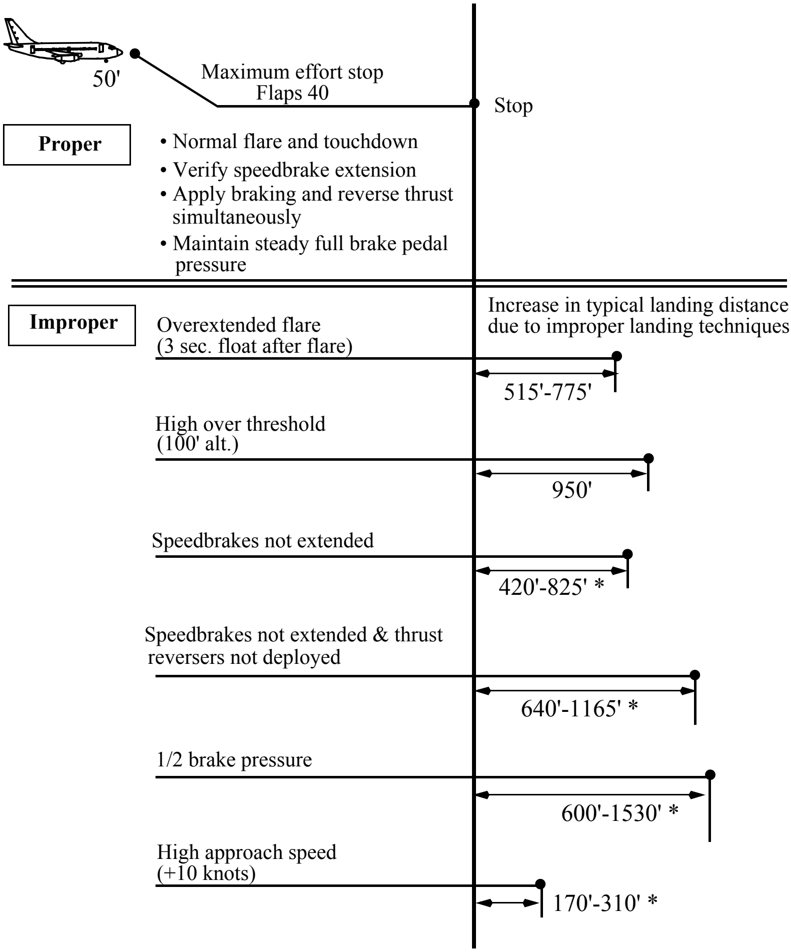
One of the commonly used runway descriptors is coefficient of friction. Ground friction measuring vehicles typically measure this coefficient of friction. Much work has been done in the aviation industry to correlate the friction reading from these ground friction measuring vehicles to airplane performance. Use of ground friction vehicles raises the following concerns:

- the measured coefficient of friction depends on the type of ground friction measuring vehicle used. There is not a method, accepted worldwide, for correlating the friction measurements from the different friction measuring vehicles to each other, or to the airplane's braking capability.
- most testing to date, which compares ground friction vehicle performance to airplane performance, has been done at relatively low speeds (100 knots or less). The critical part of the airplane's deceleration characteristics is typically at higher speeds (120 to 150 knots).

- ground friction vehicles often provide unreliable readings when measurements are taken with standing water, slush or snow on the runway. Ground friction vehicles might not hydroplane (aquaplane) when taking a measurement while the airplane may hydroplane (aquaplane). In this case, the ground friction vehicles would provide an optimistic reading of the runway's friction capability. The other possibility is the ground friction vehicles might hydroplane (aquaplane) when the airplane would not, this would provide an overly pessimistic reading of the runway's friction capability. Accordingly, friction readings from the ground friction vehicles may not be representative of the airplane's capability in hydroplaning conditions.
- ground friction vehicles measure the friction of the runway at a specific time and location. The actual runway coefficient of friction may change with changing atmospheric conditions such as temperature variations, precipitation etc. Also, the runway condition changes as more operations are performed.

The friction readings from ground friction measuring vehicles do supply an additional piece of information for the pilot to evaluate when considering runway conditions for landing. Crews should evaluate these readings in conjunction with the PIREPS (pilot reports) and the physical description of the runway (snow, slush, ice etc.) when planning the landing. Special care should be taken in evaluating all the information available when braking action is reported as POOR or if slush/standing water is present on the runway.

Factors Affecting Landing Distance (Typical)



*Landing distance varies with runway condition, wet or dry.
Data excludes contaminated runway considerations.

Wheel Brakes

Braking force is proportional to the force of the tires on the runway and the coefficient of friction between the tires and the runway. The contact area normally changes little during the braking cycle. The perpendicular force comes from airplane weight and any downward aerodynamic force such as speedbrakes.

The coefficient of friction depends on the tire condition and runway surface, (e.g. concrete, asphalt, dry, wet or icy).

Automatic Brakes

Boeing recommends that whenever runway limited, using higher than normal approach speeds, landing on slippery runways or landing in a crosswind, the autobrake system be used.

For normal operation of the autobrake system select a deceleration setting.

Settings include:

- MAX: Used when minimum stopping distance is required. Deceleration rate is less than that produced by full manual braking
- MED (2 or 3, as installed): Should be used for wet or slippery runways or when landing rollout distance is limited
- MIN (1, as installed): These settings provide a moderate deceleration effect suitable for all routine operations.

Flight crew/airline experience with airplane characteristics relative to the various runway conditions routinely encountered provide initial guidance as to the desirable level of deceleration selected.

Immediate initiation of reverse thrust at main gear touchdown and full reverse thrust allow the autobrake system to reduce brake pressure to the minimum level. Since the autobrake system senses deceleration and modulates brake pressure accordingly, the proper application of reverse thrust results in reduced braking for a large portion of the landing roll.

The importance of establishing the desired reverse thrust level as soon as possible after touchdown cannot be overemphasized. This minimizes brake temperatures and tire and brake wear and reduces stopping distance on very slippery runways.

The use of minimum reverse thrust almost doubles the brake energy requirements and can result in brake temperatures much higher than normal.

After touchdown, crewmembers should be alert for autobrake disengagement annunciations. The PM should notify the PF anytime the autobrakes disengage.

If stopping distance is not assured with autobrakes engaged, the PF should immediately apply manual braking sufficient to assure deceleration to a safe taxi speed within the remaining runway.

A table in the PI section of the QRH shows the relative stopping capabilities of the available autobrake selections.

Transition to Manual Braking

The speed at which the transition from autobrakes to manual braking is made depends upon airplane deceleration rate, runway conditions and stopping requirements. When transitioning to manual braking, keep the speedbrakes deployed and use reverse thrust as required until taxi speed. This is especially important when nearing the end of the runway where rubber deposits affect stopping ability.

When transitioning from the autobrake system to manual braking, the PF should notify the PM. Techniques for release of autobrakes can affect passenger comfort and stopping distance. These techniques are:

- stow the speed brake handle. When stopping distance within the remaining runway is assured, this method provides a smooth transition to manual braking, is effective before or after thrust reversers are stowed, and is less dependent on manual braking technique
- smoothly apply brake pedal force as in a normal stop, until the autobrake system disarms. Following disarming of the autobrakes, smoothly release brake pedal pressure. Disarming the autobrakes before coming out of reverse thrust provides a smooth transition to manual braking
- manually position the autobrake selector off (normally done by the PM at the direction of the PF).

Manual Braking

The following technique for manual braking provides optimum braking for all runway conditions:

The pilot’s seat and rudder pedals should be adjusted so that it is possible to apply maximum braking with full rudder deflection.

Immediately after main gear touchdown, smoothly apply a constant brake pedal pressure for the desired braking. For short or slippery runways, use full brake pedal pressure.

- do not attempt to modulate, pump or improve the braking by any other special techniques
- do not release the brake pedal pressure until the airplane speed has been reduced to a safe taxi speed
- the antiskid system stops the airplane for all runway conditions in a shorter distance than is possible with either antiskid off or brake pedal modulation.

The antiskid system adapts pilot applied brake pressure to runway conditions by sensing an impending skid condition and adjusting the brake pressure to each individual wheel for maximum braking effort. When brakes are applied on a slippery runway, several skid cycles occur before the antiskid system establishes the right amount of brake pressure for the most effective braking.

If the pilot modulates the brake pedals, the antiskid system is forced to readjust the brake pressure to establish optimum braking. During this readjustment time, braking efficiency is lost.

Low available braking coefficient of friction on extremely slippery runways at high speeds may be interpreted as a total antiskid failure. Pumping the brakes or turning off the antiskid degrades braking effectiveness. Maintain steadily increasing brake pressure, allowing the antiskid system to function at its optimum.

Although immediate braking is desired, manual braking techniques normally involve a four to five second delay between main gear touchdown and brake pedal application even when actual conditions reflect the need for a more rapid initiation of braking. This delayed braking can result in the loss of 800 to 1,000 feet of runway. Directional control requirements for crosswind conditions and low visibility may further increase the delays. Distractions arising from a malfunctioning reverser system can also result in delayed manual braking application.

Braking with Antiskid Inoperative

When the antiskid system is inoperative, the following techniques apply:

- ensure that the nose wheels are on the ground and the speedbrakes are extended before applying the brakes
- initiate wheel braking using very light pedal pressure and increase pressure as ground speed decreases
- apply steady pressure and DO NOT PUMP the pedals.

Flight testing has demonstrated that braking effectiveness on a wet grooved runway is similar to that of a dry runway. Caution however must be exercised when braking on any wet, ungrooved portions of the runway with antiskid inoperative to avoid blown tires.

Brake Cooling

A series of taxi-back or stop and go landings without additional in-flight brake cooling can cause excessive brake temperatures. The energy absorbed by the brakes from each landing is cumulative.

Extending the gear a few minutes early in the approach normally provides sufficient cooling for a landing. Total in-flight cooling time can be determined from the Performance Inflight section of the QRH.

The optional brake temperature monitoring system may be used for additional flight crew guidance in assessing brake energy absorption. This system indicates a stabilized value approximately fifteen minutes after brake energy absorption. Therefore, an immediate or reliable indication of tire or hydraulic fluid fire, wheel bearing problems, or wheel fracture is not available. The brake temperature monitor readings may vary between brakes during normal braking operations.

Note: Brake energy data provided in the QRH should be used to identify potential overheat situations.

To minimize brake temperature build-up:

- for airplanes without operative brake temperature monitoring systems:
  If the last ground time plus present flight time is less than 90 minutes, extend the landing gear 5 minutes early or 7 minutes prior to landing
- for airplanes with operating brake temperature monitoring systems:
  Extend the landing gear approximately one minute early for each unit of brake temperature above normal.

Close adherence to recommended landing roll procedures ensures minimum brake temperature build up.

Reverse Thrust Operation

Awareness of the position of the forward and reverse thrust levers must be maintained during the landing phase. Improper seat position as well as long sleeved apparel may cause inadvertent advancement of the forward thrust levers, preventing movement of the reverse thrust levers.

The position of the hand should be comfortable, permit easy access to the autothrottle disconnect switch, and allow control of all thrust levers, forward and reverse, through full range of motion.

Note: Reverse thrust always reduces the “brake only” stopping distance, brake and tire wear. Reverse thrust is most effective at high speeds.

After touchdown, with the thrust levers at idle, rapidly raise the reverse thrust levers up and aft to the interlock position, then to the number 2 reverse thrust detent. Conditions permitting, limit reverse thrust to the number 2 detent. The PM should monitor engine operating limits and call out any engine operational limits being approached or exceeded, any thrust reverser failure, or any other abnormalities.

Maintain reverse thrust as required, up to maximum, until the airspeed approaches 60 knots. At this point start reducing the reverse thrust so that the reverse thrust levers are moving down at a rate commensurate with the deceleration rate of the airplane. The thrust levers should be positioned to reverse idle by taxi speed, then to full down after the engines have decelerated to idle. The PM should call out 60 knots to assist the PF in scheduling the reverse thrust. The PM should also call out any inadvertent selection of forward thrust as reverse thrust is cancelled. If an engine surges during reverse thrust operation, quickly select reverse idle on all engines.

Attachment 2: SWA 737-700 Reverse Thrust Procedures

Landings under Braking Advisories Less than GOOD

Braking action reports less than GOOD are classified according to the most critical term (FAIR, POOR, NIL, or combinations). Operations are prohibited on all surfaces classified as 'NIL.'

Evaluate landing performance using the OPC. The -700 OPC landing module computes a deceleration rate as a combination of reversers and brakes. **(-300/-500)** The OPC computes landing performance based on 'brakes only' deceleration. Actual braking performance using brakes and thrust reversers will decrease computed landing distance.

Under braking advisories less than 'GOOD,' use Normal Landing procedures except for the following:

(PF) If conditions make hydroplaning a concern, make a firm Touchdown.

A firm touchdown can prevent hydroplaning from developing and will also extend the flight and ground spoilers more quickly.

Dynamic hydroplaning can occur at groundspeeds above 110 knots and once started, may continue to significantly lower speeds. If the main wheels are not aligned straight while on the runway, the aircraft will continue to hydroplane to a lower speed.

(PF) When landing in crosswind conditions combined with reduced braking action ('FAIR' down to 'POOR TO NIL'), maintain the crab angle all the way through touchdown.

Allowing the aircraft to touchdown without removing the crab angle will eliminate drift toward the downwind side of the runway.

(PF) After nose wheel touchdown, apply the brakes smoothly, symmetrically, and with moderate to firm pedal pressure.

Do not cycle or pump the brakes. Hold moderate brake pressure until a safe stop is assured.

(PF) Brakes and thrust reversers should be applied together.

- Use thrust reversers as soon as possible during landing roll.

Under emergency conditions, maximum reverse thrust may be used until reaching a complete stop.

- Use reverse thrust between a minimum of 85 percent N_1 to a maximum of go-around N_1.

Brakes are effective 3-5 seconds before the thrust reversers reach desired N_1.

After the auto speedbrakes deploy, wheel braking effectiveness should improve. If the aircraft was landed in a crab, align the aircraft with the runway centerline.

Do not pump the brakes. When brakes are applied, anti-skid cycling may occur before the anti-skid system establishes the optimum brake pressure. In addition, braking effectiveness is greatly reduced at higher speeds. Do not confuse this gradual deceleration with anti-skid failure. If you pump the brakes, the system is forced to reestablish optimum braking, increasing landing rollout distance.

If you are hydroplaning due to heavy rain, the wheels may not be rotating. If this is occurring, you will not detect any braking effectiveness or anti-skid cycling. Pilots have reported that it felt like they were sliding on ice. As long as the aircraft continues to track straight down the runway centerline, continue braking and reversing. If the aircraft begins to drift off of runway centerline, you may not regain directional control before you depart the prepared surface.

Avoid large or abrupt directional control inputs.

This may lead to skidding.

Rudder control is effective down to 60 knots. Transition to nose wheel steering using small inputs. Apply forward pressure to the control column to improve nose wheel steering effectiveness.

Caution: Do not use full forward control column position because this may exceed nose gear structural limits.

If the aircraft begins to weathervane into the wind and drift toward the downwind edge of the runway, reduce reverse thrust to idle and release the brakes. Use rudder steering and differential braking, as required, to regain the runway centerline. When re-established on the runway centerline, reapply brakes and reverse thrust, as necessary.

If the aircraft is allowed to weathervane into the wind, reverse thrust side force combined with a crosswind on a wet or slippery runway can cause the aircraft to drift to the downwind side of the runway. Main gear tire cornering forces are reduced when the anti-skid system is operating at maximum braking effectiveness. This procedure will minimize the reverse thrust side force component and provide the tire cornering forces necessary to realign with the runway centerline.

Attachment 3: Tabulated Simulation Scenario Data

Simulation Scenario Matrix

Model	737-700W	**SWA T/R stowage procedure**	80/60 knots	**Trim setup**	on-ground, flaps 40, set airspeed so that initial ground speed will vary with winds
Engines	CFM56-7B24	**Boeing T/R stowage procedure**	60/30 knots		main and nose gear touch down, ground spoilers deployed per speedbrake handle position
Flaps	40				
Brakes	Category A	**Runway 31C distance available**	5826 feet	**Backdriven variables**	stab, column, wheel, brake pressure, set TRA to match event N1
Weight	118240 lb	**Calculated event air distance**	1250 feet	**Math pilot controllers**	brake math pilot, per methodology
Center of gravity	21%MAC				
Initial airspeed (FDR)	124 knots			**Notes:**	1. Shaded cells are used to group related calculations
Environment	MDW conditions, 12/8/05, per information Victor				2. For simulation scenarios that extend beyond the end of the runway (and valid extracted airplane braking coefficient),
	altimeter 30.06 inches Hg (Hp = 492 feet), winds 100/11 deg. magnetic/knots (9 knot tailwind), temp -3 Celcius				the airplane braking coefficient will be held constant at an average value required to match the event ground speed.

Simulation Case	Description	Engine Mode at T/R Command	Delay to T/R Command	T/R Command Position	Speed at T/R stowage command (knots)	Braking Configuration (Ramp & Delay)	Airplane Braking Coefficient	Ground Spoiler Configuration	Winds	Simulation Ground Distance (feet) [constant sim mu]	Total Simulation Ground Distance (feet) [constant sim mu]	Comments	Simulation Ground Speed at Runway Exit/Blast Pad Entry (knots)	Calculated Rwy 31C Distance Remaining (feet)
30A	event_match_constant_ap_mu	per FDR	per FDR	per FDR	0	per FDR	constant ap equivalent	auto	per event	4550	4770	distance to end of blast pad	-	-
30B*	event_match_time_vary_ap_mu	per FDR	per FDR	per FDR	0	per FDR	event extraction	auto	per event	4538	4758	distance to end of blast pad	-	-
30C	event_match_constant_sim_mu	per FDR	per FDR	per FDR	0	per FDR	constant sim equivalent	auto	per event	4550	4770	distance to end of blast pad	-	-
31	event_eventwind	per FDR	per FDR	per FDR	0	per FDR	constant sim equivalent	auto	per event	5109	5329	-	50	(753)
32	event_zerowind	per FDR	per FDR	per FDR	0	per FDR	constant sim equivalent	auto	zero	4413	4633	-	13	(57)
33	event_headwind	per FDR	per FDR	per FDR	0	per FDR	constant sim equivalent	auto	opposite event	3772	3992	-	-	584
34*	N795SW_match	per FDR	per FDR	per FDR	per FDR	per FDR	N795SW extraction	per FDR	per N795SW	-	-	-	-	-
35*	N213WN_match	per FDR	per FDR	per FDR	per FDR	per FDR	N213WN extraction	per FDR	per N213WN	-	-	-	-	-
36*	N482WN_match	per FDR	per FDR	per FDR	per FDR	per FDR	N482WN extraction	per FDR	per N482WN	-	-	-	-	-
37*	N788SA_match	per FDR	per FDR	per FDR	per FDR	per FDR	N788SA extraction	per FDR	per N788SA	-	-	-	-	-
41	auto_spoiler_fwd_idle	APP idle to ground idle	N/A	stowed	N/A	per FDR	constant sim equivalent	auto	per event	6511	6731	-	60	(2155)
42	manual_spoiler_fwd_idle	APP idle to ground idle	N/A	stowed	N/A	per FDR	constant sim equivalent	manual	per event	6684	6904	-	63	(2328)
43	no_spoiler_fwd_idle	APP idle to ground idle	N/A	stowed	N/A	per FDR	constant sim equivalent	stowed	per event	9615	9835	-	93	(5259)
44	no_spoiler_event_thrust	per FDR	per FDR	per FDR	0	per FDR	constant sim equivalent	stowed	per event	6124	6344	spoilers extend with reverse thrust	81	(1768)
45	no_spoiler_detent2_rev_stow60_30	APP idle	nominal	detent 2/rev. idle	60/30	per FDR	constant sim equivalent	stowed	per event	5053	5273	spoilers extend with reverse thrust	35	(697)
46	no_spoiler_detent2_stow0	APP idle	nominal	detent 2	0	per FDR	constant sim equivalent	stowed	per event	4491	4711	spoilers extend with reverse thrust	19	(135)
51	detent2_fwd_stow80	APP idle	nominal	detent 2/fwd idle	80 (3 sec. ramp)	per FDR	constant sim equivalent	auto	per event	5847	6067	-	48	(1491)
52	detent2_fwd_stow60	APP idle	nominal	detent 2/fwd idle	60 (3 sec. ramp)	per FDR	constant sim equivalent	auto	per event	5380	5600	-	39	(1024)
53	detent2_fwd_stow80_60	APP idle	nominal	detent 2/fwd idle	80/60	per FDR	constant sim equivalent	auto	per event	5707	5927	-	46	(1351)
54	detent2_rev_stow60_30	APP idle	nominal	detent 2/rev. idle	60/30	per FDR	constant sim equivalent	auto	per event	4887	5107	-	30	(531)
55	detent2_stow0	APP idle	nominal	detent 2	0	per FDR	constant sim equivalent	auto	per event	4326	4546	-	-	30
56	detentmax_fwd_stow80	APP idle	nominal	detent max/fwd idle	80 (3 sec. ramp)	per FDR	constant sim equivalent	auto	per event	5771	5991	-	47	(1415)
57	detentmax_fwd_stow60	APP idle	nominal	detent max/fwd idle	60 (3 sec. ramp)	per FDR	constant sim equivalent	auto	per event	5239	5459	-	36	(883)
58	detentmax_fwd_stow80_60	APP idle	nominal	detent max/fwd idle	80/60	per FDR	constant sim equivalent	auto	per event	5626	5846	-	44	(1270)
59	detentmax_rev_stow60_30	APP idle	nominal	detent max/rev. idle	60/30	per FDR	constant sim equivalent	auto	per event	4727	4947	-	25	(371)
60	detentmax_stow0	APP idle	nominal	detent max	0	per FDR	constant sim equivalent	auto	per event	4085	4305	-	-	271

* Time varying airplane braking coefficient value.

Note: Add 220 feet to simulation ground distance for cases 30-60 to account for distance traveled during 1 second between touchdown and simulation start.

Simulation Scenario Matrix (Continued)

Simulation Case	Description	Engine Mode at T/R Command	Delay to T/R Command	T/R Command Position	Speed at T/R stowage command (knots)	Braking Configuration (Ramp & Delay)	Airplane Braking Coefficient	Ground Spoiler Configuration	Winds	Simulation Ground Distance (feet) [constant sim mu]	Total Simulation Ground Distance (feet) [constant sim mu]	LSPS Ground Distance (feet)	QRH/FPPM Ground Distance (feet)	QRH-PSIM	LSPS-PSIM	QRH-LSPS	Least Conserv.	In Between	Most Conserv.
61	Dry_MLW_AFM	APP idle to ground idle	N/A	stowed	N/A	max. manual	0.41	auto	zero	1501	1716	1801	1914	198	85	113	PSIM	LSPS	QRH
62	Dry_MLW_TR	APP idle	nominal	detent 2/rev. idle	60/30	max. manual	0.41	auto	zero	1447	1662	1702	1794	132	40	92	PSIM	LSPS	QRH
63	Good__MLW_TR	APP idle	nominal	detent 2/rev. idle	60/30	max. manual	0.2	auto	zero	2509	2724	2740	2740	16	16	0	PSIM	QRH	LSPS
64	Poor_MLW__TR	APP idle	nominal	detent 2/rev. idle	60/30	max. manual	0.05	auto	zero	5467	5682	5503	5502	(180)	(179)	(1)	QRH	LSPS	PSIM

Initial Conditions for Cases 61-64: 128,000 lb, 9% MAC, VB 126.7 knots, sea level, standard day, 29.92 in. Hg, 15C, zero wind.

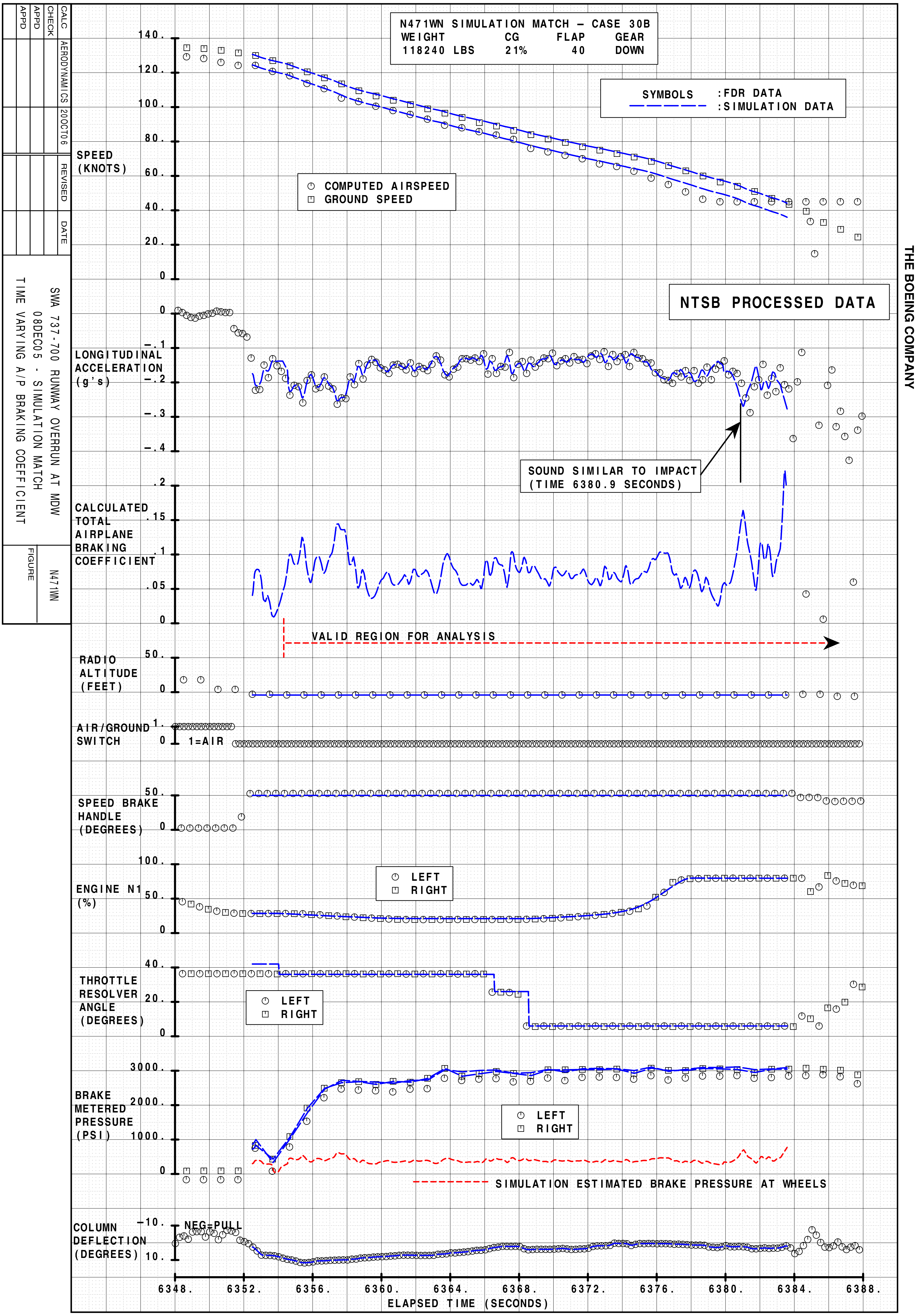
Note: Add 215 feet to simulation ground distance for cases 61-64 to account for distance traveled during 1 second between touchdown and simulation start.

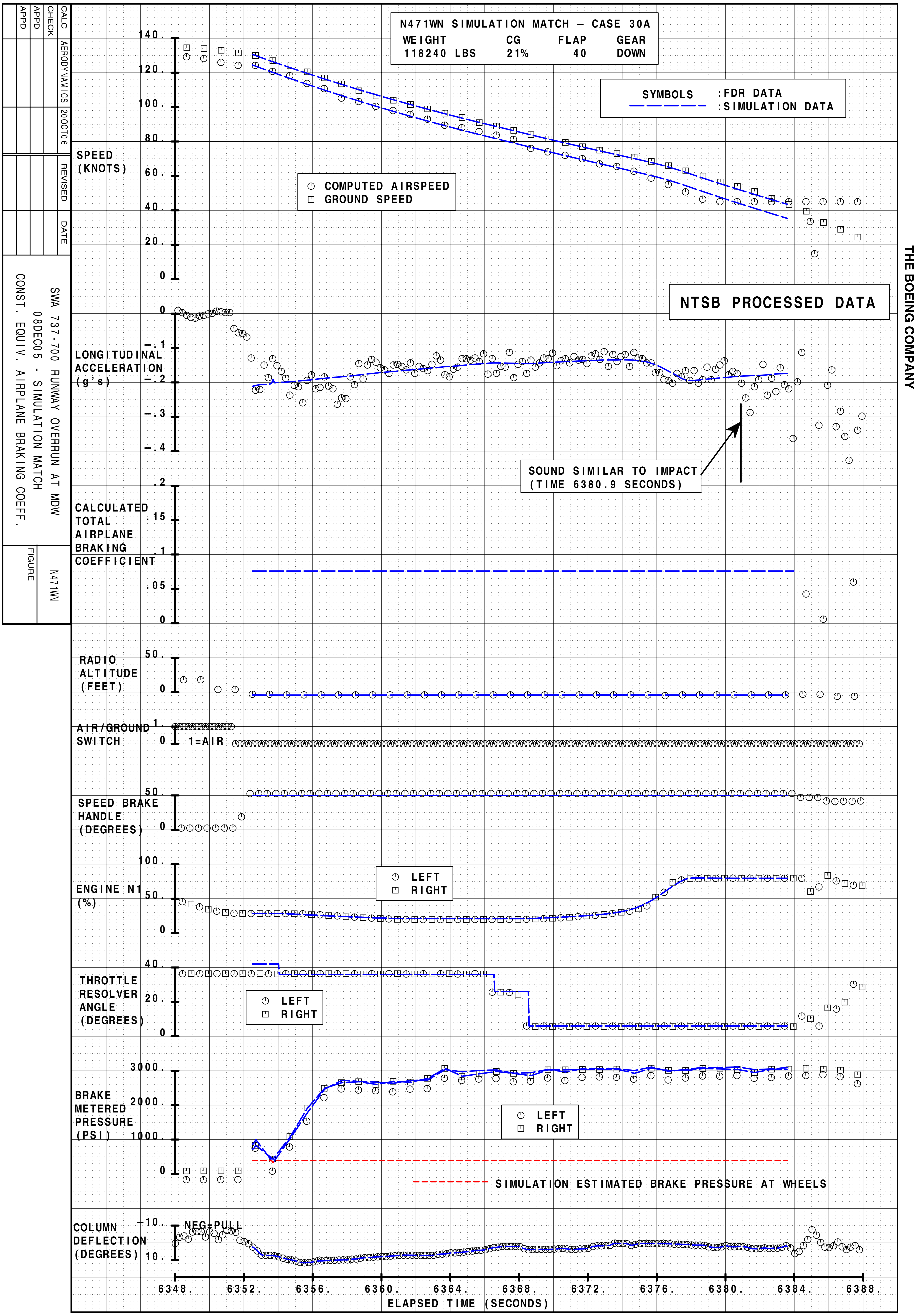
Simulation Case	Description	Engine Mode at T/R Command	Delay to T/R Command	T/R Command Position	Speed at T/R stowage command (knots)	Braking Configuration (Ramp & Delay)	Airplane Braking Coefficient	Ground Spoiler Configuration	Winds	Simulation Ground Distance (feet) [constant sim mu]	Total Simulation Ground Distance (feet) [constant sim mu]	LSPS Ground Distance (feet)	QRH/FPPM Ground Distance (feet)	QRH-PSIM	LSPS-PSIM	QRH-LSPS	Least Conserv.	In Between	Most Conserv.
101	Dry_TR_max_manual	APP idle	nominal	detent 2/rev. idle	60/30	max. manual	0.41	auto	9 knots factored	1888	1888	1765	1930	43	(123)	165	LSPS	PSIM	QRH
102	Good_TR_max_manual	APP idle	nominal	detent 2/rev. idle	60/30	max. manual	0.2	auto	9 knots factored	3032	3032	2946	3005	(27)	(86)	59	LSPS	QRH	PSIM
103	Medium_TR_max_manual	APP idle	nominal	detent 2/rev. idle	60/30	max. manual	0.1	auto	9 knots factored	4517	4517	4416	4523	5	(101)	107	LSPS	PSIM	QRH
104	Poor_TR_max_manual	APP idle	nominal	detent 2/rev. idle	60/30	max. manual	0.05	auto	9 knots factored	6458	6458	6183	6367	(91)	(275)	184	LSPS	QRH	PSIM
105	Dry_max_manual	APP idle to ground idle	N/A	stowed	N/A	max. manual	0.41	auto	9 knots factored	1962	1962	1863	2050	88	(99)	187	LSPS	PSIM	QRH
106	Good_max_manual	APP idle to ground idle	N/A	stowed	N/A	max. manual	0.2	auto	9 knots factored	3385	3385	3417	3425	40	32	8	PSIM	LSPS	QRH
107	Medium_max_manual	APP idle to ground idle	N/A	stowed	N/A	max. manual	0.1	auto	9 knots factored	5638	5638	5848	5753	115	210	(95)	PSIM	QRH	LSPS
108	Poor_max_manual	APP idle to ground idle	N/A	stowed	N/A	max. manual	0.05	auto	9 knots factored	9359	9359	9824	9237	(122)	465	(587)	QRH	PSIM	LSPS
201	Dry_TR_auto_max	APP idle	nominal	detent 2/rev. idle	60/30	autobrake max	0.41	auto	9 knots factored	2065	2065	2462	2519	453	397	57	PSIM	LSPS	QRH
202	Good_TR_auto_max	APP idle	nominal	detent 2/rev. idle	60/30	autobrake max	0.2	auto	9 knots factored	2907	2907	3098	3339	431	191	241	PSIM	LSPS	QRH
203	Medium_TR_auto_max	APP idle	nominal	detent 2/rev. idle	60/30	autobrake max	0.1	auto	9 knots factored	4440	4440	4335	4699	259	(105)	364	LSPS	PSIM	QRH
204	Poor_TR_auto_max	APP idle	nominal	detent 2/rev. idle	60/30	autobrake max	0.05	auto	9 knots factored	6425	6425	6035	6629	204	(390)	594	LSPS	PSIM	QRH
205	Dry_auto_max	APP idle to ground idle	N/A	stowed	N/A	autobrake max	0.41	auto	9 knots factored	2074	2074	2462	2539	465	388	77	PSIM	LSPS	QRH
206	Good_auto_max	APP idle to ground idle	N/A	stowed	N/A	autobrake max	0.2	auto	9 knots factored	3239	3239	3612	3799	559	373	187	PSIM	LSPS	QRH
207	Medium_auto_max	APP idle to ground idle	N/A	stowed	N/A	autobrake max	0.1	auto	9 knots factored	5539	5539	5747	5909	370	208	162	PSIM	LSPS	QRH
208	Poor_auto_max	APP idle to ground idle	N/A	stowed	N/A	autobrake max	0.05	auto	9 knots factored	9310	9310	9711	9529	219	401	(182)	PSIM	QRH	LSPS
301	Dry_TR_auto_3	APP idle	nominal	detent 2/rev. idle	60/30	autobrake 3	0.41	auto	9 knots factored	3569	3569	3789	3850	281	220	61	PSIM	LSPS	QRH
302	Good_TR_auto_3	APP idle	nominal	detent 2/rev. idle	60/30	autobrake 3	0.2	auto	9 knots factored	3596	3596	3809	3880	283	213	71	PSIM	LSPS	QRH
303	Medium_TR_auto_3	APP idle	nominal	detent 2/rev. idle	60/30	autobrake 3	0.1	auto	9 knots factored	4440	4440	4517	4774	334	77	257	PSIM	LSPS	QRH
304	Poor_TR_auto_3	APP idle	nominal	detent 2/rev. idle	60/30	autobrake 3	0.05	auto	9 knots factored	6425	6425	6068	6643	217	(357)	575	LSPS	PSIM	QRH
305	Dry_auto_3	APP idle to ground idle	N/A	stowed	N/A	autobrake 3	0.41	auto	9 knots factored	3639	3639	3790	3850	211	151	60	PSIM	LSPS	QRH
306	Good_auto_3	APP idle to ground idle	N/A	stowed	N/A	autobrake 3	0.2	auto	9 knots factored	3722	3722	3896	3930	208	174	34	PSIM	LSPS	QRH
307	Medium_auto_3	APP idle to ground idle	N/A	stowed	N/A	autobrake 3	0.1	auto	9 knots factored	5539	5539	5920	5974	435	381	54	PSIM	LSPS	QRH
308	Poor_auto_3	APP idle to ground idle	N/A	stowed	N/A	autobrake 3	0.05	auto	9 knots factored	9310	9310	9721	9523	212	411	(198)	PSIM	QRH	LSPS
401	Dry_TR_auto_2	APP idle	nominal	detent 2/rev. idle	60/30	autobrake 2	0.41	auto	9 knots factored	5075	5075	5075	5247	172	(0)	172	LSPS	PSIM	QRH
402	Good_TR_auto_2	APP idle	nominal	detent 2/rev. idle	60/30	autobrake 2	0.2	auto	9 knots factored	5075	5075	5075	5247	171	(0)	172	LSPS	PSIM	QRH
403	Medium_TR_auto_2	APP idle	nominal	detent 2/rev. idle	60/30	autobrake 2	0.1	auto	9 knots factored	5393	5393	5332	5527	133	(61)	195	LSPS	PSIM	QRH
404	Poor_TR_auto_2	APP idle	nominal	detent 2/rev. idle	60/30	autobrake 2	0.05	auto	9 knots factored	6627	6627	6412	6754	128	(215)	342	LSPS	PSIM	QRH
405	Dry_auto_2	APP idle to ground idle	N/A	stowed	N/A	autobrake 2	0.41	auto	9 knots factored	5237	5237	5184	5357	119	(53)	173	LSPS	PSIM	QRH
406	Good_auto_2	APP idle to ground idle	N/A	stowed	N/A	autobrake 2	0.2	auto	9 knots factored	5238	5238	5184	5357	119	(54)	173	LSPS	PSIM	QRH
407	Medium_auto_2	APP idle to ground idle	N/A	stowed	N/A	autobrake 2	0.1	auto	9 knots factored	5995	5995	6129	6127	132	134	(2)	PSIM	QRH	LSPS
408	Poor_auto_2	APP idle to ground idle	N/A	stowed	N/A	autobrake 2	0.05	auto	9 knots factored	9310	9310	9817	9374	64	507	(443)	PSIM	QRH	LSPS

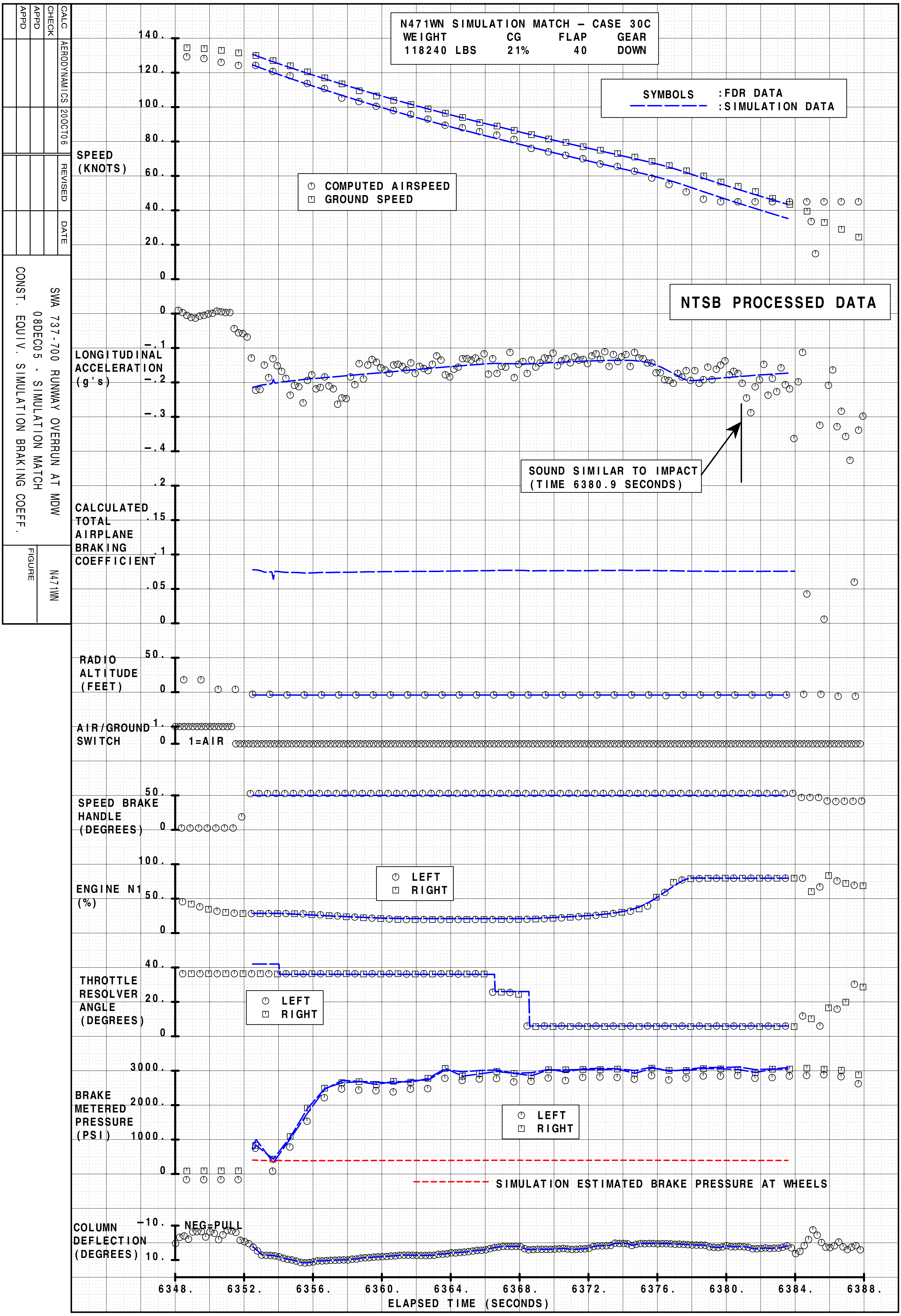
Initial Conditions for cases 101-408: 118240 lb, VREF40, 30.06 in. Hg, 492 ft, -3C, 9 kt tailwind, 0 ft air distance.
See footnote 8 on bottom of page 7 for A/C bleed, engine anti-ice, and runway slope conditions.

Note: Add zero feet to simulation ground distance for cases 101-408 because simulation starts at touchdown.

Attachment 4: N471WN Simulation Matches

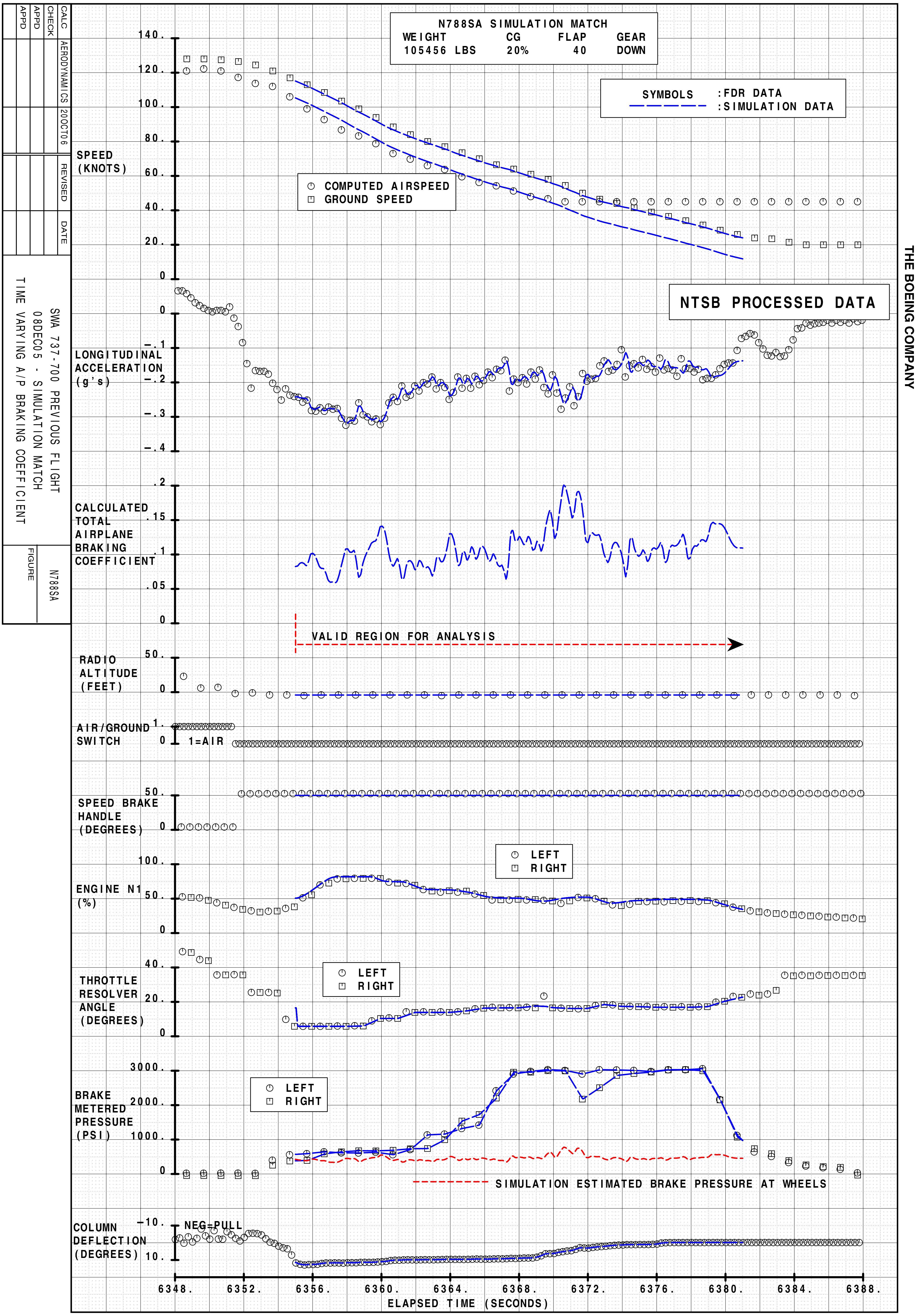

N471WN SIMULATION MATCH - CASE 30B
WEIGHT CG FLAP GEAR
118240 LBS 21% 40 DOWN
SYMBOLS :FDR DATA
:SIMULATION DATA
NTSB PROCESSED DATA
THE BOEING COMPANY
CALC
CHECK
APPD
APPD
AERODYNAMICS
20OCT06
REVISED
DATE
SWA 737-700 RUNWAY OVERRUN AT MDW
08DEC05 - SIMULATION MATCH
TIME VARYING A/P BRAKING COEFFICIENT
FIGURE
N471WN
PAGE
SPEED (KNOTS)
COMPUTED AIRSPEED
GROUND SPEED
LONGITUDINAL ACCELERATION (g's)
SOUND SIMILAR TO IMPACT (TIME 6380.9 SECONDS)
CALCULATED TOTAL AIRPLANE BRAKING COEFFICIENT
VALID REGION FOR ANALYSIS
RADIO ALTITUDE (FEET)
AIR/GROUND SWITCH
1=AIR
SPEED BRAKE HANDLE (DEGREES)
ENGINE N1 (%)
LEFT
RIGHT
THROTTLE RESOLVER ANGLE (DEGREES)
LEFT
RIGHT
BRAKE METERED PRESSURE (PSI)
LEFT
RIGHT
SIMULATION ESTIMATED BRAKE PRESSURE AT WHEELS
COLUMN DEFLECTION (DEGREES)
NEG=PULL
6348. 6352. 6356. 6360. 6364. 6368. 6372. 6376. 6380. 6384. 6388.
ELAPSED TIME (SECONDS)

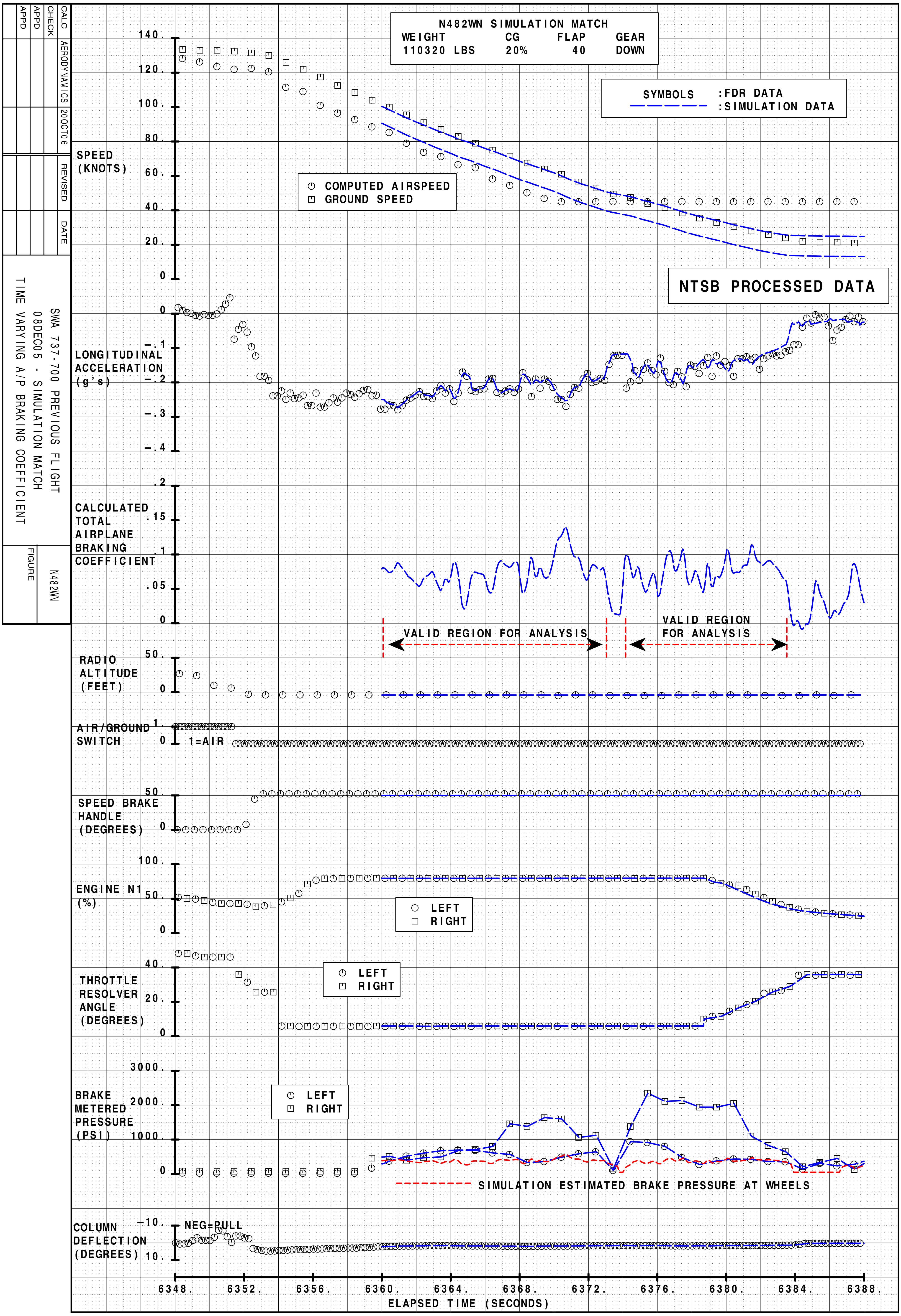

N471WN SIMULATION MATCH – CASE 30A
WEIGHT 118240 LBS CG 21% FLAP 40 GEAR DOWN
SYMBOLS :FDR DATA
:SIMULATION DATA
NTSB PROCESSED DATA
THE BOEING COMPANY
SPEED (KNOTS)
COMPUTED AIRSPEED
GROUND SPEED
LONGITUDINAL ACCELERATION (g's)
SOUND SIMILAR TO IMPACT (TIME 6380.9 SECONDS)
CALCULATED TOTAL AIRPLANE BRAKING COEFFICIENT
RADIO ALTITUDE (FEET)
AIR/GROUND SWITCH
1=AIR
SPEED BRAKE HANDLE (DEGREES)
ENGINE N1 (%)
LEFT
RIGHT
THROTTLE RESOLVER ANGLE (DEGREES)
BRAKE METERED PRESSURE (PSI)
SIMULATION ESTIMATED BRAKE PRESSURE AT WHEELS
COLUMN DEFLECTION (DEGREES)
NEG=PULL
ELAPSED TIME (SECONDS)
SWA 737-700 RUNWAY OVERRUN AT MDW
08DEC05 - SIMULATION MATCH
CONST. EQUIV. AIRPLANE BRAKING COEFF.
N471WN
FIGURE
PAGE
CALC
CHECK
APPD
APPD
AERODYNAMICS
20OCT06
REVISED
DATE

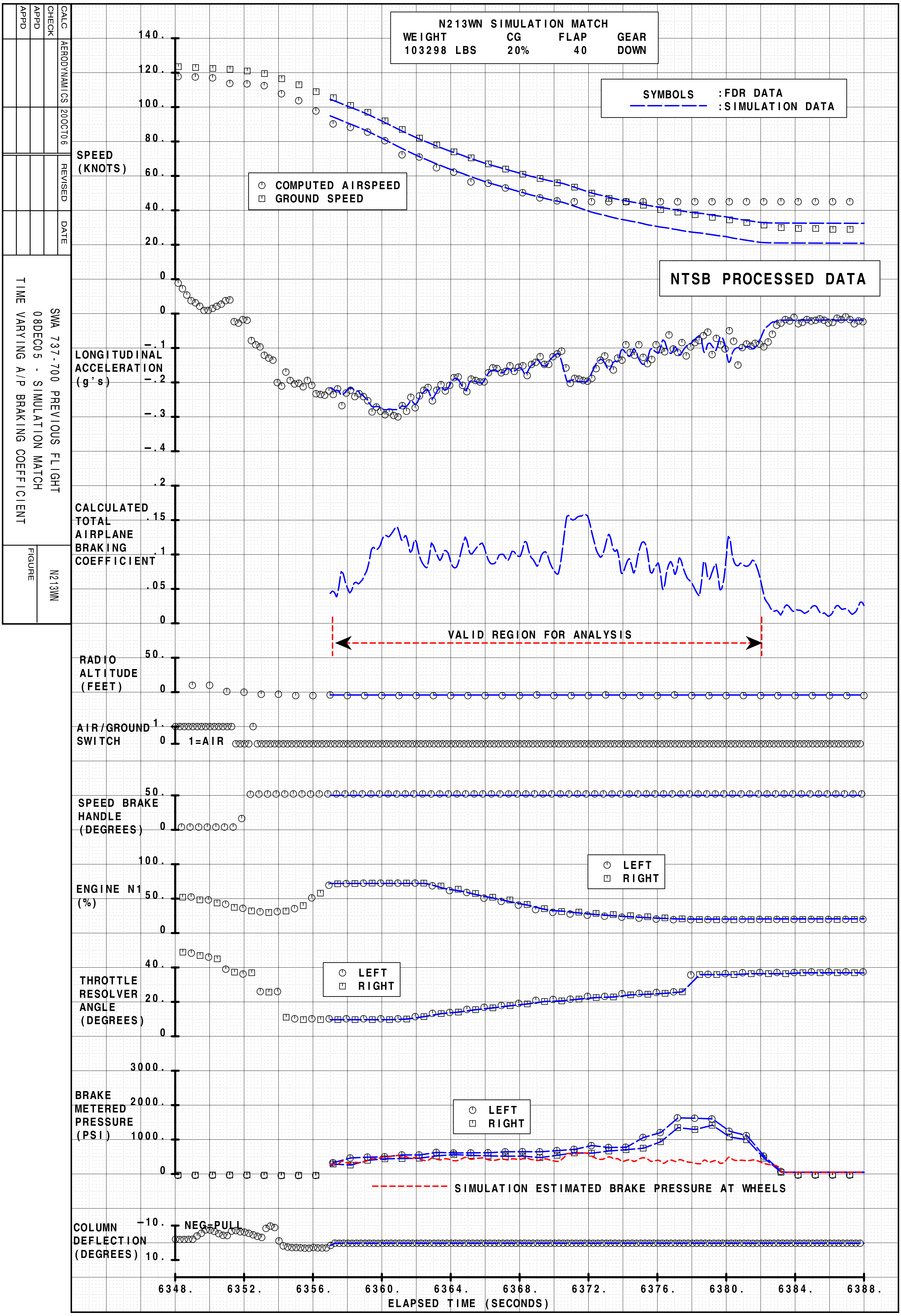


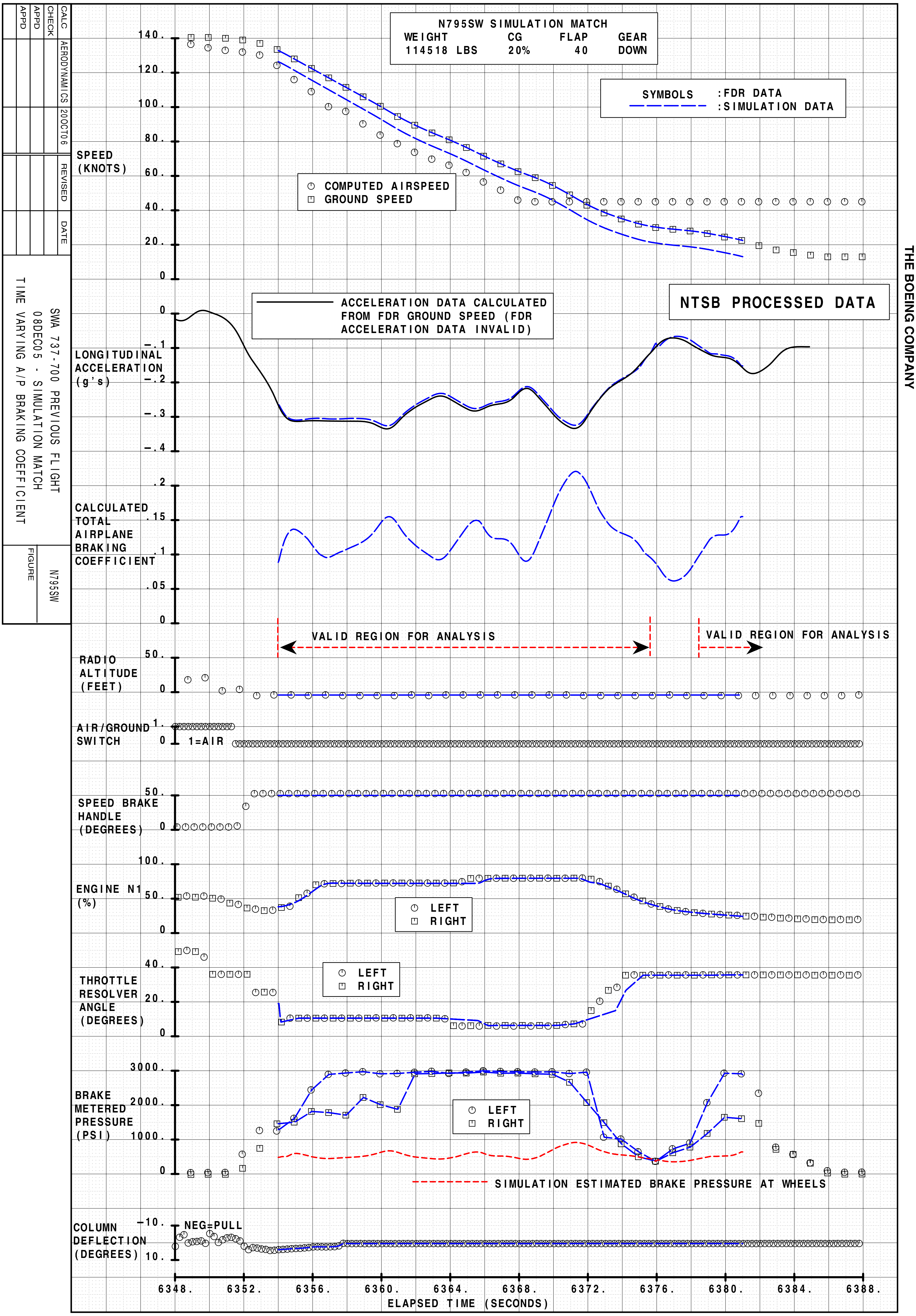
THE BOEING COMPANY

Attachment 5: Prior Landing Simulation Matches

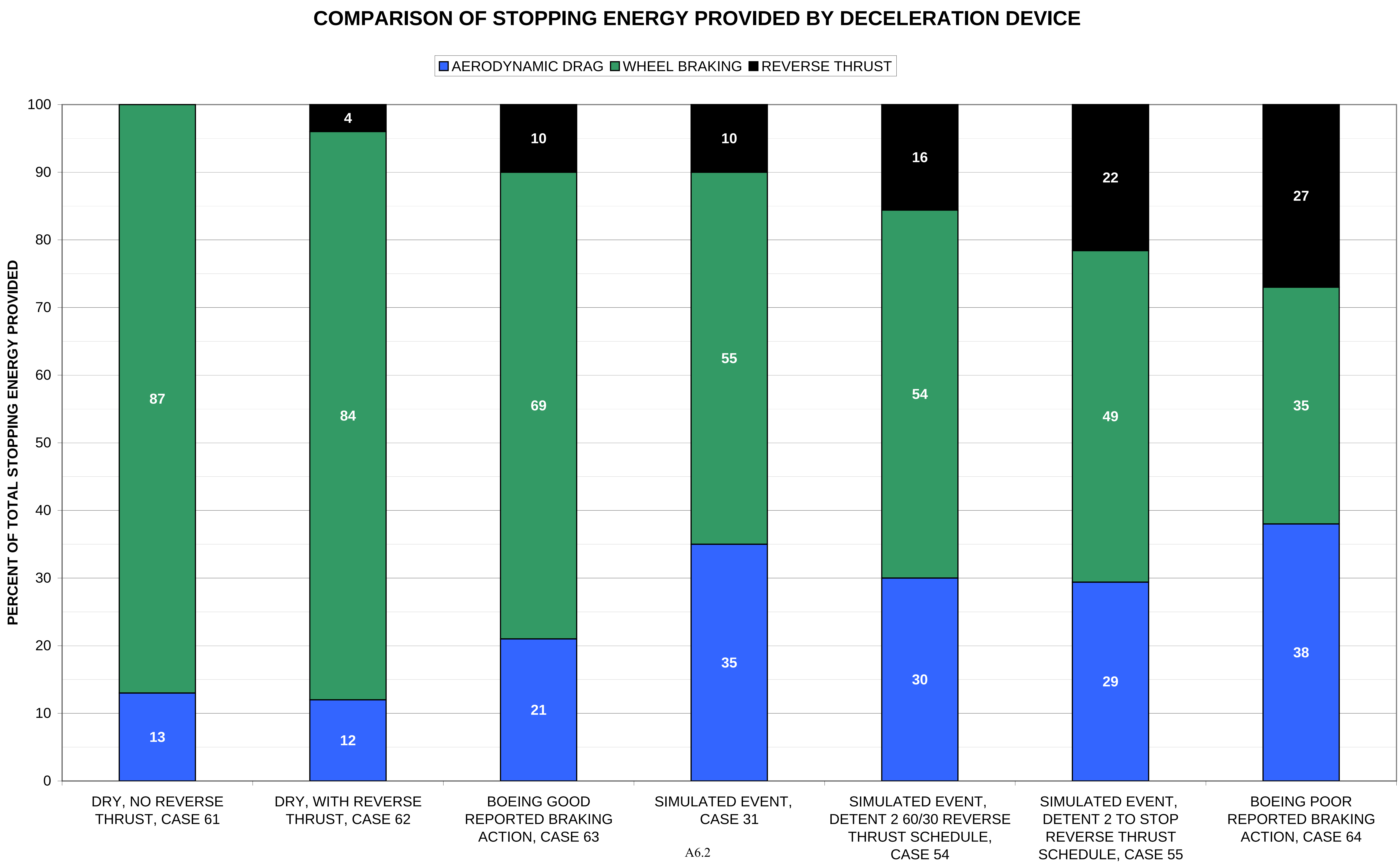

N788SA SIMULATION MATCH
WEIGHT 105456 LBS
CG 20%
FLAP 40
GEAR DOWN
SYMBOLS
:FDR DATA
:SIMULATION DATA
NTSB PROCESSED DATA
SPEED (KNOTS)
COMPUTED AIRSPEED
GROUND SPEED
LONGITUDINAL ACCELERATION (g's)
CALCULATED TOTAL AIRPLANE BRAKING COEFFICIENT
VALID REGION FOR ANALYSIS
RADIO ALTITUDE (FEET)
AIR/GROUND SWITCH
1=AIR
SPEED BRAKE HANDLE (DEGREES)
ENGINE N1 (%)
LEFT
RIGHT
THROTTLE RESOLVER ANGLE (DEGREES)
BRAKE METERED PRESSURE (PSI)
SIMULATION ESTIMATED BRAKE PRESSURE AT WHEELS
COLUMN DEFLECTION (DEGREES)
NEG=PULL
ELAPSED TIME (SECONDS)
6348. 6352. 6356. 6360. 6364. 6368. 6372. 6376. 6380. 6384. 6388.
CALC
CHECK
APPD
APPD
AERODYNAMICS
20OCT06
REVISED
DATE
SWA 737-700 PREVIOUS FLIGHT
08DEC05 - SIMULATION MATCH
TIME VARYING A/P BRAKING COEFFICIENT
FIGURE
N788SA
PAGE
THE BOEING COMPANY


N482WN SIMULATION MATCH
WEIGHT 110320 LBS
CG 20%
FLAP 40
GEAR DOWN
SYMBOLS :FDR DATA
:SIMULATION DATA
NTSB PROCESSED DATA
SPEED (KNOTS)
COMPUTED AIRSPEED
GROUND SPEED
LONGITUDINAL ACCELERATION (g's)
CALCULATED TOTAL AIRPLANE BRAKING COEFFICIENT
VALID REGION FOR ANALYSIS
VALID REGION FOR ANALYSIS
RADIO ALTITUDE (FEET)
AIR/GROUND SWITCH
1=AIR
SPEED BRAKE HANDLE (DEGREES)
ENGINE N1 (%)
LEFT
RIGHT
THROTTLE RESOLVER ANGLE (DEGREES)
LEFT
RIGHT
BRAKE METERED PRESSURE (PSI)
LEFT
RIGHT
SIMULATION ESTIMATED BRAKE PRESSURE AT WHEELS
COLUMN DEFLECTION (DEGREES)
NEG=PULL
ELAPSED TIME (SECONDS)
CALC
CHECK
APPD
APPD
AERODYNAMICS
20OCT06
REVISED
DATE
SWA 737-700 PREVIOUS FLIGHT
08DEC05 - SIMULATION MATCH
TIME VARYING A/P BRAKING COEFFICIENT
FIGURE
N482WN
PAGE
THE BOEING COMPANY


N213WN SIMULATION MATCH
WEIGHT 103298 LBS
CG 20%
FLAP 40
GEAR DOWN
SYMBOLS
○ :FDR DATA
— — :SIMULATION DATA
NTSB PROCESSED DATA
SPEED (KNOTS)
COMPUTED AIRSPEED
GROUND SPEED
LONGITUDINAL ACCELERATION (g's)
CALCULATED TOTAL AIRPLANE BRAKING COEFFICIENT
VALID REGION FOR ANALYSIS
RADIO ALTITUDE (FEET)
AIR/GROUND SWITCH
1=AIR
SPEED BRAKE HANDLE (DEGREES)
ENGINE N1 (%)
LEFT
RIGHT
THROTTLE RESOLVER ANGLE (DEGREES)
BRAKE METERED PRESSURE (PSI)
SIMULATION ESTIMATED BRAKE PRESSURE AT WHEELS
COLUMN DEFLECTION (DEGREES)
NEG=PULL
ELAPSED TIME (SECONDS)
CALC
CHECK
APPD
APPD
AERODYNAMICS
20OCT06
REVISED
DATE
SWA 737-700 PREVIOUS FLIGHT
08DEC05 - SIMULATION MATCH
TIME VARYING A/P BRAKING COEFFICIENT
FIGURE
N213WN
PAGE
THE BOEING COMPANY


N795SW SIMULATION MATCH
WEIGHT 114518 LBS
CG 20%
FLAP 40
GEAR DOWN
SYMBOLS :FDR DATA
:SIMULATION DATA
NTSB PROCESSED DATA
SPEED (KNOTS)
COMPUTED AIRSPEED
GROUND SPEED
LONGITUDINAL ACCELERATION (g's)
ACCELERATION DATA CALCULATED FROM FDR GROUND SPEED (FDR ACCELERATION DATA INVALID)
CALCULATED TOTAL AIRPLANE BRAKING COEFFICIENT
VALID REGION FOR ANALYSIS
VALID REGION FOR ANALYSIS
RADIO ALTITUDE (FEET)
AIR/GROUND SWITCH
1=AIR
SPEED BRAKE HANDLE (DEGREES)
ENGINE N1 (%)
LEFT
RIGHT
THROTTLE RESOLVER ANGLE (DEGREES)
LEFT
RIGHT
BRAKE METERED PRESSURE (PSI)
LEFT
RIGHT
SIMULATION ESTIMATED BRAKE PRESSURE AT WHEELS
COLUMN DEFLECTION (DEGREES)
NEG=PULL
6348. 6352. 6356. 6360. 6364. 6368. 6372. 6376. 6380. 6384. 6388.
ELAPSED TIME (SECONDS)
CALC
CHECK
APPD
APPD
AERODYNAMICS
20OCT06
REVISED
DATE
SWA 737-700 PREVIOUS FLIGHT
08DEC05 - SIMULATION MATCH
TIME VARYING A/P BRAKING COEFFICIENT
FIGURE
N795SW
PAGE
THE BOEING COMPANY

Attachment 6: Stopping Energy Comparison


COMPARISON OF STOPPING ENERGY PROVIDED BY DECELERATION DEVICE
AERODYNAMIC DRAG
WHEEL BRAKING
REVERSE THRUST
PERCENT OF TOTAL STOPPING ENERGY PROVIDED
0
10
20
30
40
50
60
70
80
90
100
13
87
12
84
4
21
69
10
35
55
10
30
54
16
29
49
22
38
35
27
DRY, NO REVERSE THRUST, CASE 61
DRY, WITH REVERSE THRUST, CASE 62
BOEING GOOD REPORTED BRAKING ACTION, CASE 63
SIMULATED EVENT, CASE 31
SIMULATED EVENT, DETENT 2 60/30 REVERSE THRUST SCHEDULE, CASE 54
SIMULATED EVENT, DETENT 2 TO STOP REVERSE THRUST SCHEDULE, CASE 55
BOEING POOR REPORTED BRAKING ACTION, CASE 64