

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Washington, D.C. 20594

April 20, 2016

Aircraft Performance Study

by John O'Callaghan

Location: Conroe, TX (Lone Star Executive Airport (KCXO))

Date: September 19, 2014

Time: 08:47 Central Daylight Time (CDT)
(13:47 Universal Coordinated Time (UTC))

Aircraft: Embraer EMB-505, N322QS

NTSB#: CEN14FA505

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APPENDIX A: KCXO Airport Diagram and Other Information

APPENDIX B: Data Reduction Procedures for Using Ground Vehicle Friction Measurements to Calculate Aircraft Tire Friction Performance (NASA CFME μ_B Model)

APPENDIX C: FAA Safety Alert For Operators (SAFO) 15009

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B. GROUP

Chairman: John O'Callaghan
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C. HISTORY OF FLIGHT

On September 19, 2014, about 08:47 central daylight time¹, an Embraer EMB-505 airplane, N322QS, encountered soft terrain and mud after overrunning the runway while landing at the Lone Star Executive Airport (KCXO), Conroe, Texas. Neither of the airline transport rated pilots on board were injured. The airplane was substantially damaged. The airplane was operated by NetJets Aviation, Inc. as a 14 Code of Federal Regulations Part 91 positioning flight. Instrument meteorological conditions (IMC) prevailed for the flight, which was operated on an instrument flight rules flight plan. The flight originated from the Nashville International Airport (KBNA), Nashville, Tennessee, at 07:10.

¹ Local time at Conroe on the day of the accident was Central Daylight Time (CDT). CDT = UTC - 5 hours. Times in this *Aircraft Performance Study* are those recorded on the Flight Data Recorder (FDR), in CDT, unless otherwise noted.

According to the air traffic controller who witnessed the accident, the pilots flew the area navigation (RNAV) runway 1 approach and broke out of the clouds at the minimums for the approach. The controller stated the airplane touched down just past the 1,000 foot marker on the runway but did not appear to decelerate as it continued down the runway. The airplane traveled off the departure end of the runway and continued about 400 feet through soft/muddy terrain before coming to rest half way down a ditch. The controller stated there was moderate to heavy rain at the time of the accident.

Objective and scope of the Aircraft Performance Study

The objective of this *Aircraft Performance Study* is to determine and analyze the motion of the airplane and the physical forces that produce that motion. In particular, the *Study* attempts to define the airplane's position and orientation during the relevant portion of the flight, and determine the airplane's response to control inputs, external disturbances, ground forces, and other factors that could affect its trajectory.

The data used to determine and analyze the airplane motion includes the following:

- Wreckage location and condition.
- Ground scars / markings.
- Flight Data Recorder (FDR) data.
- Cockpit Voice Recorder (CVR) information.
- Runway macrotexture, cross-slope, and friction measurement information.
- Weather information.
- Airplane thrust and aerodynamic performance information.
- Output from aircraft performance computer programs and simulations.
- Models of braking friction on wet runways.
- Models of water drainage from runways.

This *Study* describes the results of using the data listed above in defining, as far as possible, the position of N322QS relative to the KCXO runway 1 threshold throughout the approach, landing, and overrun. The *Study* introduces the aircraft motion data collected during the investigation, describes the methods used to extract additional aircraft motion information from the FDR, and presents the results of these calculations.

In addition, this *Study* examines this accident within the larger context of the stopping performance of airplanes on wet runways. The physics of wheel braking is reviewed, as are the operational requirements for dispatching to a runway that is forecast to be wet, and for evaluating the landing distance required when conditions at arrival have deteriorated from the dispatch assumptions. The *Study* also presents the background and status of a number of NTSB recommendations addressing landing distance assessments and the wet runway landing distance advisory data in some Airplane Flight Manuals (AFMs). Several models for defining the wheel braking friction coefficient (μ_B) on wet runways are described and evaluated, and five other wet runway landing accidents and two wet runway flight tests are discussed.

Summary of results

The results of this *Study* indicate that the approach of N322QS to runway 1 complied with the operator's stabilized approach criteria, with the airplane tracking the RNAV final approach course and glide slope at an airspeed of about 130 kt. (within the +20/-0 kt. tolerance on the 112 kt. nominal landing reference speed (V_{REF}) corresponding to the airplane's landing weight and flap setting, and within the ± 10 kt. tolerance of the $V_{REF} + 10$ kt. (122 kt.) final approach target speed). The airplane crossed the runway threshold at about 121 kt. (9 kt. faster than V_{REF}), and touched down about 903 ft. from the threshold, at a groundspeed of 118 kt. The headwind component at touchdown was negligible.

After touchdown, the pilot's brake pedal deflections progressively increased to maximum braking over a period of about 11 seconds, and the airplane achieved a maximum deceleration (longitudinal load factor, n_x) of about -0.17 G's about 7 seconds after touchdown. The airplane maintained an n_x between -0.15 and -0.17 G's for about another 6 seconds, until the wheel speeds dropped to zero, consistent with the application of the emergency / parking brake (EPB) and the beginning of a full, locked-wheel skid. The wheel speeds reached zero 13.5 seconds after touchdown, and the wheels remained "locked" until the aircraft came to rest. During the skid, the n_x steadily increased² from -0.17 G's to about -0.09 G's, before dropping again to about -0.12 G's as the airplane passed the end of the runway. The airplane exited the runway about 27 seconds after touchdown, at a groundspeed of about 61 knots, and came to rest about 400 ft. past the end of the runway.

During the landing roll, the Cockpit Voice Recorder (CVR) recorded the crew making several statements expressing concern about the airplane's speed and deceleration.

This *Study* also presents an estimate of the braking friction coefficient (μ_B) developed by the airplane during the landing roll, using FDR data, and airplane thrust and aerodynamic data provided by Embraer. After the airplane touches down, the computed μ_B increases steadily as the brake pedals are depressed, reaching a peak of about 0.16 before decreasing steadily to about 0.06 after the EPB is applied and the airplane enters a full, locked-wheel skid. However, even before the EPB is applied, the computed μ_B is significantly lower than the μ_B that would be predicted using models prescribed in 14 Code of Federal Regulations (CFR) Part 25 for computing accelerate-stop distances on a wet runway.³ The computed μ_B (before the EPB is applied) is also significantly lower than the μ_B implied by the unfactored, wet-runway landing distances published in the EMB-505 Pilot's Operating Handbook, which are computed as 25% greater than the unfactored (demonstrated) landing distances on a dry runway.

However, the μ_B achieved during the accident is consistent with the μ_B predicted using a National Aeronautics and Space Administration (NASA) model that is based on runway

² I.e., the n_x value became less negative, indicating decreased deceleration. Positive values of n_x indicate acceleration (increasing speed), and negative values of n_x indicate deceleration (decreasing speed).

³ Specifically, the μ_B model is prescribed in 14 CFR 25.109(c).

friction measurements taken with a Continuous Friction Measurement Equipment (CFME) device. These results reflect NTSB findings in other accidents, and confirm that the actual μ_B that can be achieved on a wet runway may be significantly lower than the μ_B predicted by industry-standard models, or the μ_B required to match the manufacturer's published unfactored, wet-runway landing distances. The results also indicate that a more accurate estimate of the degraded stopping performance (and consequent longer landing distances) that are possible on wet runways may be obtained by applying the NASA μ_B model to the minimum CFME friction levels prescribed in Advisory Circular (AC) 150/5320-12C for airports certified per 14 CFR Part 139.

The decrease in μ_B after the EPB is applied is consistent with research indicating that the braking friction achieved in a full locked-wheel skid (a braking slip ratio of 1.0) is significantly less than the maximum μ_B that can be achieved at lower slip ratios. Examination of N322QS's tires revealed evidence of reverted-rubber hydroplaning, which is also consistent with locked-wheel skids and a reduction in μ_B . The *Study* indicates that had the μ_B remained at the levels attained prior to the EPB being set, the airplane would have stopped on the runway.

D. DETAILS OF THE INVESTIGATION

I. The Embraer EMB-505 Phenom 300 Airplane

Figure 1 shows a 3-view image of the EMB-505, taken from Reference 1. Table 1 provides some dimensions of the airplane, as well as relevant mass properties for N322QS on the accident flight. The mass properties were computed using the weight and balance buildup shown in Table 2.

Item	Value
Reference dimensions (from References 2 & 4):	
Wing area	28.5 m ² = 306.8 ft. ²
Wing span	15.91 m = 52.19 ft.
Mean Aerodynamic Chord (MAC)	2.05 m = 80.71 in. = 6.726 ft.
Fuselage station of the MAC leading edge (LEMAC)	264.57 inches
Mass properties for N322QS:	
FDR-recorded weight at landing	15476 pounds
Basic Operating Weight	12346 pounds
Payload weight	0 pounds
Computed fuel weight at landing	3130 pounds (= 15476 – 12346 pounds)

Table 1. Dimensions of the Embraer EMB-505 airplane, and relevant mass properties for N322QS.

Item	W, lb.	Arm, in.	Moment, in*lb
Basic Operating Weight	12346	291.1	3594279
Payload	0		0
Fuel weight	3130	264.3	827134
Total	15476	285.7	4421413
Center of Gravity (CG), % MAC =		26.2	

Table 2. N322QS weight-and-balance buildup for accident landing.

The Basic Operating weight and moment arm for N322QS shown in Table 2 was obtained from Reference 3. The fuel load of 3130 lb. is computed as the difference between the airplane's weight at landing as recorded by the Flight Data Recorder (FDR), and the Basic Operating Weight, as shown in Table 1. The moment arm of the fuel (264.3 in.) was computed based on the fuel distribution table in the Pilot's Operating Handbook (POH, Reference 4).

For a landing weight of 15476 lb., the POH specifies a Flaps 3 V_{REF} of 112 KIAS.

II. Ground Scars and Markings

KCXO runway 1 is 5000 ft. long and 100 ft. wide, at threshold elevation of 230 ft. (for additional details about KCXO and its runways, see Appendix A). Several scrub marks on the runway, and ruts or furrows in the ground past the end of the runway, provided evidence of the trajectory of the airplane's landing gear following the initial touchdown. The runway coordinates⁴ of these items are listed in Table 3. The items in Table 3 are also plotted in runway coordinates in Figures 2 and 4.

Item	x-coordinate (ft.)	y-coordinate (ft.)
Start of left main gear runway scrub mark	3505	-15
End of left main gear runway scrub mark	4995	-9
Start of right main gear runway scrub mark	3797	-9
End of right main gear runway scrub mark	4995	-1
Start of nose gear ground furrow	5027	4
End of nose gear ground furrow	5226	19
Start of left main gear ground furrow	5007	-6
End of left main gear ground furrow	5374	28
Start of right main gear ground furrow	4991	-1
End of right main gear ground furrow	5375	37
Airplane resting position (based on photographs)	5400	37

Table 3. Runway coordinates of selected ground scars and markings. The elevation data for these points and the coordinates of the airplane rest position were obtained from the *Google Earth* computer program.

⁴ These coordinates were measured by an Embraer investigator at the scene using a hand-held Global Positioning System (GPS) device. The latitude and longitude coordinates recorded by the GPS have been converted into runway coordinates for use in this *Study*. The origin of the runway coordinate system is on the centerline at the runway threshold. The runway x axis runs from the origin down the runway centerline, and the runway y axis runs from the origin to the right side of the runway, at 90° to the centerline (see Figures 2 and 3).

Photographs⁵ of tire scrub marks at the end of the runway, ground furrows past the end of the runway, and of the final resting position of the airplane are shown in Figure 5.

III. Recorded flight data

FDR and CVR data description

The aircraft cockpit voice recorder (CVR) and flight data recorder (FDR) were recovered and sent to the NTSB Recorders Laboratory in Washington, DC for readout.

Descriptions of the FDR and CVR and the recorder readout processes can be found in References 5 and 6, respectively. The FDR readout results in tabulated and plotted values of the recorded flight parameters versus time. The CVR readout results in a transcript of the CVR events, a partial list of which is shown in Table 4. The paraphrased version of the selected CVR events listed in Table 4 are also presented along with other information in various Figures throughout this *Study*. For the complete list of CVR events, see Reference 6.

FDR time	Full CVR transcript text	Paraphrased text on plots
08:45:41.2		[HOT-1] 1000.
08:46:27.5		[HOT] 500 [ev].
08:46:36.6		[HOT]400 [ev].
08:46:38.9		[HOT-1] 100.
08:46:39.7		[HOT] autopilot [ev].
08:46:43.2		[HOT-2] Comment about field being in sight.
08:46:44.7		[HOT-1] Comment about runway being in sight.
08:46:45.4		[HOT] 300 [ev].
08:46:49.2		[HOT] minimums, minimums [ev].
08:46:55.4		[HOT] 200 [ev].
08:47:02.4		[HOT] 100 [ev].
08:47:13.8		[CAM] [sound similar to aircraft touchdown].
08:47:20.4		[HOT-1] Comment 1 concerning aircraft speed.
08:47:21.1		[HOT-2] Comment 2 concerning aircraft speed.
08:47:23.0		[HOT-2] Comment 1 concerning braking action.
08:47:25.4		[HOT-2] Comment 2 concerning braking action.
08:47:26.5		[HOT-2] Comment 3 concerning braking action.
08:47:28.9		[HOT-2] Comment 4 concerning braking action.
08:47:35.7		[HOT-1] Comment concerning aircraft alignment with runway.
08:47:41.8		[CAM] [sounds similar to impact].

Table 4. Full CVR transcript text corresponding to paraphrased text on plots in this Study.

Correlation of FDR, and CVR Times

The FDR and CVR record their information with respect to time, but these recorded times are not synchronized. To use these data sources together, their times must be synchronized to a single reference time. This reference time is based on the UTC parameters recorded on the FDR, converted into CDT.

⁵ These photographs were taken by an FAA investigator at the scene.

Time on the FDR is measured in terms of the Subframe Reference Number (SRN), with one SRN equivalent to one second of time. Comparing the FDR SRNs associated with the recorded UTC parameters results in the following relationship:

$$(\text{Seconds elapsed since midnight CDT}) = (\text{FDR SRN}) - 18000.414 \text{ seconds} \quad [1]$$

Equivalently,

$$08:47:00 \text{ CDT FDR time} = 49620.414 \text{ FDR SRN} \quad [2]$$

The correlation between the FDR and CVR times is described in Reference 6. The CVR transcript provided in Reference 6 uses the FDR UTC time.

Several of the plots in this *Study* portray selected CVR content. For example, plots of data vs. time include CVR content overlaid on vertical lines that intersect the x axis of the plot at the times that the CVR content was recorded. The CVR content portrayed on the plots is not the verbatim CVR transcript text, but rather a paraphrase or short-hand code for this text. The full CVR transcript text associated with each paraphrase or code is shown in Table 4.

IV. Performance Calculations based on FDR Data

Overview

The FDR records many, but not all, performance parameters of interest. Many additional parameters can be derived from the FDR parameters; however, the FDR parameters themselves can suffer from inherent measurement errors⁶ and must be corrected before being used in these calculations.

This section describes the corrections applied to the FDR data, and the calculations used to derive additional performance parameters from the corrected data. The airplane weight and CG used in these calculations are 15476 lb. and 26.2% MAC, respectively.⁷ Further details on the derivation of the equations and calculation methods used in this *Study* can be found in Appendix A of Reference 7.

The FDR corrections discussed in this *Study* attempt to remove the following errors:

⁶ "Measurement error" in this context means the difference between the actual true value of the quantity being measured and the measured or recorded value. It does not necessarily imply defects or malfunctions in the measurement and recording equipment itself. This difference can result from, among other things, limitations in the sensor accuracy and / or resolution.

⁷ See Table 2.

- Accelerometer bias errors.
- Errors in the recorded Global Positioning System (GPS) airplane positions that place the airplane to the right of the runway centerline and of the observed tire scrub marks on the runway and furrows in the ground past the end of the runway.

The additional performance parameters derived from the corrected FDR data include:

- True airspeed and altitude.
- Airplane positions and velocities from accelerometer integration that match the corrected GPS position data and tire scrub mark / furrow evidence.
- Winds.
- Braking friction coefficient developed during the ground roll.

The results of these corrections and derivations for the last 138 seconds of recorded data (corresponding to the airplane's descent through 1100 ft. above the runway to its resting position about 400 ft. past the end of the runway) are presented in Figures 2 - 14.⁸

True airspeed calculation

True airspeed equals Mach number multiplied by the speed of sound; the speed of sound is a function of the static temperature. Static temperature is obtained from total temperature and Mach number.

Mach number can be computed from calibrated airspeed and static pressure. Calibrated airspeed and total temperature are recorded directly by the FDR, and the static pressure can be determined from the pressure altitude recorded by the FDR (which is based on the standard sea-level pressure of 29.92 "Hg).

Figure 7 shows the results of the true airspeed calculation, compared with the indicated (calibrated) airspeed recorded by the FDR. Note that after the "sound of impact" recorded on the CVR at 21:40:21, the FDR calibrated airspeed exhibits unrealistic behavior (erratic jumps between 08:47:39 and 08:47:43), likely as a result of disruptions to the pitot / static system. The true airspeed calculation terminates at the point the airplane exits the runway, at 08:47:37.4. The true airspeed at this point is about 60 kts. Figure 7 also shows the groundspeed recorded by the FDR, and the groundspeed computed from integration of the accelerometer data (this calculation is described below). The close match between the computed true airspeed and computed groundspeed confirms that the headwind was negligible at the time of the landing (the KCXO weather reported in several hourly and special weather observations is shown in

⁸ Several Figures in this *Study* have an "a" and a "b" version, which present the same information but at different scales, or with different background images. When the *Study* refers to a Figure with two or more versions without specifying the version, all versions are meant to be included in the reference.

Table 5⁹). A calculation of the winds during the approach and rollout is described below, and presented in Figure 11.

Parameter \ Report	KCXO SPECI 08:32 CDT	KCXO SPECI 08:41 CDT	KCXO METAR 08:53 CDT
Sky condition	700 ft. scattered 2400 ft. broken 8000 ft. overcast	500 ft. few 8000 ft. broken 10000 ft. overcast	400 ft. few 5500 ft. broken 9000 ft. overcast
Visibility	2 statute miles	2 statute miles	2.5 statute miles
Winds	Calm	Calm	Calm
Temperature / Dew Point	23°C / 22°C	23°C / 22°C	23°C / 22°C
Altimeter setting	29.93 "Hg	29.93 "Hg	29.94 "Hg
Precipitation	Rain, mist	Heavy rain, mist	Rain, mist

Table 5. Weather observations at KCXO surrounding the time of the accident.

Pressure-based true altitude and density altitude calculations

The altitude recorded by the FDR is pressure altitude; i.e., it is the altitude in the standard atmosphere corresponding to the pressure sensed at the airplane's static pressure ports. The altitude in the actual atmosphere corresponding to the local static pressure generally does not equal the pressure altitude, and it is insufficient to simply adjust the pressure altitude for the local sea level pressure because, in general, the lapse rate of pressure with altitude does not match the lapse rate in the standard atmosphere.

To estimate the actual altitude of N322QS, the recorded pressure altitude is first adjusted to account for the 29.93 "Hg altimeter setting (see Table 5). During the approach, the change in altitude corresponding to a change in static pressure is calculated by solving the hydrostatic equation continuously (the hydrostatic equation describes the pressure increment across a differential element of air required to balance the weight of the element). With static pressure and the static temperature values from the speed calculations, the density and weight of the air elements can be calculated.

The results of this calculation are shown in Figures 2 and 3 as the red line labeled "True altitude." Note that this line has a different slope than the green line labeled "Indicated altitude (using 29.93" Hg)," which is the FDR pressure altitude adjusted only for non-standard pressure (i.e., 29.93" Hg), but not for the higher-than-standard temperature of the day¹⁰. The indicated altitude is the altitude shown on the airplane's altimeters, and is lower than the actual altitude.

The density altitude is the altitude in the standard atmosphere corresponding to the actual air density at each point in the flight. Because of the warmer-than-standard day, the density altitude throughout the flight was about 900 ft. higher than the true MSL altitude (see Figure 3).

⁹ The total rainfall and rainfall rate leading up to the time of the accident are discussed in Section D-VI.

¹⁰ The standard-day temperature at the field elevation of about 240 ft. is 58.1° F (14.5° C); at 73.0° F (22.8° C), the temperature was 14.9° F (8.3° C) higher than standard.

True altitude based on radio altimeter and terrain elevation data

The dark yellow line in Figures 2 and 3 labeled “FDR radio altitude + terrain” is the altitude that results from adding the height of the airplane’s landing gear above the ground (measured by the radio altimeter) to the elevation of the terrain underneath the airplane. The terrain elevation is determined from the FDR GPS latitude and longitude data to obtain the airplane’s track over the ground, and then obtaining the terrain elevation underneath the airplane’s track from Shuttle Radar Topography Mission (SRTM) elevation data provided by the United States Geological Survey (USGS). The USGS provides SRTM digital elevation data with a resolution of 1 arc-second (about 100 ft.) for the United States and 3 arc-seconds (300 ft.) for global coverage¹¹. The resolution of the terrain data used in this *Study* is 1 arc-second.

Note that the “FDR radio altitude + terrain” altitude matches the “True altitude” well during the approach, and is also well-behaved during the flare and touchdown, whereas the pressure-based altitude exhibits unrealistic “waviness” in this area. The waviness of the pressure-based altitude is the result of static pressure sensing errors, which are likely due to ground effects and the pitch rates present during the flare and landing.

While the radio altimeter-based altitude is better behaved than the pressure-based altitude during the landing itself, on approach the radio altimeter-based data shows oscillations that are likely due to the low resolution of the terrain data, and errors in the recorded GPS position of the airplane (more on these below), which introduce error into the computed elevations underneath the airplane. In addition, while the FDR GPS data provides a relatively accurate measure of the airplane’s position, the recorded GPS positions do not overlay the tire marks left by the airplane on the runway, and so are clearly offset from the airplane’s true position (see Figure 4). Furthermore, unrealistic “noise” results when speeds are computed by taking the time derivative of the GPS data. The FDR GPS-based groundspeed data is smooth, but the GPS-based ground track angle is not recorded.

In light of these errors and uncertainties, the best estimate of the airplane’s altitude and horizontal position throughout the approach and landing is obtained by integrating the load factor data recorded on the FDR. This calculation is described below.

Accelerometer data corrections and integration

The red line in Figures 2 and 3 labeled “True altitude from accelerometer integration” is the altitude that results from integrating¹² the FDR load factor data twice to derive aircraft position. It is a better estimate of the actual path of the airplane since it does not suffer from the static pressure sensing errors inherent in the FDR altitude data, or from errors in the determination of the terrain elevation under the airplane inherent in the radio-altitude based data.

¹¹ See <http://viewer.nationalmap.gov/viewer/>.

¹² In the following discussion, “integrating” the load factor data refers to mathematical integration with respect to time, per the theorems of Calculus.

An accurate estimate of the flight path of the airplane during relatively short intervals (about 30 to 60 seconds) can be obtained by integrating the accelerations recorded at the CG of the airplane. In general, the accelerometers are not located exactly on the CG, and so the accelerations at the CG must be computed by adjusting the FDR-recorded load factors for the effects of angular rates and accelerations. In the present case, the angular rates and accelerations are sufficiently small that this correction is negligible.

However, accelerometers generally contain small offsets, or “biases,” that produce large errors in speed and position if not removed prior to integration¹³. In addition, the initial values of speed, rate of climb, and track angle are required during the integration process (these are essentially the “constants of integration” when integrating acceleration to get speeds). The constants of integration and the values of the accelerometer biases can be estimated by selecting them such that the aircraft position that results from the integration agrees with known “target” positions determined from another source.

The accelerometer biases are not necessarily constant over an entire flight, but can drift over time. It is for this reason that integrating the accelerometers works best over relatively short intervals, during which the accelerometer biases are approximately constant. In order to obtain an integrated flight path for N322QS’s approach, landing, and rollout, the flight path was divided into two segments, and the accelerometer data was integrated separately for each segment. For the approach segment, the “target” positions for the accelerometer integration are defined by a quadratic curve fit through the FDR GPS data, and by the “True altitude” shown in Figures 2 and 3. For the landing and rollout segment, the “target” positions are defined by the FDR GPS data.

For the approach segment, the constants of integration (the initial groundspeed, track angle, and rate of climb) are chosen to minimize the root-mean-square difference between the integrated flight path and the target flight path throughout the entire segment. The accelerometer biases are chosen to minimize the error between the integration and the target at the end point of the integration; i.e., the biases are chosen so that the integrated flight path and target flight path coincide at the end of the approach segment (at about 368 ft. MSL, or 138 ft. above the runway threshold).

For the landing and rollout segment, the initial ground speed, track angle, and rate of climb are set equal to the values of these parameters at the end of the approach segment, so that these quantities remain continuous throughout the calculation. The horizontal position resulting from the integration is then shifted to match the tire scrub marks described in Section D-II (see Figure 4).

The approach segment starts at about 1300 ft. MSL and ends at 368 ft. MSL; the landing and rollout segment starts at the end of the approach segment, and ends as the end of runway 1 (at $x = 5000$ ft.; the integration does not include the airplane’s track over the grass to its final resting point). The beginning and end times, constants of integration,

¹³ For details about the equations to be integrated and the bias correction technique described in this *Study*, see Appendix A of Reference 7.

and accelerometer biases used for the two segments are shown in Table 6. The constants of integration are expressed as increments, or biases, on the initial groundspeed, track, and rate of climb that would be computed using the target trajectory. For the landing and rollout segment, the initial groundspeed, track, and rate of climb are set equal to the final value of these parameters from the approach segment, and so the increment or bias is not applicable.

Segment	Start time (CDT)	End time (CDT)	Speed bias, knots	Track bias, degrees	Rate of climb bias, ft/min	n_x bias, G's	n_y bias, G's	n_{lf} bias, G's
Approach	8:45:40.1	8:47:00.0	0.2	-0.12	24.7	0.00246	0.00580	-0.00746
Landing & Rollout	8:47:00.0	8:47:37.5	n/a	n/a	n/a	0.00065	0.00648	-0.00606

Table 6. Constants of integration and accelerometer biases for accelerometer integrations.

The airplane position and altitude resulting from the final integrated trajectory for both segments (approach, and landing / rollout) are shown in Figures 2, 3, 4, and 6 as the lines with the “accelerometer integration” label. The groundspeed and rate of climb resulting from the integrated trajectory are plotted in Figure 7.

The corrected load factors are compared to the load factors recorded by the FDR in Figure 8. Figure 8c shows the FDR load factors for the portion of the airplane’s motion past the end of the runway.

The dashed black line labeled “RNAV RWY1 3° glide path” in Figure 2 depicts a 3° glide path to KCXO runway 1, that crosses the threshold 49 ft. above the runway, consistent with the approach plate for the RNAV runway 1 approach (see Figure 9). Figure 2 indicates that the airplane remained essentially on the glide path until shortly after the autopilot disconnected at 08:46:39.70, after which it climbed to about 40 ft. above the glide path before descending back onto it, crossing the threshold about 46 ft. above the runway.

Flight path angle (γ), angle of attack (α), and sideslip angle (β) calculations

The flight path angle is defined by

$$\gamma = \sin^{-1}\left(\frac{\dot{h}}{V}\right) \quad [3]$$

where γ is the flight path angle, $\dot{h}$ is the rate of climb, and V is speed. Using airspeed gives γ relative to the airmass, and using groundspeed gives γ relative to the Earth. If $\dot{h}$ and V from the pressure-based altitude¹⁴ and true airspeed calculations described above are used in Equation [3], the resulting γ is very noisy (i.e., it contains unrealistic “spikes”

¹⁴ This is the altitude labeled “True altitude” in Figures 2 and 3.

and oscillations). A better (smoother) calculation of γ results from using $\dot{h}$ and V from integrated accelerometer data in Equation [3]. The γ relative to the Earth using integrated accelerometer data is shown as the blue line in the top plot of Figure 10. The corresponding $\dot{h}$ used in the calculation is shown in the bottom plot of Figure 7.

The sideslip angle (β) is the angle that the velocity vector of the airplane relative to the airmass makes with the airplane's plane of symmetry (see Figure 11). This angle is required to resolve the airspeed of the airplane into components along each of the airplanes axes, which in turn is required to estimate the atmospheric wind from the FDR data. Consequently, the behavior of β during the approach is of interest.

β is not sensed or recorded by the FDR, but an estimate of β can be made if the side force (Y) characteristics of the airplane are known and if the side force generated during the flight can be calculated. The most significant contributors to the side force are β and rudder deflection (δr):

$$C_Y = \frac{Y}{\frac{1}{2}\rho V^2 S} = \frac{\mathcal{C}_Y}{\partial\beta} \beta + \frac{\mathcal{C}_Y}{\partial\delta r} \delta r + \{\text{smaller terms}\} \quad [4]$$

Where C_Y is the side force coefficient, ρ is the air density, V is true airspeed, and S is the wing reference area. Ignoring the smaller terms, Equation [8] can be solved for an estimate of β :

$$\beta \cong \frac{C_Y - \frac{\partial C_Y}{\partial\delta r} \delta r}{\frac{\partial C_Y}{\partial\beta}} \quad [4]$$

The derivatives $\mathcal{C}_Y / \partial\beta$ and $\mathcal{C}_Y / \partial\delta r$ are aerodynamic characteristics of the airplane.

The side force Y can be calculated using

$$Y = (W)(n_y) \quad [5]$$

Where W is the weight of the airplane and n_y is the lateral load factor recorded by the FDR, corrected to the CG location and for accelerometer bias, as described above.

In the present case, the corrected n_y during the approach is very small, and consequently, Y and β are also very small. Therefore, this *Study* assumes that $\beta \cong 0$.

Once γ and β are computed, they can be used along with the pitch angle (θ) and roll angle (ϕ) recorded by the FDR to compute the angle of attack, α .

$$\alpha = \tan^{-1}\left(\frac{\tan \theta}{\cos \phi}\right) - \sin^{-1}\left(\frac{\sin \gamma + \sin \beta \cos \theta \sin \phi}{\cos \beta \sqrt{1 - \cos^2 \theta \sin^2 \phi}}\right) \quad [6]$$

Note that when $\beta = \phi = 0$, Equation [6] simplifies to the well-known result that

$$\alpha = \theta - \gamma \quad [7]$$

As shown in Figure 10, during the approach $\phi < 5^\circ$, and so Equation [7] is a good approximation. The α resulting from Equation [6], using γ based on $\dot{h}$ from pressure altitude, is noisy, since the γ used is also noisy (the gray line in the top plot of Figure 10). However, this α estimate is accurate enough for resolving the airplane's airspeed vector into components along the airplane body axes, a necessary step in the computation of winds, as described below. The α resulting from Equation [7], using γ based on $\dot{h}$ from the accelerometer integration, is smooth (the red line in the top plot of Figure 10), and in good agreement with the α computed from the barometric γ .

Wind calculations

Airspeed, groundspeed, and wind are related as follows:

$$\vec{V}_w = \vec{V}_G - \vec{V} \quad [8]$$

where $\vec{V}$ is the airspeed vector, $\vec{V}_G$ is the groundspeed vector and $\vec{V}_w$ is the wind vector. The components of $\vec{V}_G$ in body axes result from the integration of the accelerometer data described above. The components of the airspeed $\vec{V}$ in body axes, as indicated by Figure 11, are related to α and β as follows:

$$u = V \cos(\beta) \cos(\alpha) \quad [9a]$$

$$v = V \sin(\beta) \quad [9b]$$

$$w = V \cos(\beta) \sin(\alpha) \quad [9c]$$

where in the present case $\beta \cong 0$ and α is computed using Equation [6]. Once the components of $\vec{V}_w$ in the airplane body axes are computed using Equation [8], they can be transformed into Earth axes using the known θ , ϕ , and true heading (ψ_T). The results of the wind calculations are shown in Figure 12. Figure 12 also presents the winds transformed into runway coordinates, with wind blowing from the +x axis towards the -x axis depicted as a headwind, and wind blowing from the +y axis towards the -y axis depicted as a right crosswind.

Once the airplane is on the ground, it is hard to determine the true value of β , and so Equations [8] and [9] cannot be used to determine the winds. However, since in the

present case the winds were light, what is of most interest is the headwind component. On the runway, this is computed as

$$\text{Headwind} = \text{True airspeed} - \text{Groundspeed} \quad [10]$$

Where the groundspeed used is the result of the accelerometer integration.

Figure 12 indicates that during the approach, at 1300 ft. MSL (about 1100 ft. above the runway) the winds were from the east at about 10 knots, resulting primarily in a right crosswind. The wind speed gradually reduced to zero as the airplane crossed the threshold and touched down, consistent with the calm winds reported on the surface (see Table 5). The wind computed using Equation [10] indicates a tailwind of 3.5 knots or less during the landing roll.

Braking friction calculations

The CVR recorded several statements by the flight crew expressing concern about the deceleration of the airplane on the runway (see Table 4); ultimately, these concerns prompted them to set the airplane's emergency / parking brake (EPB), which applied sufficient hydraulic pressure to the brakes to prevent them from spinning, thereby "locking" them up and causing the airplane to skid.¹⁵ Consequently, it is of interest to determine the braking friction coefficient (μ_B) generated on the runway prior to the EPB being set, and compare the μ_B levels achieved with those that would be expected on a wet runway given current industry models, and the wet runway landing distances published in the EMB-505 Airplane Flight Manual (AFM) and Pilot's Operating Handbook (POH) (Reference 4). This sub-section presents various FDR parameters relevant to the braking system operation and performance, and describes the method for computing μ_B using FDR-based parameters, and additional information about the airplane provided by Embraer. The results of the μ_B calculation are also presented. The computed μ_B is compared with expected μ_B levels in Section D-VI.

The pilot left and right brake pedal positions, EPB status, left and right brake pressures, and left and right wheel slip ratios (s) are presented in Figure 13. The wheel slip ratio is defined as

$$s = 1 - \frac{V_{WHEEL}}{V_G} \quad [11]$$

Where V_G is the airplane's ground speed, and V_{WHEEL} is the tangential speed of the tire:

$$V_{WHEEL} = \omega_{WHEEL} r_{TIRE} \quad [12]$$

Where ω_{WHEEL} is the angular velocity of the wheel, and r_{TIRE} is the effective radius of the tire (the distance from the center of rotation of the wheel to the point where the tire contacts the runway). Per Equation [11], when the tires are free-rolling and $V_{WHEEL} = V_G$,

¹⁵ The FDR parameters that support these observations are presented in Figure 13.

then $s = 0$. Conversely, when the tires are locked and $V_{WHEEL} = 0$, then $s = 1$. The left and right V_{WHEEL} parameters are recorded by the FDR, and plotted in Figure 7.

The result of the μ_B calculation is presented along with the engine N1 speeds recorded by the FDR, and the n_x achieved during the landing roll, in Figure 14. As described further below, the engine thrust, which is measured by N1, and the achieved n_x are used in the μ_B calculation.

The μ_B can be computed from n_x , engine N1, and knowledge of the airplane's aerodynamic and thrust characteristics. Figure 15 is a free-body diagram showing the forces and moments acting on the airplane during the braking portion of the ground roll. The lift, pitching moment, drag, and thrust forces shown in Figure 15 can be estimated based on the recorded FDR data, and the known aerodynamic and thrust properties of the airplane. The vertical and longitudinal reaction forces at the main and nose gear (N_N , F_N , N_M , and F_M) are unknown, but can be computed by solving the following system of equations:

$$F_N = \mu_N N_N \quad [13]$$

$$F_M = \mu_B N_M \quad [14]$$

$$\sum F_x = W n_x + W_x = W(n_x - \sin \theta) \quad [15]$$

$$\sum F_z = W n_z + W_z = W(n_z + \cos \theta) \quad [16]$$

$$\sum M_y = 0 \quad [17]$$

Where:

N_N = vertical reaction at nose gear

μ_N = rolling friction coefficient at nose gear

F_N = longitudinal reaction at nose gear (rolling friction on nose gear)

N_M = vertical reaction at main gear

μ_B = wheel braking friction coefficient at main gear

F_M = longitudinal reaction at main gear (braking friction on main gear)

$\sum F_x$ = sum of forces along body x-axis

W = airplane weight

W_x = component of airplane weight along body x-axis

n_x = longitudinal load factor

θ = airplane pitch angle

$\sum F_z$ = sum of forces along body z-axis

W_z = component of airplane weight along body z-axis

n_z = vertical load factor (= normal load factor multiplied by -1)

$\sum M_y$ = sum of moments about body y-axis

Assuming the rolling friction on the nose gear (μ_N) is about 0.03,¹⁶ Equations [13]-[17] can be reduced to three equations for the three unknowns N_N , N_M , and μ_B . As is evident in Figure 15, the geometry of the landing gear, thrust line, CG location, and aerodynamic reference point of the airplane must be known. This geometry, as well as aerodynamic coefficient and thrust data for the EMB-505, were provided to the NTSB by Embraer.

For the μ_B calculation, the θ recorded on the FDR was used, and a runway gradient of 0% (as reported in Reference 8) was assumed. Tables of thrust as a function of true airspeed and engine N1 for the pressure and temperature conditions of the accident were provided by Embraer; the true airspeed shown in Figure 7, and the engine N1 shown in Figure 14, were used with these tables to compute total thrust during the ground roll.

The result of solving Equations [13]-[17] for μ_B is shown in Figure 14, and in several subsequent Figures discussed in Section D-VI.

Sequence of events during approach and landing

Figures 2, 3, 6, and 7 indicate that below 1200 ft. MSL during the final approach, the airplane was aligned with the vertical and horizontal final approach path, and that the airspeed and rate of climb were stable, at approximately 130 KIAS and -700 ft./min. At about 08:46:40 and 590 ft. MSL (360 ft. above the runway threshold), the CVR recorded an electronic voice stating “autopilot,” indicating that the autopilot had been disconnected. At this point, the nose pitched up slightly, the airspeed and rate of descent started to decrease, and the airplane started to rise slightly above the vertical glide path. At about 08:46:54 (468 ft. MSL, 238 ft. above the threshold), the engine N1 decreased from about 46% to about 29% (see Figure 14), and the rate of descent increased, bringing the airplane back onto the glide path, while the airspeed continued to decrease. The airplane crossed the runway threshold at about 08:47:06 at 275 ft. MSL (45 ft. above the threshold), at an airspeed of 121 KIAS, and touched down at about 08:47:10, 903 ft. from the threshold, at a groundspeed of about 118 kt. and with negligible headwind.

The final approach met the stabilized approach criteria cited in the NetJets Aviation, Inc. (NJA) EMB-505 Airplane Operations Manual (AOM, Reference 43), which requires that in instrument meteorological conditions (IMC) for a “straight-in-to-land” approach (as opposed to a “circle maneuver-to-land” approach), the following criteria be maintained below 1000 ft. above the touchdown zone elevation (TDZE):

- Airspeed: V_{REF} to $V_{REF} + 20$ kt. As noted above, the V_{REF} for the landing weight of 15476 lb. was 112 kt.; so the airspeed requirement was $112 \text{ kt.} \leq V \text{ KIAS} < 132 \text{ kt.}$
- Target airspeed: $V_{AP} \pm 10$ kt., where $V_{AP} = V_{REF} + 10$ kt. (= 122 kt. in this case)
- Rate of descent: Less than 1000 ft./min.
- Configuration: Correct for approach
- Thrust: Appropriate for configuration

¹⁶ This is the value of rolling friction assumed by Embraer for its performance analyses.

The FDR recorded a “ V_{AP} ” (approach speed) parameter of 123 kt. during final approach. According to NJA, V_{AP} “is not defined by Embraer, however NJA uses it to define the target speed of V_{REF} plus 10 knots which is flown until transitioning to V_{REF} by 50 feet.”¹⁷ Hence, the recorded V_{AP} is consistent with NJA’s policy and a V_{REF} of 113 kt. (corresponding to a slightly higher weight than the FDR touchdown weight). However, the threshold crossing speed of 121 KIAS recorded on the FDR was above NJA’s target speed of V_{REF} by 50 ft. This higher speed resulted in increased runway distance required to stop, though as will be seen below, runway 1 was more than long enough for the landing even with the higher threshold crossing speed, assuming that the airplane braking performance implied in the AFM landing distances could be achieved. In this case the AFM braking performance was not in fact achieved, for reasons that will also be discussed below.

Figures 7 and 13 indicate that the airplane touched down at about 08:47:10, when the left and right wheel speeds started to increase from 0, and the corresponding slip ratios started to decrease from 1. At nearly the same time, the left and right brake pedals started to deflect, and the corresponding brake pressures started to rise, indicating that the pilot started applying the brakes immediately upon touchdown. Over the next 11 seconds, the pilot’s brake pedal deflections progressively increased, reaching the maximum deflection of 35 mm at about 08:47:21.

Shortly after 08:47:11.5 the speedbrake (spoiler) surfaces on the wings started to deflect, reaching their maximum deflection of about 35° between 08:47:12.9 and 08:47:13.6.¹⁸ The speedbrakes are significant contributors to the deceleration performance of the airplane, since they add drag and, more importantly, reduce lift, thereby increasing the vertical load supported by the landing gear and the associated retarding friction force provided by the tires (see Equation [14]).

As shown in Figure 14, the airplane achieved a maximum deceleration (negative n_x) of about -0.17 G’s at 08:47:17, about 7 seconds after touchdown. Between 08:47:19 and 08:47:22 (an interval of 3 seconds), the n_x rose briefly to -0.15 G’s, and then dropped back down to -0.17 G’s until about 08:47:23.5 (13.5 seconds after touchdown), as the wheel speeds decreased to zero, consistent with the application of the EPB and the beginning of a full, locked-wheel skid.¹⁹ The wheels remained “locked” ($V_{WHEEL} = 0$) until the aircraft came to rest. During the skid, the n_x steadily increased (i.e., deceleration decreased) from -0.17 G’s to about -0.09 G’s, before dropping again to about -0.12 G’s as the airplane passed the end of the runway at 08:47:37.4. The airplane exited the runway about 27 seconds after touchdown, at a groundspeed of about 61 knots, and came to rest about 400 ft. past the end of the runway.

¹⁷ Email from NJA to NTSB, dated 12/17/2015.

¹⁸ The precision with which these times can be specified is limited by the 1Hz sample rate of the FDR speedbrake surface parameter.

¹⁹ The behavior of various FDR brake system parameters as the parking brake is applied is discussed further below.

Figure 14 also shows that as the brake pedal deflection and brake pressures increased, the μ_B also increased, reaching a maximum of about 0.16 at 08:47:17, coincident with the time the minimum n_x (maximum deceleration) was achieved. The computed μ_B mirrors the oscillation in n_x between 08:47:19 and 08:47:22, dipping to about 0.13 before rising again to about 0.155. After the airplane entered the locked-wheel skid at 08:47:23.5, the μ_B decreased steadily, to about 0.065 as the airplane passed the end of the runway.

The decrease in μ_B after the EPB was applied is consistent with research indicating that the braking friction achieved in a full locked-wheel skid ($s = 1.0$) is significantly less than the maximum μ_B that can be achieved at lower slip ratios. Examination of N322QS's tires revealed evidence of reverted-rubber hydroplaning,²⁰ which is also consistent with locked-wheel skids and a reduction in μ_B .

In Section D-VI of this *Study*, the values of μ_B achieved prior to the locked-wheel skid are compared to the wet-runway μ_B levels predicted by various industry models, and to the μ_B levels implied by the unfactored wet runway landing distances published in the EMB-505 AFM.

Behavior of FDR brake system parameters as emergency / parking brake is applied

The brake pedal parameters plotted in Figure 13 exhibit some counter-intuitive characteristics around the time that the EPB is set. For example, at about 08:47:23.5, the brake pressures *dropped* to under 100 psi (the same value recorded before the pedals were depressed), while at the same time the wheel speeds decreased to zero (indicating that the brakes were locking the wheels). The brake pressures subsequently jump to 3000 psi at 08:47:26.7. Furthermore, the sample of the EPB discrete recorded at 08:47:23.9 indicates that the EPB *was not* on, even though the wheel speeds reached zero at 08:47:23.7, by which time the EPB presumably was on.

To understand the behavior of these parameters, the architecture of the EMB-505 brake system and associated sensors and recording logic must be considered. In response to an NTSB request, Embraer offered the following explanation:²¹

The recorded brake pressures are the pressures in the normal brake system lines, upstream of the respective shuttle valves. The shuttle valve provides the brake assembly with the higher pressure between the emergency/parking brake (EPB) system and the normal brake system. Consequently, the recorded brake pressures are not necessarily the pressures being delivered to the brake assemblies. The Phenom 300 (EMB 505) FDR does not record the pressure delivered by the EPB system. The EPB FDR parameter is a discrete parameter (ON/OFF) based on a pressure switch which is activated with a maximum pressure of 140 psi.

In [Figure 7], it is possible to observe that the wheels took at least 2 seconds (4 samples) to reach a speed compatible with the aircraft groundspeed, which suggests either a soft landing or a low friction coefficient between the aircraft tires and the pavement, or both.

²⁰ The three types of hydroplaning are described in Section D-VI.

²¹ In an email to NTSB dated 12/18/2015.

Between 13:47:12 and 13:47:22, a progressive increase in the brake pedal application is observed, until full brake application (above 32.3 mm). Throughout this period, the wheel speed parameters show oscillations coherent with antiskid normal operation. The brake pressure increased from approximately 100 psi (before wheels touch down), to an average pressure of approximately 450 psi, indicating that the antiskid limited brake pressure application, while the longitudinal deceleration reached -0.17 g.

Between 13:47:22 and 13:47:23, the right wheel speed parameter shows a rapid reduction, followed by the same behavior on the left wheel speed parameter in the next sample. The brake pressures drop to 70 psi and remains in this level between 13:47:23 and 13:47:24. After that, the brake pressure increases to values around 3,000 psi.

This behavior is expected for a simultaneous brake pedal and emergency parking brake application. When the pressure commanded by the emergency/parking brake system overcomes the one commanded via the normal brake system and locks the wheels, the normal brake system commands the release of the brake pressure in an attempt to release the wheels and keep them spinning. However, as this expected behavior is not confirmed after some seconds, (around 1.8 seconds), the [Brake Control Unit (BCU)] considers the wheel speed transducers have failed, declares "ANTISKID FAIL" and commands the brake pressure application according to the brake pedals demand.

...

The point that needs further study is the reason that the emergency/parking brake parameter had an apparent delay to be triggered after the wheels speed parameters first shows signs of locking. For this question, it is necessary to involve Garmin, as it involves avionics processing times.

V. Regulations and guidance concerning operations on wet runways

Overview

Section D-VI of this *Study* compares the actual μ_B achieved during the landing roll (as described above and presented in Figure 14) with the μ_B that would predicted on a wet runway by various models in use in the aerospace industry and specified in certain airplane certification regulations, and with the μ_B that is required to match the unfactored²² landing distances published in the EMB-505 AFM, for a wet runway under the weight, wind, temperature, and pressure conditions of the accident. In addition, the landing distance that would be required given the actual μ_B achieved during the landing roll (prior to the activation of the EPB) is compared to the AFM distances and to the distances computed using other μ_B models.

The relevance of the μ_B models, of the landing distances they imply, and of the landing distances published in the AFM is determined both by the accuracy of these models and data, and by how this information is used to operate the airplane. The landing distance data that must be provided in the AFM is specified by the Federal Aviation Administration (FAA) certification requirements of the airplane itself; and the use of this information during the operation of the airplane is governed by the type of operation in question. The

²² As described further below, the "unfactored" landing distance means the actual distance from the runway threshold required to land the airplane and bring it to a stop, without any safety factors applied.

EMB-505 is certificated to the commuter category airworthiness standards²³ specified in 14 CFR Part 23 (as opposed to the transport category standards in Part 25), and therefore, in the USA, the airplane is restricted to Part 91 and Part 135 operations.²⁴ It cannot be used for Part 121 operations. Consequently, the operational requirements of Part 121 are not directly relevant to this airplane, except by way of comparison, and in the manner that certain Part 121 requirements are used to derive the factored landing distances in the AFM.

To provide context for the presentation of the wet-runway μ_B models and the landing distances that follow from those models, this Section will briefly outline the airplane certification standards that govern the landing distance information presented in the AFM, and the operating regulations that govern how that information is to be used.

Required AFM landing distance data for Part 23 commuter category airplanes

14 CFR §23.1587, “Performance Information,” dictates the landing distance information that must be presented in the AFMs of airplanes certificated under Part 23:²⁵

Unless otherwise prescribed, performance information must be provided over the altitude and temperature ranges required by §23.45(b).

(a) For all airplanes, the following information must be furnished—

...

(3) The landing distance, determined under §23.75 for each airport altitude and standard temperature, and the type of surface for which it is valid ...

The landing distance is defined in §23.75 as “the horizontal distance necessary to land and come to a complete stop from a point 50 feet above the landing surface.” Furthermore, §23.45(g) states that the landing distance of §23.75 “must be determined on a smooth, dry, hard-surfaced runway.”

Advisory Circular (AC) 23-8C, *Flight Test Guide for Certification of Part 23 Airplanes* (Reference 34) “sets forth an acceptable means, but not the only means, of showing compliance with [Part 23] concerning flight tests and pilot judgements.” Regarding §23.1587 as it applies to turbine and commuter category airplanes (such as the EMB-505), AC 23-8C states

²³ The *Agência Nacional de Aviação Civil* (ANAC) of Brazil issued Brazilian Type Certificate No. 2009T12 to the EMB-505 on 12/03/2009, based on the *Regulamento Brasileiro de Homologação Aeronáutica* (RBHA) 23, which endorses 14 CFR Part 23.

²⁴ In the following discussion, “Part” will be used as shorthand for Parts of Title 14 of the Code of Federal Regulations (14 CFR), governing Aeronautics and Space. Part 23 specifies airworthiness standards for normal, utility, acrobatic, and commuter category airplanes. Part 25 specifies airworthiness standards for transport category airplanes. Part 91 specifies general operating and flight rules, and includes Part 91K, governing fractional ownership operations. Part 135 specifies operating requirements for commuter and on-demand operations. Part 121 specifies operating requirements for domestic, flag, and supplemental operations. See 14 CFR for further details about airplane categories and the different types of operations.

²⁵ The parallel requirement for Part 25 airplanes is §25.1587, and refers to landing distances determined under §25.125.

Landing Distance. The landing distance from a height of 50 feet should be presented together with associated ambient temperature, altitude, wind conditions, and weights up to the maximum landing weight. Operational landing distance data should be presented for smooth, dry, and hard-surfaced runways. At the option of the applicant, with concurrence by the FAA, additional data may be presented for wet or contaminated runways and for other than smooth, hard-surfaced runways.

In general, the dry-runway landing distances are *required* to be published in airplane AFMs (for both Part 23 and Part 25 airplanes), and are based on performance demonstrated during flight tests on smooth, dry, hard-surfaced runways. The regulations do *not* require the publication of landing distances on other than dry runways, though applicants may choose to present this information as well. In this case, the information is not necessarily based on flight tests (largely because of the difficulty of achieving a consistent “wet” or “contaminated” runway surface), but is derived by calculations based on assumptions agreed to by the regulator.

The EMB-505 was first certified by the Brazilian regulator (the *Agência Nacional de Aviação Civil* (ANAC)), which, like the FAA, does not require the publication of landing distances on other than dry runways. However, the European Aviation Safety Agency (EASA) does require the publication of landing distances on other than dry runways, if the airplane is to be operated on such runways (see EASA Certification Specification (CS) 23.1587(a)(4), and the discussion of CS 25.1591 below). Therefore, in order to certify the airplane in Europe, Embraer proposed to EASA that the unfactored wet-runway landing distances presented in the EMB-505 AFM would be computed as 125% of the demonstrated, unfactored dry-landing distance.²⁶ EASA accepted this proposal.

The factored wet-runway landing distances in the EMB-505 AFM are 115% of the factored dry distances, or 192% of the unfactored dry distances (see Figure 16). The safety factors used to obtain the factored dry- and wet-runway distances in Figure 16 are those specified in Part 135 and 121 for dispatching an aircraft to a runway that is forecasted to be either dry or wet upon arrival (these factors are discussed further below).

Interestingly, in its discussion of §23.75, AC 23-8C notes that

Adverse Landing Conditions. The airplane should be satisfactorily controllable when landing under the most unfavorable conditions to be encountered in service, including crosswinds, wet runway surfaces, and with one engine inoperative. Demonstration of landing with an adverse crosswind of at least $0.2 V_{SO}$ is addressed in § 23.233. Operations on wet (but not contaminated) runway surfaces have been simulated by disconnecting the nosewheel steering on large part 23 airplanes. The effect of weight on the landing distance due to its influence on controllability of reverse thrust should be considered. The criticality of the adverse landing conditions should guide the level of complexity applicants use in determining controllability. Existing flight test practices have proven adequate for propeller driven part 23 airplanes, but they may not be adequate for small jets. Additional guidance may be found in AC 25-7B. *Part 23 jets typically have higher landing speeds and little drag to help slow the airplane. Landing accidents dominate the non-fatal*

²⁶ Per email and telephone correspondence w/ Embraer.

*accidents for small jets. This is a critical phase of flight for small jets and adequate attention should be given to adverse landing conditions such as wet runways [emphasis added].*²⁷

It should be noted that Part 23 does not specify any μ_B models for wet runways, unlike Part 25. §25.109 defines the accelerate-stop distance for transport category airplanes, and describes how this distance is to be determined. In particular, §25.109(c) defines the μ_B to be assumed in the calculation of the accelerate-stop distance for a smooth, wet runway, such as runway 1 at KCXO on the day of the accident; however, Part 25 does not prescribe the μ_B to be used when calculating the *landing* distance on a wet runway. As with Part 23, Part 25 does not require the publication of wet-runway landing distances in the AFM, though applicants may choose to provide this information as advisory data. The §25.109 μ_B model, which has been *proposed* as a regulatory basis for computing wet landing distances provided in Part 25 AFMs, is discussed in greater detail below.²⁸

Operational regulations concerning dispatch and arrival landing distance assessments

The accident flight was conducted under the provisions of Part 91. The corresponding regulation regarding the runway lengths required at a destination airports are governed by §91.103, “Preflight Action:”

Each pilot in command shall, before beginning a flight, become familiar with all available information concerning that flight. This information must include—

- (a) ...
- (b) For any flight, runway lengths at airports of intended use, and the following takeoff and landing distance information:
 - (1) For civil aircraft for which an approved Airplane or Rotorcraft Flight Manual containing takeoff and landing distance data is required, the takeoff and landing distance data contained therein; ...

Note that the regulation only specifies that the pilot in command shall “become familiar” with the available runway lengths and AFM takeoff and landing distances requirement; by implication, the runway lengths available should be at least as long as the AFM required lengths, but no safety factor on the available length is specified.

In contrast, for Part 135 operations, the use of the AFM landing distances required by §23.1587 is mandated by §135.385²⁹, which states, in part,

- (b) Except as provided in paragraph (c), (d), (e), or (f) of this section, no person operating a turbine engine powered large transport category airplane may take off that airplane unless its weight on arrival, allowing for normal consumption of fuel and oil in flight (in accordance with the landing

²⁷ The EMB-505 was certified in December 2009, before AC 23-8C was published on 11/16/2011, and while AC 23-8B (published 8/14/2003) was current. The emphasized text in the citation from AC 23-8C does not appear in AC 23-8B.

²⁸ In April 2009, the Takeoff/Landing Performance Assessment Aviation Rulemaking Committee (TALPA ARC) presented several recommendations to the FAA to increase the safety of operations on wet and contaminated runways. Among these recommendations was a requirement for manufacturers of Part 25 airplanes to provide wet-runway landing distances based on the μ_B computed per the method described in §25.109. The TALPA ARC recommendations are discussed further below.

²⁹ The parallel requirement for Part 121 operations is in §121.195.

distance in the Airplane Flight Manual for the elevation of the destination airport and the wind conditions expected there at the time of landing), would allow a full stop landing at the intended destination airport within 60 percent of the effective length of each runway described below from a point 50 feet above the intersection of the obstruction clearance plane and the runway.

The factored dry runway landing distances in Figure 16 are based on the actual (unfactored) landing distances for a dry runway, multiplied by a mandated safety factor of $1/0.6 \cong 1.67$; this guarantees that the actual demonstrated dry runway landing distance is at most 60% of the factored dry distance. For Part 135 operations, the factored dry distances in Figure 16 are used by the crew during pre-flight planning to determine the dry-runway field length required and / or maximum allowable landing weight.

If, prior to takeoff, the destination runway is not forecast to be dry, then §135.385(d) applies:

(d) Unless, based on a showing of actual operating landing techniques on wet runways, a shorter landing distance (but never less than that required by paragraph (b) of this section) has been approved for a specific type and model airplane and included in the Airplane Flight Manual, no person may take off a turbojet airplane when the appropriate weather reports or forecasts, or any combination of them, indicate that the runways at the destination airport may be wet or slippery at the estimated time of arrival unless the effective runway length at the destination airport is at least 115 percent of the runway length required under paragraph (b) of this section.

Hence, when the destination runway is forecast to be wet, the wet factored landing distance is the dry factored distance in Figure 16, multiplied by an additional safety factor of 1.15. This results in a required landing distance of about 1.92 times the actual, unfactored demonstrated dry runway distance ((unfactored distance / 0.6) x 1.15 $\cong$ unfactored distance x 1.92). Note that this wet-runway landing distance is obtained by applying safety factors to demonstrated dry runway performance, not on actual demonstrated wet-runway landing performance. Furthermore, the wet factored distances in Figure 16 have no basis in the wet unfactored distances shown in that Figure; as described above, the wet unfactored distances in Figure 16 are obtained by multiplying the dry unfactored distances by 1.25, per the agreement between Embraer and EASA. As it turns out, the wet factored distances in Figure 16 are equivalent to the wet unfactored distances multiplied by about 1.53:

$$\frac{(\text{wet factored})}{(\text{wet unfactored})} = \frac{\left(\frac{(\text{dry unfactored})}{0.6}\right)(1.15)}{(\text{dry unfactored})(1.25)} \cong 1.53 \quad [18]$$

Note that §135.385 refers to a “turbine engine powered large transport category airplane.” Nonetheless, §135.385 also applies to commuter category airplanes like the EMB-505, per §135.398(c):

(c) No person may operate a commuter category airplane unless that person complies with the landing limitations prescribed in §§135.385 and 135.387 of this part. For purposes of this paragraph, §135.385 and 135.387 are applicable to all commuter category airplanes notwithstanding their stated applicability to turbine-engine-powered large transport category airplanes.

The EMB-505 AFM also provides a table of landing distances for landings on runways covered with standing water, slush, or wet snow at depths of 0.125, 0.250, and 0.375 inches. The table for standing water at landing flap 3 is shown in Figure 17. The data in this table is computed per the methods described in the EASA Acceptable Means of Compliance (AMC) document 25.1591, *The derivation and methodology of performance information for use when taking-off and landing with contaminated runway surface conditions* (AMC 25.1591). AMC 25.1591 provides one acceptable means of compliance with the provisions of EASA Certification Specification (CS) 25.1591, *Performance Information for Operations with Contaminated Runway Surface Conditions*, which states

- (a) Supplementary performance information applicable to aeroplanes operated on runways contaminated with standing water, slush, snow or ice may be furnished at the discretion of the applicant. If supplied, this information must include the expected performance of the aeroplane during take-off and landing on hard-surfaced runways covered by these contaminants. If information on any one or more of the above contaminated surfaces is not supplied, the AFM must contain a statement prohibiting operation(s) on the contaminated surface(s) for which information is not supplied. Additional information covering operation on contaminated surfaces other than the above may be provided at the discretion of the applicant.
- (b) Performance information furnished by the applicant must be contained in the AFM. The information may be used to assist operators in producing operational data and instructions for use by their flight crews when operating with contaminated runway surface conditions. The information may be established by calculation or by testing.
- (c) The AFM must clearly indicate the conditions and the extent of applicability for each contaminant used in establishing the contaminated runway performance information. It must also state that actual conditions that are different from those used for establishing the contaminated runway performance information may lead to different performance.

Note that EASA CS 25.1591, which prohibits operations on contaminated runways unless performance data is provided for those surface conditions, has no counterpart in the American Federal Aviation Regulations (14 CFR). It should be noted that a runway that is merely wet (not flooded with at least 3 mm of standing water³⁰) is not considered “contaminated” and hence is not covered by CS 25.1591. Consequently, neither the EASA CS or American 14 CFR regulations specify methods or μ_B models for computing landing distances on wet (but not contaminated) runways.

En-route landing distance assessments: EU OPS 1.400 and FAA SAFO 06012

European operational regulation EU OPS 1.400 requires what amounts to an en-route landing distance assessment, i.e., a determination by the pilot while in flight whether or not a successful landing can be made at the intended destination, considering the best information available concerning the expected weather and condition of the runway at the time of arrival. However, other than specifying that this determination must be made “having regard to the performance information contained in the Operations Manual,” OPS 1.400 does not provide guidance for making the determination. Challenges pilots

³⁰ European operational regulations (EU OPS 1.480(a)(2)) consider a runway “contaminated” with standing water (i.e., “flooded”) when more than 25% of the runway surface is covered with surface water more than 3 mm (0.118 inches) deep.

may face in this regard include evaluating the runway condition based on weather, friction, or braking action reports, and selecting a safety factor to apply to landing distances computed from AFM guidance material.

There is no equivalent to EU OPS 1.400 in the 14 CFR. However, following the Southwest Airlines landing overrun accident involving a Boeing 737-700 at Chicago Midway Airport (KMDW) in December 2005, the FAA performed an internal audit of regulations and guidance information concerning landing distance requirements, and on August 31, 2006 issued Safety Alert For Operators (SAFO) 06012, titled *Landing Performance Assessments at Time of Arrival (Turbojets)* (Reference 45). While a SAFO is not regulatory, it “contains important safety information and may include recommended action. SAFO content should be especially valuable to air carriers in meeting their statutory duty to provide service with the highest possible degree of safety in the public interest.” SAFO 06012

urgently recommends that operators of turbojet airplanes develop procedures for flightcrews to assess landing performance based on conditions actually existing at time of arrival, as distinct from conditions presumed at time of dispatch. Those conditions include weather, runway conditions, the airplane’s weight, and braking systems to be used. Once the actual landing distance is determined an additional safety margin of at least 15% should be added to that distance. Except under emergency conditions flightcrews should not attempt to land on runways that do not meet the assessment criteria and safety margins as specified in this SAFO.

The SAFO also notes that “the FAA has undertaken rulemaking that would explicitly require the practice described above.”

The SAFO points out that the dry-runway landing distances established during flight test, and that are the basis for the factored landing distances used for dispatch, are shorter than the landing distances achieved in practice. In addition, AFM landing distances for wet and contaminated runways may also be based on the minimum dry distances obtained during flight tests. Consequently, landing distances on wet or contaminated runways computed from AFM data with little or no additional safety margin may be too short for normal operations. The SAFO recommends a conservative approach to assessing the landing distance requirements, including using the most adverse reliable braking action report or expected conditions for the runway, and using values for air distances and approach speeds that are representative of actual operations. The SAFO recommends that a 15% safety margin be then added to the computed (unfactored) landing distance, as “the FAA considers a 15% margin between the expected actual airplane landing distance and the landing distance available at the time of arrival as the minimum acceptable safety margin for normal operations.”

En-route landing distance assessments: TALPA ARC recommendations

As noted in SAFO 06012, following the Southwest Airlines accident at KMDW, the FAA initiated rulemaking that would require the practice recommended in the SAFO. In October 2007, FAA order 1110.149 established the “Takeoff/Landing Performance Assessment Aviation Rulemaking Committee” (TALPA ARC). According to the order, the objectives and scope of the TALPA ARC were to

... provide a forum for the U.S. aviation community to discuss the landing performance assessment methods provided in SAFO 06012. Additionally, takeoff performance for contaminated runway operations and issues relevant to part 139, Certification of Airports, will be discussed. These discussions will be focused on turbine powered aircraft including both turbojet and turboprop airplanes operated under parts 121, 135, 125, and 91 subpart K.

In addition, the TALPA ARC “will provide advice and recommendations to the Associate Administrator for Aviation Safety. The committee will act solely in an advisory capacity.” Furthermore,

the committee will discuss and present information, guidance, and recommendations that the members of the committee consider relevant to disposing of issues. Discussion will include, but is not limited to, the following:

- (1) Operational objectives, recommendations, and requirements.
- (2) Recommendations for rulemaking necessary to meet objectives.
- (3) Guidance material and the implementation process.
- (4) Global harmonization issues and recommendations.

The TALPA ARC presented landing performance recommendations to the FAA in April, 2009. The recommendations are transmitted in separate documents prepared by each working group of the TALPA ARC (References 9-13)³¹, corresponding to distinct areas of regulation, including:

- Part 139: certification of airports.
- Part 121: operating requirements: domestic, flag, and supplemental operations.
- Parts 91K, 125, and 135: Fractional ownership operations (Part 91K); certification and operations: airplanes having a seating capacity of 20 or more passengers or a maximum payload capacity of 6,000 pounds or more; and rules governing persons on board such aircraft (Part 125); and operating requirements: commuter and on demand operations and rules governing persons on board such aircraft (Part 135).
- Part 25: airworthiness standards: transport category airplanes.
- Part 26: continued airworthiness and safety improvements for transport category airplanes.

Each of the separate documents notes that the regulations addressed by each working group is affected by the work of the others, and that consequently substantial agreement and cooperation between the groups was necessary to generate working proposals. Accordingly, the recommendations from the Part 121, Part 139, Part 25, and Part 26 subgroups are harmonized and crafted to work together as a whole. Of note, however, is that the working group responsible for Parts 91K, 125, and 135 expressed serious reservations about the applicability of the recommendations of the other groups to the

³¹ Copies of the documents can be found in the NTSB public docket for accident # DCA08MA085, Hawker Beechcraft BAe 125-800A, registration N818MV, Owatonna, MN, July 31, 2008, available by searching for DCA08MA085 at <http://www.nts.gov/investigations/SitePages/dms.aspx>.

operations covered by 14 CFR Parts 91K, 125, and 135. As stated in the group's recommendation document,

As of the time of the drafting of these introductory comments, it appears that, indeed, some representatives of the FAA, a majority of the Part 121 Working Group, and others believe that there should be one landing performance assessment rule for all operations. This working group rejects the "one size fits all" direction that the FAA appears to be following in this rulemaking process, as a sudden departure from historical precedent throughout the history of aviation regulation in the United States and elsewhere. Sufficient differences exist among aircraft operations conducted under Parts 91, subpart K, 125, 135 and 121 in the types of aircraft flown, airports used, expectation of passengers, economic factors, and accident history to justify differing rules.³²

The regulatory changes proposed by the other groups in the TALPA ARC would codify many of the provisions of SAFO 06012, and introduce a new "Runway Condition and Braking Action Reports" table that would provide a mapping between a six-level runway "code" and corresponding runway contaminant type and depth, Continuous Friction Measuring Equipment (CFME) measured friction coefficient values, airplane wheel braking coefficient values, and pilot braking action reports.³³ The runway codes range from "6," for a dry runway, to "0," for runways contaminated with various forms of wet ice, and for which braking action is "minimal to non-existent." Aircraft manufacturers would have to supply data from which "operational" (i.e., unfactored) landing distances could be calculated for runway codes 6 through 1;³⁴ operations would be prohibited on code "0" runways.³⁵ The methods and assumptions to be used for generating this data would be specified in new regulations added to 14 CFR Part 25, "airworthiness standards: transport category airplanes." Specifically, the new rules would require that the braking coefficients on wet, ungrooved runways be computed per the method described in 14 CFR §25.109 (this method is described in detail in Section D-VI).³⁶

In addition, pilots would be required to perform an en-route landing distance assessment prior to landing. This assessment would "consider the runway surface condition, aircraft landing configuration, and meteorological conditions, using approved operational landing performance data in the Airplane Flight Manual supplemented as necessary with other data acceptable to the Administrator."³⁷ A 15% safety margin would be added to the computed operational landing distance to determine the runway length required for landing.³⁸ The Part 121 working group recommendation document notes that "it is anticipated that [landing performance] data for aircraft operating at the time of this rule change may not be available in the AFM, so the use of supplementary data acceptable to the Administrator is provided as an alternate means of compliance"³⁹

³² Reference 11, p. 2.

³³ Reference 9, p. 3; Reference 10, p. 1.28; and Reference 12, p. 2.16.

³⁴ Reference 12, p. 2.15.

³⁵ Reference 10, p. 1.28; and Reference 12, p. 2.16.

³⁶ Reference 12, p. 2.16.

³⁷ Reference 10, p. 1.9.

³⁸ Reference 10, p. 1.10.

³⁹ Reference 10, p. 1.10.

The regulations through which manufacturers or type-certificate holders of existing airplanes would be required to provide additional data with which to conduct en-route landing distance assessments would be added to 14 CFR Part 26, “continued airworthiness and safety improvements for transport category airplanes.” A new regulation in this Part would require the type-certificate holders of transport category, turbine-powered airplanes with a type certificate issued after January 1, 1958, and operated under parts 121, 125, 135, and 91K, to publish performance data to meet the intent of the new landing distance assessment regulations.⁴⁰ The methods and assumptions for producing these data would be those specified in the additions to Part 25. Consequently, the μ_B used to determine landing distances on wet runways would be those defined in §25.109, which (as shown in Section D-VI) would result in more conservative distances than those currently found in the EMB-505 AFM, which are simply the dry, unfactored distances multiplied by 1.25 (nonetheless, as will also be shown, even the §25.109 model overestimates the μ_B achieved on the accident runway, consistent with findings in other wet runway overrun accidents). The EMB-505 AFM would be required to be updated with these more conservative distances. The proposed timetable for compliance is within 2 years of the approval of the regulations for airplanes that are still in production, and within 4 years for airplanes that are out of production.⁴¹

The changes to the operational regulations proposed by the Parts 91K, 125, and 135 subgroup are substantially different from those proposed by the Part 121 subgroup. The Part 135 regulations proposed by the former group would also require pilots to perform an en-route landing distance assessment prior to landing, but would require either an 11% safety margin (“for certificate holders authorized by the Administrator to conduct eligible on-demand operations and conducting an eligible on-demand flight”), or an 18% safety margin (“for certificate holders operating under Part 135 that do not meet the requirements for eligible on-demand operations”)⁴². These safety margins would not be required if the landing distance assessment calculations do not take credit for the effect of reverse thrust, and conditions that make the effective use of reverse thrust more dependable are present.⁴³ In addition, the group proposed that part 135 certificate holders meeting certain criteria⁴⁴ could develop their own landing distance assessment program “as an alternative to the landing distance assessment requirements” just described. Furthermore, the dispatch requirements of §135.385 would be amended to be consistent with the proposed 11% or 18% safety margin (i.e., the airplane would not be permitted to take off unless, given the conditions expected at the destination at the time of landing, the calculated landing distance plus either an 11% or 18% safety margin is less than the available runway length).⁴⁵

⁴⁰ Reference 13, p. 2.2.

⁴¹ Reference 13, p. 2.8.

⁴² Reference 11, p. 9.

⁴³ Specifically, the aircraft must be equipped with, and use, thrust reversers; there may be no limitations on the use of thrust reversers during the ground roll; and procedures must call for the use of thrust reversers on all installed engines (Reference 11, p. 9).

⁴⁴ The criteria specify requirements in the following areas: experience with turbine airplanes, training programs, line checks, go-around criteria and crew coordination procedures, and operational performance tracking (Reference 11, p. 9).

⁴⁵ Reference 17, p. 11.

The current status of the TALPA ARC recommendations is discussed below.

En-route landing distance assessments: NTSB recommendations A-07-057 & A-07-061

As a result of its investigation of the 2005 Southwest Airlines overrun accident at KMDW, the NTSB issued two recommendations concerning landing distance assessments to the FAA:

Immediately require all 14 *Code of Federal Regulations* Part 121, 135, and 91 subpart K operators to conduct arrival landing distance assessments before every landing based on existing performance data, actual conditions, and incorporating a minimum safety margin of 15 percent. (A-07-057) Urgent (Supersedes Safety Recommendation A-06-016 and classified “Open—Unacceptable Response”).

Require all 14 *Code of Federal Regulations* Part 121, 135, and 91 subpart K operators to accomplish arrival landing distance assessments before every landing based on a standardized methodology involving approved performance data, actual arrival conditions, a means of correlating the airplane’s braking ability with runway surface conditions using the most conservative interpretation available, and including a minimum safety margin of 15 percent. (A-07-061)

Recommendations A-07-057 and A-07-061 differ in that A-07-057 recommends that landing distance assessments be required *immediately* using existing performance data, while A-07-061 recommends that landing distance assessments be *eventually* required based on a “standardized methodology” that would have to be developed. Both recommendations include the minimum 15% safety margin recommended by the FAA in SAFO 06012.

Recommendation A-06-057 and A-06-061 are currently classified “Closed – Unacceptable Action” and “Open – Unacceptable Response,” respectively. Tables 7 and 8 summarize the correspondence between the NTSB and the FAA concerning these recommendations.

Date From/To	Summary of actions re: A-07-057	Recommendation Status
10/04/2007 NTSB/FAA	Original recommendation transmittal letter. NTSB notes that FAA decided not to issue mandatory Operations Specification (OpsSpec) N 8400.C082, which would have satisfied the intent of previously issued NTSB recommendation A-06-16, and instead issued SAFO 06012 as an interim guidance measure. Since compliance with the SAFO is voluntary, not mandatory, the SAFO is not responsive to A-06-16. Consequently, A-0-057 supersedes A-06-16 and adopts its status of "Open – Unacceptable Response."	Open – Unacceptable Response (OUR)
11/08/2007 NTSB/FAA	Added A-07-57 to NTSB "Most Wanted List" (MWL), in renamed category "Improve Runway Safety."	OUR
12/17/2007 FAA/NTSB	FAA notes that a survey of part 121 operators indicates that 92% of U.S. airline passengers are being carried by air carriers in full or partial compliance with SAFO 06012. FAA formed TALPA ARC on 12/06/2007 to review regulations affecting certification and operation of airplanes and airports for operations on contaminated runways.	OUR
06/17/2008 NTSB/FAA	A-07-057 reiterated on 06/17/2008 in response to the landing overrun of Pinnacle Airlines flight 4712 at KTVC on 04/12/2007. Crew did not perform a landing distance assessment, as required by Pinnacle's OpsSpecs. An assessment would have shown insufficient runway length for the landing. This case underscores the importance of landing distance assessments before every landing, taking into account conditions at the time of arrival and adding a safety margin of at least 15% to calculated landing distances.	OUR
06/27/2008 NTSB/FAA	NTSB cites the 02/18/2007 runway overrun of Delta Connection flight 6448 and the fact that its operator, Shuttle America, did not require landing distance assessments as recommended in SAFO 06012. NTSB also raises concerns re: the FAA's 12/17/2007 letter addressing A-07-057; specifically: FAA did not indicate the percentage of Part 121 carriers that had fully adopted the SAFO or those parts of the SAFO that had not been adopted by other Part 121 carriers; among those parts of the SAFO that have not yet been adopted is the minimum 15% safety margin; the FAA did not indicate whether SAFO 06012 had been adopted in full or in part by Part 135 and Part 91K operators; and the FAA did not describe the actions that it would take to encourage those operators that have not complied with the SAFO (such as Shuttle America) to do so.	OUR
08/23/2010 FAA/NTSB	The FAA received the TALPA ARC recommendations for landing performance assessment in April 2009 and intends to initiate rulemaking in 2011. In the interim, FAA in cooperation with 10 airports and 2 air carriers is validating the accuracy & usability of the Runway Surface Condition Reporting Matrix developed by the ARC.	OUR
01/31/2011 NTSB/FAA	NTSB cites its investigation of the 07/31/2008 East Coast Jets accident at KOWA and the fact that East Coast Jets did not require its pilots to perform landing distance assessments. The NTSB points out that A-07-057 was issued as an interim solution recognizing that the standardized methodology recommended in A-07-61 would take time to develop. Since FAA's actions have not been responsive, A-07-057 is classified Closed – Unacceptable Action.	Closed – Unacceptable Action (CUA)
03/04/2015 NTSB/FAA	NTSB comments on draft Advisory Circulars 25-31 & 25-32 concerning landing and takeoff performance data for operations on contaminated runways (see discussion below).	CUA

Table 7. Summary of NTSB/FAA correspondence re: A-07-057. For full correspondence, see: <http://www.ntsb.gov/safety/safety-recs/layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-057>.

Date From/To	Summary of actions re: A-07-061	Recommendation Status
10/16/2007	Original recommendation transmittal letter, issued following conclusion of investigation of SWA 1248 accident at KMDW.	Open – Await Response
01/08/2008 FAA/NTSB	FAA developed OpsSpec C082 and issued SAFO 06012. FAA notes that a survey of part 121 operators indicates that 92% of U.S. airline passengers are being carried by air carriers in full or partial compliance with SAFO 06012. FAA formed TALPA ARC on 12/06/2007 to review regulations affecting certification and operation of airplanes and airports for operations on contaminated runways. On 11/06/2007 FAA issued AC 91-79 that provides ways for operators to mitigate risks associated with runway overruns during landing, and provides detailed information that may be used to develop operating procedures to mitigate those risks.	Open – Await Response
06/13/2008 NTSB/FAA	Formation of the TALPA ARC is a responsive first step addressing A-07-061, which was classified Open – Acceptable Response at the NTSB's 04/15/2008 meeting re: Shuttle America flight 6448.	Open – Acceptable Response (OAR)
06/27/2008 NTSB/FAA	NTSB cites the 02/18/2007 runway overrun of Delta Connection flight 6448 and the fact that its operator, Shuttle America, did not require landing distance assessments as recommended in SAFO 06012. NTSB also raises concerns re: the FAA's 12/17/2007 letter addressing A-07-057; specifically: FAA did not indicate the percentage of Part 121 carriers that had fully adopted the SAFO or those parts of the SAFO that had not been adopted by other Part 121 carriers; among those parts of the SAFO that have not yet been adopted is the minimum 15% safety margin; the FAA did not indicate whether SAFO 06012 had been adopted in full or in part by Part 135 and Part 91K operators; and the FAA did not describe the actions that it would take to encourage those operators that have not complied with the SAFO (such as Shuttle America) to do so. Pending the prompt completion of the TALPA ARC's work and the FAA's timely action in response to the committee's recommendations, A-07-61 is classified OAR.	OAR
8/23/2010 FAA/NTSB	FAA received the TALPA ARC recommendations for landing performance assessment in April 2009 and intends to initiate rulemaking in 2011. In the interim, FAA in cooperation with 10 airports and 2 air carriers is validating the accuracy & usability of the Runway Surface Condition Reporting Matrix developed by the ARC.	OAR
01/31/2011 NTSB/FAA	The FAA's efforts to address A-07-61 are responsive, and the NTSB encourages the FAA to complete timely rulemaking in response to the TALPA ARC's recommendations.	OAR
12/07/2011 NTSB/FAA	NTSB reiterated A-07-61 with the 12/07/2011 issuance of A-11-92 through A-11-95, in response to the 12/22/2009 incident involving American Airlines flight 331 in Kingston, Jamaica. The investigation revealed that SAFO 06012 is not being consistently disseminated or implemented. More than 4 years after A-07-61 was issued, the continued lack of its requirements increases the risk of a runway overrun on contaminated runways. Therefore, the NTSB reiterates A-07-61 and reclassifies it Open – Unacceptable Response.	Open – Unacceptable Response (OUR)

Table 8. Summary of NTSB/FAA correspondence re: A-07-061 (p. 1 of 2). For full correspondence, see: <http://www.nts.gov/safety/safety-recs/layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-061>.

Date From/To	Summary of actions re: A-07-061	Recommendation Status
09/06/2013 FAA/NTSB	Rulemaking related to the TALPA ARC recommendations has been delayed to allocate resources to rulemaking projects mandated by Congress. However, FAA supports implementation of the ARC recommendations through non-regulatory activity, including revising SAFO 06012. Review and analysis of the Runway Surface Condition Reporting Matrix developed by the ARC continues.	OUR
12/16/2013 NTSB/FAA	Because operators are not required to implement the SAFO recommendations, critical parts of the guidance are often ignored. NTSB believes that few operators have requested the optional OpSpec/MSpec that is based on the SAFO, and asks that the FAA provide information on the number of operators who are using that voluntary OpSpec/MSpec.	OUR
10/28/2014 FAA/NTSB	The FAA cites two new technologies that calculate and convey airplane braking ability required and/or available to stop the airplane during the landing roll. The FAA encourages the voluntary use of such technology, and is no longer considering rulemaking related to TALPA ARC or regulating performance data. However, FAA plans many document changes as a result of the ARC recommendations, including to SAFO 06012. Information contained in SAFO 06012 will be incorporated into Advisory Circulars; Aeronautical Information Manual; Notices to Airmen; Air Traffic Control guidance and manuals; and Airport guidance and manuals. In addition, FAA is developing the Runway Condition Assessment Matrix (RCAM), which takes a known assessment criteria provided from the airport and provides the pilot with a downgrade assessment criterion. This criterion is based on the reported runway conditions, such as the reported runway friction and reported braking action. This will provide the pilot with an expected braking ability to slow or stop the airplane during the landing roll.	OUR
02/10/2015 NTSB/FAA	NTSB does not believe that non-regulatory guidance is effective; therefore, it does not consider such action to be an acceptable response to A-07-061. NTSB is currently arranging a staff-level briefing on the details of how FAA will implement the TALPA ARC recommendations through non-regulatory means.	OUR
03/04/2015 NTSB/FAA	NTSB comments on draft Advisory Circulars 25-31 & 25-32 concerning landing and takeoff performance data for operations on contaminated runways (see discussion below).	OUR

Table 8. Summary of NTSB/FAA correspondence re: A-07-061 (p. 2 of 2). For full correspondence, see: <http://www.nts.gov/safety/safety-recs/layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-07-061>.

En-route landing distance assessments: FAA Advisory Circulars 25-31 & 25-32

On December 22, 2015, the FAA issued two Advisory Circulars (ACs) concerning performance data for takeoff and landing operations on contaminated runways: AC 25-31, "Takeoff Performance Data for Operations on Contaminated Runways," and AC 25-32, "Landing Performance Data for Time-of-Arrival Landing Performance Assessments" (References 50 and 38, respectively). The FAA posted draft versions of these ACs on its website for comment on January 21, 2015, and on March 4, 2015, the NTSB provided comments on the draft ACs as follows (see Reference 14):

Both of these draft ACs provide guidance and standardized methods that data providers, such as type certificate (TC) holders, supplemental type certificate (STC) holders, applicants, and airplane operators can use when developing performance data for transport category airplanes for operations on contaminated runways. The AC also promotes the use of consistent terminology for runway surface conditions used among data providers and FAA personnel.

The NTSB has investigated several accidents within the last 10 years that involve issues addressed by these ACs. As a result of these investigations, the NTSB issued Safety Recommendations A-07-57 through -64, A-08-17, A-08-41 through -43, and A-11-28 and -29. Although the NTSB recommendations concern needed requirements, and ACs are advisory only, the draft ACs address in part most of these recommendations.

The NTSB is pleased that the ACs take some steps toward addressing the recommendations of the Takeoff and Landing Performance Assessment Aviation Rulemaking Committee (TALPA ARC). The NTSB believes that it is valuable to define common methods to assess runway surface conditions along with common terms to report those conditions, and that it is critical to develop a correlation between runway surface condition descriptions, pilot-reported braking action and expected airplane wheel braking coefficients. The related industry-developed Runway Condition Assessment Matrix (RCAM) tool can support and improve operational decisions on the flight deck, in the back offices, and on the ground.

...

The ACs also provide some guidance that data providers can use to develop appropriate data to support operational assessments of takeoff or landing performance on wet or contaminated runways, as well as guidance for incorporating existing advisory performance data into the framework suggested in the ACs.

However, the NTSB is disappointed that the FAA does not plan to undertake rulemaking to require turbojet operators to use a standardized methodology and FAA-approved data to perform takeoff and landing distance assessments for operations on wet or contaminated runways. Although many manufacturers, operators, and airports have elected to incorporate elements of the TALPA ARC recommendations that will improve industry operations and safety, the ACs provide guidance material only. Since the planned AC content is neither mandatory nor regulatory, the recommended data to support takeoff and landing distance assessments may or may not be developed. If the data are developed and optional assessments are performed, operators remain free to choose the performance data basis, the means of correlating the airplane's braking ability with runway surface conditions, and the added safety margin, if any. The FAA has no plan to approve existing or future performance data developed by TC holders to support takeoff and landing distance assessments or the accompanying calculation methods that may inadvertently or purposely deviate from the TALPA ARC recommendations. As a result, it is likely that many components of the FAA's AC guidance will be ignored by segments of the intended audience, even if it is consistent with the TALPA ARC's vision. In addition, both ACs are aimed at transport category airplanes, but the guidance should, at a minimum, extend to all turbojet airplane operations.

The FAA's disposition of these (and other commentators') comments are contained in Reference 52. Concerning the NTSB comments cited above, the FAA responded:

The NTSB comments on the AC have been noted, and the letter they provided is in proper channels to be answered directly.

As to the final point of this comment, the TALPA ARC did include recommendations for 14 CFR part 23 implementation. The NTSB's concerns with part 23 apparent inaction will be forwarded to the appropriate directorate.

The NTSB comments also address the reliance of the draft ACs on the wet-runway μ_B model advocated by the TALPA ARC (i.e., the §25.109(c) model). This item, and the FAA's response, will be discussed further in Section D-VII.

NJA Operations / Management Specifications

The certification of air carriers and commercial operators in the USA is governed by 14 CFR Part 119 §119.33(b)(3), which states that “a person other than a direct air carrier may not conduct any commercial passenger or cargo aircraft operation for compensation or hire under part 121 or part 135 of this chapter unless that person ... obtains operations specifications that prescribe the authorizations, limitations, and procedures under which each kind of operation must be conducted.” The content of operations specifications is defined in §119.49.

NJA holds operations specifications (OpsSpecs) for its operations conducted under Part 135, and similar management specifications (MSpecs) for its operations conducted under Part 91. The NJA Flight Operations Manual (FOM, Reference 15) states that

Operations and Management Specifications issued to NJA are incorporated directly into the policies and procedures of this manual, where applicable. Compliance with these policies and procedures is mandatory and meets the requirements of FAA authorized Operations and Management Specifications.

Reference 15 specifies requirements and procedures for NJA operations that go beyond the requirements of 14 CFR Part 135 described above. In the case of landing distances, Reference 15 states that “every landing requires an adjustment to planned landing distance. The type of operation dictates which adjustments are applied.” The “planned landing distance” is the unfactored AFM dry landing distance for the airplane and environmental conditions at landing. The “type of operation” is dictated by the regulatory Part under which the flight is operated (i.e., Part 91, 91K, or 135).

For dispatching a flight to a runway that is expected to be wet at the time of arrival, Reference 15 states that for Part 91 flights, the required landing distance is the unfactored wet landing distance specified in the AFM FAA-approved landing performance data or the AFM advisory data, with no safety factor applied. However, in practice, NJA dispatchers divide the unfactored AFM distance by 0.8, resulting in a required landing distance greater than that specified in Reference 15.⁴⁶ For Part 91K and Part 135 flights, the required landing distance is the unfactored dry landing distance from the AFM, divided by a safety factor of 0.6,⁴⁷ and with an additional safety factor of 15% applied. In this regard, the dispatch requirements of Reference 15 are equivalent to those of Part 135.

⁴⁶ Per an email from NJA to NTSB, dated 12/17/2015.

⁴⁷ Reference 15 allows a less conservative safety factor of 0.8 for dispatch to certain pre-specified airports when a number of other requirements are met, per the FAA Destination Airport Analysis Program (DAAP; see Reference 54).

However, for all operations, Reference 15 also requires the crew to perform a Landing Performance Assessment (LPA) to re-calculate the required landing distance “if weather, runway surface condition, aircraft status, or any other relevant factor has degraded from those shown in the flight release package.” An additional safety factor of 15% must then be added to the re-calculated distance. This element of NJA’s FOM amounts to an en-route landing distance assessment with a safety factor of 15%, as recommended in SAFO 06012 and NTSB recommendations A-07-57 and A-07-061. In this regard, Reference 15 (adherence to which is mandatory for NJA operations) is more demanding than 14 CFR Parts 135 and 121.

The accident flight was dispatched to runway 14 assuming the full Landing Distance Available (LDA) length of 5411 ft. was available.⁴⁸ However, several Notices to Airmen (NOTAMs), which were overlooked by the dispatcher, indicated that because of construction, on the day of the accident the runway 14 LDA was only 4123 ft., and the Instrument Landing System (ILS) and RNAV approaches to runway 14 were not available. CVR information indicates that the crew first learned of the construction on runway 14 via the Automatic Terminal Information Service (ATIS) broadcast during their approach to KCXO. The crew decided to use runway 1 instead, for which the RNAV approach was available, and which at 5000 ft. had a longer LDA (that day) than runway 14. However, the runway 1 LDA was shorter than that planned for in the flight release package, so Reference 15 required an LPA prior to the accident landing. The CVR was inconclusive as to whether the crew performed an LPA for runway 1. The results of an LPA conducted per Reference 15 for the conditions of the accident landing are described in Section D-VI, and indicate that runway 1 met the requirements of the LPA.

VI. Comparison of wet-runway μ_B models and resulting landing distances

Overview

This Section compares the μ_B achieved during the accident landing roll (described in Section D-IV) with the μ_B that would be predicted using several wet-runway friction models, and with the μ_B that is required to match the unfactored wet-runway landing distances published in the EMB-505 AFM. In addition, the landing distance that would be required given the actual μ_B achieved during the landing roll (prior to the activation of the EPB) is compared to the AFM distances and to the distances computed using other μ_B models.

It will be shown that the computed μ_B is well below both the μ_B predicted using the §25.109(c) model and the μ_B implied by the AFM data, but matches the μ_B predicted using a NASA model based on CFME measurements quite well. These results mirror findings in other wet-runway landing events, as discussed in Section D-VII. The details of the μ_B models in question, and the landing distances that result from these models, will also be described in the present Section.

⁴⁸ Per flight release information provided by NJA via email on 9/30/2014. Construction on runway 14 was completed in Spring 2015, and the runway was lengthened from 6000 ft. to 7501 ft.

The FAA has recognized that the actual μ_B achieved on some wet runways may be less than that specified in §25.109(c), and that the runway length required to stop on these runways may exceed the lengths specified in some airplane AFMs. Accordingly, the FAA issued SAFO 15009 on August 11, 2015 (Reference 16 or Appendix C), warning operators and pilots that “the advisory data for wet runway landings may not provide a safe stopping margin under all conditions.” Furthermore, on March 8, 2013, the FAA assigned an additional task addressing wet runway stopping performance to an Aviation Rulemaking Advisory Committee (ARAC) (Reference 17). These items are discussed below.

Physical parameters affecting μ_B

As indicated by Equation [14], the retarding force provided by the main gear tires during braking is equal to the normal force on the gear, N_M (acting perpendicular to the runway surface), multiplied by μ_B . N_M is approximately proportional to the weight of the airplane, minus the lift provided by the wings (see Figure 15). The lift depends on the flap setting, pitch attitude on the runway, dynamic pressure (airspeed and air density), and the position of the spoilers or speedbrakes (if the airplane is so equipped). As mentioned above, deploying the spoilers or speedbrakes after landing greatly improves braking by reducing the airplane’s lift, thereby increasing N_M .

The physical parameters affecting μ_B have been the object of much study over the last 50 years. A convenient summary of much of this research can be found in the Engineering Science Data Unit (ESDU) Items 71025 and 71026, *Frictional and retarding forces on aircraft tires*, Parts I and II, respectively (References 18 and 19).

References 18 and 19 indicate that μ_B increases above the rolling (unbraked) coefficient of friction (μ_N in Equation [13]) when the slip ratio s (see Equation [11]) of the main gear tires increases above 0. μ_B increases to a maximum $\mu_{B,MAX}$ at a slip ratio $s_{\mu,MAX}$, and then decreases to the locked-wheel skidding coefficient of friction ($\mu_{B,SKID}$) at $s = 1$, as shown in Figure 18. Reference 19 notes that “the shape of the curve of μ_B against s is affected by surface texture and tire tread pattern and is particularly variable in the region between $\mu_{B,MAX}$ and $\mu_{B,SKID}$.” Reference 18 adds that “in practice, curves of μ_B against s vary considerably depending on many factors,” and cites a number of references to this point. Reference 18 also lists a number of physical parameters that affect the values of $\mu_{B,MAX}$ and $\mu_{B,SKID}$:

- Tire factors:
 - o Tire design and construction
 - o Tire tread material
 - o Tire tread pattern (particularly important on wet runways); “the primary function of a tread pattern is to improve the tire frictional properties on wet surfaces.”

- o Inflation pressure: on dry and wet runways, μ_B tends to decrease with increasing inflation pressure; however, higher inflation pressure will increase the hydroplaning speed in standing water (see below).
- Runway surface factors:
 - o Surface material and texture (see Figure 19):
 - Large or macro-scale texture (macrotexture): “this depends on the sizes and relative quantities of the aggregates used. This scale of texture may be judged approximately by the eye.”
 - Small or micro-scale texture (microtexture): “this is the texture of the individual stones of which the runway is constructed and depends on the shape of the stones and how they wear. It may not, in general, be judged by the eye but differences may be apparent to the touch.”
 - o Fluid depth on runway: on wet runways, μ_B is a strong function of forward speed, as shown in Figure 19. When, in addition, the runway is flooded (water deeper than 3 mm or 0.1 inches above the top of the surface asperities), then hydroplaning is possible (see below). On flooded runways at high speeds, fluid drag on the tire and spray impingement can provide additional retarding forces.
 - o Surface deposits:
 - Loose surface deposits such as sand, grit or dust: decrease μ_B on a dry surface, and may increase or decrease μ_B on a wet surface depending on the surface texture and water depth.
 - Rubber deposits, hardened smears of asphalt binder, and paint: these deposits “can cover large areas of busy runways, particularly near the touch-down region ... in dry conditions no appreciable effects are observed. In wet conditions, large reductions may occur in both $\mu_{B,MAX}$ and $\mu_{B,SKID}$ - depending in part on the initial texture of the underlying surface.”
- Aircraft design and operational factors:
 - o Forward speed: “In general, $\mu_{B,MAX}$ and $\mu_{B,SKID}$ decrease with increase in forward speed,” though this effect is much more pronounced on wet runways than on dry ones (see Figure 19). The effect of speed on μ_B on a wet runway is described further below.
 - o Tire wear: “For the aircraft operator, tire wear is a most important factor ... the available μ_B in wet conditions decreases as a tire wears. For a typical aircraft-type, rib-tread tire, when groove depths have been reduced to about 20% or less of the unworn value, the remaining tread may be ‘flattened out’ under load and the tire may then behave as if smooth.”

Reference 39 (published in 1962) states the following regarding typical values of $s_{\mu,MAX}$:

The relationship between friction coefficient μ_B and slip ratio s has considerable significance with regard to wheel braking. For example, to obtain maximum effectiveness, automatic braking systems must be designed to operate near peak μ_B ($\mu_{B,MAX}$ usually occurs at a slip ratio between 0.1 and 0.2). If operation occurs at a slip ratio greater than that required for peak friction, tire tread life is reduced by skidding and braking effectiveness is reduced. Operation at a slip ratio below that required for peak friction simply results in reduced braking action.

Because of the transient nature of the tire-slip phenomenon, operation by the pilot or antiskid unit at $\mu_{B,MAX}$ is not generally realized without some overshooting or undershooting of the slip ratio for $\mu_{B,MAX}$. For this reason, the average friction coefficient $\mu_{B,av}$ developed between slip ratios of 0.1 and 0.5 ..., rather than $\mu_{B,MAX}$ was arbitrarily chosen in this paper as more nearly representative of the friction coefficient attainable with present-day braking systems.

Advances in anti-skid braking systems since 1962 have improved their ability to detect and operate near $s_{\mu,MAX}$, but they still cannot do so perfectly. The ability of these systems to operate at $s_{\mu,MAX}$ is a measure of their efficiency (η_{AS}), and is discussed further below.

The computed wheel-slip ratio s for the accident landing is shown in Figure 13. Although the 2-Hz sample rate of the wheel speed parameters is too low to provide a precise measure of s at every instant, the plot in Figure 13 indicates that prior to the EPB being set, s varied between about 0.05 and 0.3, suggesting that the anti-skid system was active.

μ_B on wet runways

As shown in Figure 19, on a wet runway μ_B decreases precipitously with forward speed, particularly on runways with relatively low macrotexture and / or microtexture. Reference 18 explains this phenomenon as follows:

The presence of a fluid, which is usually water, on a runway decreases the available tire-ground coefficient of friction.

The tire-ground contact area in wet conditions can be divided into three zones, as illustrated in Figure [20a].

Zone 1 is the region where impact of the tire with the surface fluid generates sufficient pressure to overcome the inertia of the fluid. Much of the fluid is either ejected as spray or forced beneath the tire into the tread grooves (if present) or into the drainage paths provided by the surface texture. Throughout Zone 1 a continuous, relatively thick fluid layer exists between the tire and the runway surface and the only retarding force developed is that due to fluid drag

Zone 2 is a transition region. After the bulk of the fluid is displaced, a thin film remains between the tire and the surface. At the rear of Zone 1, and in Zone 2, a rapid outflow of fluid is prevented, and fluid pressures are maintained, by viscous effects. The thin film first breaks down at points where the local bearing pressure is high, e.g. at sharp surface asperities. In the presence of a lubricant such as water, the coefficient of friction of rubber on hard surfaces is greatly reduced from the dry surface value and varies little with changes in sliding speed and temperature Thus, in general, very little frictional force is generated wherever a thin film of fluid persists.

Zone 3 is the region of predominantly dry contact and, although obviously smaller than the contact area in dry conditions, it is here that most of the braking force is generated

In wet conditions, the tire-ground coefficient of friction depends on the relative sizes of Zones 1, 2 and 3. These are determined by the surface texture, the depth, density and viscosity of the fluid, the tread pattern and inflation pressure of the tire and the time ... for a tread element to pass through the contact area

Figure [20] also shows the effect of increased forward speed on the relative sizes of Zones 1, 2 and 3. In Figure [20b] the tire forward speed is higher than in Figure [20a] so that Zone 1 extends farther back into the contact area and Zones 2 and 3 occupy a horseshoe-shaped region at the rear. In Figure [20c], at a still higher speed, contact with the ground is all but lost. In this condition the tire develops very little braking force. Finally, in Figure [20d], the tire is moving at a speed such that Zone 1 extends throughout the contact area. (When dry contact with the ground ceases, the tire is said to be "planing".)

Viscous and dynamic hydroplaning

The "planing" referred to in Reference 18 is also called "dynamic hydroplaning," and is one of three types of hydroplaning. As described in Reference 20, the other two types are viscous hydroplaning, and reverted-rubber hydroplaning. Reverted-rubber hydroplaning will be discussed below. Reference 20 describes dynamic and viscous hydroplaning as follows:

Water pressures developed on the surface of the tire footprint and on the ground surface beneath the footprint have been measured during a recent investigation This research showed that it was possible for this water-pressure buildup under the tire footprint to originate from the effects of either fluid density or fluid viscosity, depending upon conditions; hence the classification of hydroplaning into two types, namely dynamic or viscous.

Accordingly, "viscous hydroplaning" is associated with the buildup of water pressure due to viscosity, and corresponds to the situation in "Zone 2" described by Reference 18 and illustrated in Figure 20. This kind of hydroplaning is inferred when a surface is described as "slippery when wet," e.g., a wet bathtub. "Dynamic hydroplaning" is associated with the buildup of water pressure due to water density, and corresponds to the situation shown in Figure 20d, where "Zone 1 extends throughout the contact area." Dynamic hydroplaning is commonly referred to simply as "hydroplaning," and can be experienced by driving a car through a deep puddle at high speed.

Both a minimum water depth above the runway macrotexture asperities, and a minimum airplane ground speed, are required to support dynamic hydroplaning. Reference 21 addresses the minimum water depth required to support dynamic hydroplaning, and the factors that affect water depth on the runway:

An optimum runway design is one that delays surface flooding during natural rain until less frequent high rainfall rates are reached, such as the grooved runway shown in figure [21]. In general, runway water depths increase with increasing rainfall intensity and drainage path lengths, and decrease with increasing runway transverse slope and surface macrotexture (ref. [22]). Surface winds do not affect runway water drainage appreciably until surface flooding occurs, and water then flows as a sheet along the runway surface. At this point, surface winds tend to increase drainage path lengths and can greatly increase water depths on the runway, depending upon the wind magnitude and direction as shown in figure [21]. The horizontal lines drawn in figure [21] qualitatively indicate the critical water depths required for dynamic tire hydroplaning to occur when the aircraft on the runway is traveling at speeds greater than the tire hydroplaning speed. During this speed and water depth regime, the aircraft is like a sailboat without a keel, and is hard to steer

and stop without lateral drift (in crosswinds), due to absence of tire cornering and braking forces. It should be noted that on crowned runways, minimum water depths are encountered by aircraft tires when the pilot lands and maintains a course directly down the runway centerline. (Minimum drainage path lengths for aircraft tires are obtained.)

Reference 21 also addresses the minimum aircraft ground speed required to support dynamic hydroplaning (i.e., the hydroplaning speed, V_p). The V_p depends on both the tire inflation pressure, p , and on whether the tire is rolling (as on a takeoff roll), or nonrotating (as just before touchdown during landing):

$$V_{p,spin\ down} = 9\sqrt{p} \quad (\text{rotating tire}) \quad [19a]$$

$$V_{p,spin\ up} = 7.7\sqrt{p} \quad (\text{nonrotating tire}) \quad [19b]$$

Where p is in pounds per square inch (psi), and V_p is in knots. The p of the main gear tires on N322QS were measured at 180 psi after the accident, resulting in a $V_{p,spin\ up}$ of 103 kt. Reference 21 cites Reference 22 as a source for determining the water depths illustrated in Figure 21.⁴⁹ Reference 22 will be used below to determine the likely water depth on KCXO runway 1 during the accident. The potential for dynamic hydroplaning during the accident landing, based on this computed water depth and the $V_{p,spin\ up}$ of 103 kt., is evaluated below.

As noted in Reference 18, during dynamic hydroplaning, tire “contact with the ground is all but lost” and “the tire develops very little braking force.” Similarly, Reference 20 states that tests on flooded runways indicate “a total traction loss at ... the predicted hydroplaning speed.” The AMC 25.1591 flooded runway model introduced above specifies that, above the hydroplaning speed, $\mu_B = 0.05$ constant, which is slightly above the unbraked rolling friction coefficient μ_N (typically modeled as 0.02 to 0.03).

Reference 23 describes another interesting effect of dynamic hydroplaning – the spin-down of unbraked hydroplaning tires:

Perhaps the most striking manifestation of tire hydroplaning is the now well substantiated condition in which free rolling (unbraked) wheels slow down or stop completely on wet runways Unbraked-wheel spin-down arises from two hydrodynamic lift effects which combine to produce a total wheel spindown moment in excess of the wheel spin-up moment due to all tire drag sources. First, as ground speed increases, the hydrodynamic lift progressively detaches the tire footprint from the pavement surface ... and makes the tire-ground frictional spin-up moment ... tend toward zero values. Secondly, the center of pressure of the hydrodynamic pressure and resulting lift developed between the tire footprint and ground surface shifts increasingly forward of the axle as the ground speed increases ... and produces the wheel spin-down moment At some high forward speed near the total hydroplaning speed of the tire, this wheel spin-down moment overcomes the wheel spin-up moment from all the drag sources and wheel spin-down commences.

⁴⁹ Figure 21 does not indicate the pavement macrotexture depth used to construct the curves in the Figure; at a given rainfall rate, the water depth will be higher for lower macrotexture depths, and lower for higher macrotexture depths. Reference 22 provides a model for computing water depths including the macrotexture depth as a variable, and is discussed below.

Reverted-rubber hydroplaning

Reference 20 describes reverted-rubber hydroplaning (which it calls “reverted rubber skidding”):⁵⁰

Evidence from skidding accidents.- A recent survey of conditions that prevailed during landing accidents on wet runways showed a very interesting correlation. In numerous documented cases on wet runways involving aircraft departure off the side of the runway or in an overrun (both types of accidents indicate drastic loss of tire traction), the runway surface was found to have developed white streaks in the tire paths. The aircraft tires showed evidences of prolonged locked wheel skids with indications that the rubber in the skid patches had reverted to an uncured state. ... In [a photograph] where effects of an overrun accident are shown, the white streaks persisted down to the point that the aircraft stopped.

In contrast, if the wheels lock on dry runways at speed, black streaks from molten rubber eroding from the tire are immediately deposited in the tire paths. Although friction decreases under this condition, at least one-third of the maximum dry friction coefficient is still available for stopping the aircraft It thus appears that some mechanism other than viscous or dynamic hydroplaning must be at work to prevent the skidding tire from developing traction on wet textured pavements even at very low ground speeds

...

A series of tests was made ... with tires locked to prevent rotation on dry, wet, and flooded runways at speeds ranging from about 25 to 100 knots. ... Under all conditions of the tests, if reverted rubber developed in the footprint, the traction values fell to very low values in comparison with those obtained with the tire under normal rubber tread conditions ... the reverted rubber condition tends to make all runway surfaces smooth acting. Pavement surface texture, which (as discussed previously) has such a large effect on traction losses from dynamic and viscous hydroplaning (normal rubber curves), has but little effect for the reverted rubber condition for the texture-depth range [tested].

Reference 20 includes several photographs of aircraft tires with patches of reverted rubber resulting from locked-wheel skids on wet runways. The tires from N322QS show similar patches (see Figure 22). Figure 22, and the white scrub marks shown in Figure 5a (similar to the “white streaks” mentioned by Reference 20), indicate that N322QS likely experienced reverted-rubber hydroplaning during the locked-wheel skid after the EPB was set.

Water depth on KCXO runway 1 at the time of the accident

The airplane touched down at about 118 kt. groundspeed, above the $V_{p,spin up}$ of 103 kt. given by Equation [19b]. If the depth of water on the runway was sufficient to support dynamic hydroplaning, then between touchdown and the time that the airplane decelerated through 103 kt., conditions that could have supported dynamic hydroplaning were present. Consequently, it is of interest to determine the possible water depths on the runway during the accident.

⁵⁰ Reference 53 states, “the three presently known types of hydroplaning were first defined in reference [20], that is, dynamic, viscous, and ‘reverted’ rubber hydroplaning,” even though Reference 20 uses the term “reverted rubber skidding.” This *Study* uses the “reverted rubber hydroplaning” term of Reference 53.

In steady-state, equilibrium conditions during a rain event over a runway, the water depth at a given point from the runway centerline is constant (neither increasing nor decreasing). In this condition, the amount of water flowing towards that point from the crown (centerline) of the runway equals the amount of water flowing away from the point towards the runway edge. The volume of water per unit runway length flowing past a given point from the centerline is proportional to the speed of the water times the water depth. The water volume will increase with rainfall rate and distance from the centerline (the further from the centerline, the more runway area is available for collecting water that flows towards the point in question), and the water speed will increase with the runway cross-slope (the steeper the slope, the faster the flow). Thus, for a given slope, the water depth will increase with distance from the runway centerline (to accommodate the increasing volume of water) and with rainfall rate. At a given rainfall rate and distance from the centerline, the water depth will decrease as the runway cross-slope increases, since the increased speed of the water accommodates the same volume of water flow at a lesser water depth.

The runway macrotexture depth is the average depth of irregularities in the surface of the runway, produced by the coarseness of the surface texture (see Figure 19). The greater the number and magnitude of these irregularities, the more “channels” are provided for water to flow through, and the higher the rainfall rate required to submerge the “peaks” of the irregularities.

Under some conditions, the required water depth to accommodate the volume of water flow will be less than the average macrotexture depth of the runway; in this case, the tips of the macrotexture irregularities will be above the water. If the required water depth is greater than the macrotexture depth, then the tips of the macrotexture irregularities will be below the water.

Reference 22 documents the results of experiments performed at the Texas Transportation Institute (TTI) that quantified the water depths resulting from various combinations of rainfall intensity, pavement cross slope, surface texture, and drainage length. The TTI report provides the following equation to describe the experimental results:

$$d = (0.00338) \left(\frac{1}{T}\right)^{-0.11} (L)^{0.43} (I)^{0.59} \left(\frac{1}{S}\right)^{0.42} - T \quad [20]$$

where:

d = average water depth above the top of the macrotexture irregularities (inches);

T = average macrotexture depth, inches;

L = drainage path-length (i.e., distance from runway centerline), feet;

I = rainfall intensity (inches / hour)

S = runway cross slope, ft/ft (= slope in % divided by 100)

In May 2015, the NTSB and the parties to the investigation conducted tests on KCXO runway 1 to measure the runway macrotexture depth T , and the runway cross slope S (see Reference 24).⁵¹ The measurements indicated some small variations in T and S over the runway, with the average values and standard deviations shown in Table 9.

Item	Value
Overall average macrotexture (mm) =	0.54
Overall macrotexture standard deviation (mm) =	0.04
Overall average slope (%) =	1.44
Overall slope standard deviation (%) =	0.11

Table 9. Average and standard deviation of KCXO runway 1 macrotexture and cross-slope measurements, from Reference 24.

The macrotexture depth values shown in Table 9 are the “estimated texture depth” (ETD) values reported by the ELAtextur laser scanning device used to take the measurements.⁵² However, the device does not measure ETD directly; as described in Reference 24, the “mean profile depth” (MPD) is the actual physical measurement taken by the device, and ETD is computed from MPD according to the equation

$$\text{ETD} = 0.80 * (\text{MPD}) + 0.20 \text{ mm} \quad [21]$$

With both ETD and MPD in millimeters. Furthermore, macrotexture measurements taken on runway 3/21 at the Roswell International Air Center (KROW) using a variety of methods (including measurements with the ELAtextur device) indicate that Equation [21] does not provide the best correlation between the MPD measured by the device, and the ETD measured using other methods (the “NASA Grease Sample” and “Water Outflow Meter” methods; see Reference 25).⁵³ Instead, the measurements indicate that a better correlation between ETD and MPD is that given in Reference 26:

$$\text{ETD}' = 0.91 * (\text{MPD}) + 0.053 \text{ mm} \quad [22]$$

Where the symbol ETD' is used to distinguish the ETD computed using Equation [22] from that computed using Equation [21]. Solving Equation [21] for MPD and substituting the result into Equation [22] gives ETD' in terms of the reported ETD:

$$\text{ETD}' = 1.1375 * (\text{ETD}) - 0.1745 \text{ mm} \quad [23]$$

Using Equation [23], the average ETD' on KCXO runway 1 is 0.44 mm, 0.1 mm lower than the ETD recorded in Table 9. The ETD' value is more “conservative,” since lower

⁵¹ In addition, the friction on runway 1 was measured using a Continuous Friction Measuring Equipment (CFME) device, as described further below.

⁵² See Reference 24 and http://www.iwsmesstechnik.de/elatextur_en.htm (accessed 06/05/2015).

⁵³ Reference 25 documents the NASA Grease Sample and Water Outflow Meter measurements taken at KROW in January 2012; the ELAtextur device measurements on KROW runway 3/21 were taken by an NTSB investigator in January 2013 and are recorded in an internal NTSB document.

macrotexture depth implies lower μ_B , and lower rainfall rates required to flood the runway. The ETD' of 0.44 mm (0.017") is used in the calculations discussed below.

The rainfall rate at KCXO on the day of the accident was recorded by an automated Airport Surface Observation System (ASOS) at intervals as short as 1 minute.⁵⁴ Table 10 shows the ASOS rainfall measurements, and corresponding rainfall rates, for the approximately 7 minutes preceding the accident.

Time (CDT)	Intensity	Hourly precipitation (inches) ⁵⁵	Precipitation rate (in./hr., computed) ⁵⁶
08:40	Heavy rain	0.21	
			0.24
08:45	Heavy rain	0.23	
08:46	Heavy rain		0.30
08:47	Rain	0.24	

Table 10. ASOS rainfall measurements at KCXO during the 7 minutes preceding the accident.

Figure 23 shows the computed water depth on the runway as a function of distance from the runway centerline, at various rainfall rates, using Equation [20] with $T = 0.44$ mm (0.017"), and $S = 1.44\%$. This Figure provides a calculation of the expected water depth on the runway at the time of the accident,⁵⁷ and indicates that even at a rainfall rate of 0.9 inch/hour (three times that recorded in Table 10), the water depth at the edge of the runway would have remained less than 0.05" above the top of the macrotexture asperities, and within the "Safe Zone" identified in Reference 21. Prior to the setting of the EPB, the main gear remained within 20 ft. of the runway centerline (see Figure 6b); per Figure 23, the maximum water depth that would have been encountered by the gear in this area would have been about 0.006 inches at a rainfall rate of 0.3 inches/hour. Consequently, the rainfall rate, runway macrotexture, and runway cross slope indicate that the water depth on the runway at the time of the accident was far below the Reference 1 "Hydroplaning Danger Zone" and "Caution Zone" levels, as well as far below the 3 mm (0.017 inches) that AMC 25.1591 considers a "flooded" runway. Therefore, it is unlikely that N322QS experienced dynamic hydroplaning during the landing, even when its ground speed was above the $V_{p,spin up}$ of 103 kt.

Additional evidence that N322QS did not experience dynamic hydroplaning includes:

- Brake pressure increased with brake pedal application, indicating that the tires could support some drag force (see Figure 13);
- As the brake pressure increased, μ_B rose well above the 0.05 value that AMC 25.1591 assigns to dynamic hydroplaning conditions (see Figure 14);

⁵⁴ This data was provided to the NTSB Aircraft Performance Group Chairman by an NTSB meteorologist.

⁵⁵ The hourly precipitation is the total rainfall, in inches, since the beginning of the recording hour; the recording hour starts 50 minutes after the chronological hour (e.g., at 06:50 CDT, 07:50 CDT, etc.).

⁵⁶ This rate is computed as the difference in rainfall between reports, divided by the time between reports.

⁵⁷ Equation [20] assumes that rain can drain from the edges of the runway with no obstructions. Reference 24 notes that "the runoff and drainage of rain from the edges of the runway was observed during a rain event ... no significant ponding or pooling of water at the runway edges was observed."

- The tires spun up to about 90% - 95% of the airplane's groundspeed, resulting in a slip ratio of 0.05-0.1, and didn't appear to "spin down" significantly until the EPB was set (see Figures 7 and 13);
- The crew's comments concerning the airplane's speed and braking action all occur after the airplane had already decelerated below the $V_{p,spin\ up}$ of 103 kt. (see Figure 7).
- The computed μ_B is consistent with a NASA model based on CFME measurements for a runway that is wet, but not flooded (see below).

Based on this evidence, the μ_B levels shown in Figure 14 are not the result of dynamic hydroplaning, but of viscous hydroplaning – i.e., the fact that runways become more slippery when wet. Hence, it is of interest to compare the computed μ_B with models of μ_B for runways that are wet, but not flooded. Several of these models are considered below.

Definition of 14 CFR §25.109 wet runway braking friction coefficients

14 CFR §25.109 defines the accelerate-stop distance for transport-category airplanes, and describes how this distance is to be determined. The accelerate-stop distance is the distance required to accelerate from a stop to V_1 ,⁵⁸ and then bring the airplane back to a stop in the remaining runway length.⁵⁹ §25.109(a) defines the accelerate-stop distance on a dry runway, and §25.109(b) defines the accelerate-stop distance on a wet runway. §25.109(c) defines the μ_B to be assumed in the calculation of the accelerate-stop distance for a smooth, wet runway (the μ_B for wet runways that are grooved or treated with porous friction coarse material are defined in §25.109(d)).

For a smooth, wet runway, §25.109(c) defines the μ_B as follows:

The wet runway braking coefficient of friction for a smooth wet runway is defined as a curve of friction coefficient versus ground speed and must be computed as follows:

- (1) The maximum tire-to-ground wet runway braking coefficient of friction is defined as:

⁵⁸ Per 14 CFR 1.2, V_1 "means the maximum speed in the takeoff at which the pilot must take the first action (e.g., apply brakes, reduce thrust, deploy speed brakes) to stop the airplane within the accelerate-stop distance. V_1 also means the minimum speed in the takeoff, following a failure of the critical engine at V_{EF} , at which the pilot can continue the takeoff and achieve the required height above the takeoff surface within the takeoff distance."

⁵⁹ This simplified definition suffices for the intent of this *Study*; §25.109 defines additional details regarding how this maneuver is to be accomplished, that account for engine failures and pilot reaction times.

<u>Tire Pressure (psi)</u>	<u>Maximum Braking Coefficient (tire-to-ground)</u>
50	$\mu_{t/gMAX} = -0.0350 \left(\frac{V}{100} \right)^3 + 0.306 \left(\frac{V}{100} \right)^2 - 0.851 \left(\frac{V}{100} \right) + 0.883$
100	$\mu_{t/gMAX} = -0.0437 \left(\frac{V}{100} \right)^3 + 0.320 \left(\frac{V}{100} \right)^2 - 0.805 \left(\frac{V}{100} \right) + 0.804$
200	$\mu_{t/gMAX} = -0.0331 \left(\frac{V}{100} \right)^3 + 0.252 \left(\frac{V}{100} \right)^2 - 0.658 \left(\frac{V}{100} \right) + 0.692$
300	$\mu_{t/gMAX} = -0.0401 \left(\frac{V}{100} \right)^3 + 0.263 \left(\frac{V}{100} \right)^2 - 0.611 \left(\frac{V}{100} \right) + 0.614$

Where—

Tire Pressure = maximum airplane operating tire pressure (psi);

$\mu_{t/gMAX}$ = maximum tire-to-ground braking coefficient;

V = airplane true ground speed (knots); and

Linear interpolation may be used for tire pressures other than those listed.

(2) The maximum tire-to-ground wet runway braking coefficient of friction must be adjusted to take into account the efficiency of the anti-skid system on a wet runway. Anti-skid system operation must be demonstrated by flight testing on a smooth wet runway, and its efficiency must be determined. Unless a specific anti-skid system efficiency is determined from a quantitative analysis of the flight testing on a smooth wet runway, the maximum tire-to-ground wet runway braking coefficient of friction determined in paragraph (c)(1) of this section must be multiplied by the efficiency value associated with the type of anti-skid system installed on the airplane:

Type of anti-skid system	Efficiency value [η_{AS}]
On-Off	0.30
Quasi-Modulating	0.50
Fully Modulating	0.80

Consequently, §25.109(c) defines the wet runway braking coefficient as

$$\mu_B = (\mu_{t/gMAX}) \times (\eta_{AS}) \quad [24]$$

Where $\mu_{t/gMAX}$ (or μ_{max})⁶⁰ and the anti-skid efficiency η_{AS} are defined in the rule as shown above.

FAA AC 25-7C, *Flight Test Guide for Certification of Transport Category Airplanes*, dated 10/16/2012 (Reference 33), describes the three types of anti-skid braking systems identified in §25.109 as follows:⁶¹

⁶⁰ Throughout this *Study*, $\mu_{t/gMAX}$ and μ_{max} are used equivalently.

⁶¹ See AC-25 7C, paragraph 11(c)(4)(b)(1), “Classification of Types of Anti-Skid Systems.”

(aa) The efficiency values specified in §25.109(c)(2) are a function of the type of anti-skid system installed on the airplane. Three broad system types are identified in the rule: on/off, quasi-modulating, and fully modulating. These classifications represent evolving levels of technology and differing performance capabilities on dry and wet runways. The classification of anti-skid system types and the assigned efficiency values are based on information contained in Society of Automotive Engineers (SAE) Aerospace Information Report (AIR) 1739, titled “Information on Anti-Skid Systems.”

(bb) On/off systems are the simplest of the three types of anti-skid systems. For these systems, full-metered brake pressure (as commanded by the pilot) is applied until wheel locking is sensed. Brake pressure is then released to allow the wheel to spin back up. When the system senses that the wheel is accelerating back to synchronous speed (i.e., ground speed), full-metered pressure is again applied. The cycle of full pressure application/complete pressure release is repeated throughout the stop (or until the wheel ceases to skid with pressure applied).

(cc) Quasi-modulating systems attempt to continuously regulate brake pressure as a function of wheel speed. Typically, brake pressure is released when the wheel deceleration rate exceeds a preselected value. Brake pressure is re-applied at a lower level after a length of time appropriate to the depth of the skid. Brake pressure is then gradually increased until another incipient skid condition is sensed. In general, the corrective actions taken by these systems to exit the skid condition are based on a pre-programmed sequence rather than the wheel speed time history.

(dd) Fully modulating systems are a further refinement of the quasi-modulating systems. The major difference between these two types of anti-skid systems is in the implementation of the skid control logic. During a skid, corrective action is based on the sensed wheel speed signal, rather than a pre-programmed response. Specifically, the amount of pressure reduction or reapplication is based on the rate at which the wheel is going into or recovering from a skid.⁶²

As noted above, the inflation pressure of the main tires on N322QS was measured at 180 psi. Interpolating the $\mu_{t/gMAX}$ tables above for a tire pressure of 180 psi gives

$$\mu_{t/gMAX} = -0.0352 \left(\frac{V_G}{100} \right)^3 + 0.266 \left(\frac{V_G}{100} \right)^2 - 0.687 \left(\frac{V_G}{100} \right) + 0.714 \quad [25]$$

Where V_G is the groundspeed in knots. The μ_B resulting from multiplying the $\mu_{t/gMAX}$ defined in Equation [25] by anti-skid system efficiencies of 0.80 and 0.95 are shown in the bottom plot of Figure 24 as the lines labeled “ $\mu_B = \eta_{AS} \mu_{t/gMAX}$, $\eta_{AS} = 0.80$ ” and “ $\mu_B = \eta_{AS} \mu_{t/gMAX}$, $\eta_{AS} = 0.95$,” respectively. The $\eta_{AS} = 0.80$ value was selected to correspond to the value §25.109(c) allows for a fully-modulating anti-skid braking system. The $\eta_{AS} = 0.95$ value was determined to be the anti-skid system efficiency required to obtain a μ_B profile that is consistent with the unfactored wet landing distance for the accident conditions published in the EMB-505 AFM, as described further below.

Note that the §25.109 μ_B curves in Figure 24 are substantially higher than the computed μ_B based on the accident data, even prior to the setting of the EPB at about 08:47:23.7 (at a ground speed of about 87 kt.). The top plot in Figure 24 plots distance from the runway threshold as a function of ground speed, and compares the curve computed from the FDR data with the curves that would have resulted from the airplane achieving and

⁶² The Meggitt anti-skid system installed on the EMB-505 is a fully modulating system.

maintaining the μ_B performance predicted by various models, including those based on §25.109. With the §25.109 model and $\eta_{AS} = 0.80$, the airplane would have come to a stop about 4210 ft. from the threshold, with 790 ft. of runway remaining. With the §25.109 model and $\eta_{AS} = 0.95$ (i.e., equivalent to the EMB-505 AFM unfactored wet runway performance), the airplane would have come to a stop about 3953 ft. from the threshold, with 1047 ft. of runway remaining.

The curve labeled “ $\mu_B = \text{ESDU class A}, \eta_{AS} = 0.80$ ” in the bottom plot of Figure 24 approximately matches the computed μ_B between about 110 and 90 knots. Assuming that the EPB had not been set and that the airplane had continued to perform in a manner consistent with this “ESDU class A” curve, then the top plot in Figure 24 indicates that the airplane would have come to a stop about 4669 feet from the threshold, with 331 ft. of runway remaining.

The “ESDU class A” curve is constructed per Equation [24], using μ_{hgMAX} from a model described in ESDU Item 71026 (Reference 19), and $\eta_{AS} = 0.80$ from the value allowed for fully-modulating anti-skid systems in §25.109(c). This particular model was selected so as to match the computed μ_B before the EPB was set, and between 110 and 90 knots the “ESDU class A” curve is approximately equivalent to the μ_{hgMAX} defined by Equation [25] multiplied by an η_{AS} of 0.63. The ESDU models are described further below.

Range of μ_{max} defined in ESDU 71026

The development of the μ_B calculation method in §25.109(c) is described in Reference 27, which explains that the method is based on wet runway friction data from the Engineering Sciences Data Unit (ESDU), NASA, and the aerospace industry. In particular, ESDU 71026 (Reference 19) contains extensive information about the maximum μ (μ_{max}), as a function of ground speed, obtainable on wet and dry runways of various textures, with different tire tread depths and at various tire inflation pressures. ESDU 71026 introduces the μ_{max} data it presents as follows:

Curves of μ_{max} for unyawed tires are plotted against forward speed ... for five prepared, hard runway surfaces: A, B, C, D and E, in both dry and wet conditions. Each of these surfaces typifies a class of runways having surface macro-texture depths lying within a specified range (see [Table 11] for classification of surfaces). Data are presented at four values of inflation pressure and, for wet conditions, include curves for rib tread ([tread depth] > 5 mm, 0.2 in) and smooth tread tires.

In [the data plots], the thick lines are average values of μ_{max} drawn through the available data for each class of surface. The thin lines enclose most of the available data and thereby include the scatter due to the effects of variation in surface texture (within the stated class of surface), runway wetness, tire characteristics and experimental method. To complete the curves, the available data are extrapolated where necessary, particularly at speeds above 100 kt.

Table 11 presents the runway macrotexture depths and surface descriptions for the five “classes” of runways identified in ESDU 71026 (classes A-E, in increasing order of roughness). Note that runway 1 at KCXO, with an average macrotexture depth of 0.017

inches, falls into class C. Per Reference 8 and observations of the runway during the tests described in Reference 24, runway 1 is constructed of brushed concrete.

ESDU runway class	Minimum macrotexture depth, in. (mm)	Maximum macrotexture depth, in. (mm)	Surface description
A	0.004 (0.10)	0.006 (0.15)	Mainly very smooth concrete runways, some smooth asphalt runways
B	0.006 (0.15)	0.01 (0.25)	Typical of most lightly textured concrete and most small aggregate asphalt runways
C	0.01 (0.25)	0.02 (0.51)	Heavily textured concretes and the majority of harsher types of asphalt
D	0.02 (0.51)	0.04 (1.02)	Shallow grooving and scoring, some large aggregate asphalt
E	0.04 (1.02)	0.10 (2.54)	Deep grooved surfaces, "open textured" and "porous friction course" surfaces

Table 11. Classification of runway surfaces, per ESDU 71026 (Reference 19).

Figure 25 presents the range of ESDU 71026 μ_{max} values, corresponding to the KCXO runway 1 macrotexture depth of 0.017 inches (0.44 mm), a tire pressure of 180 psi, and a tire tread depth of 0.118 inches (about 80% worn).⁶³ The average μ_{max} for 80% and 54% worn tires are also shown; the greater wear reduces μ_{max} by about 4.5% at 140 knots, but makes no difference by about 30 knots.⁶⁴ The average μ_{max} values for a class "A" wet runway for these tire conditions are also presented.⁶⁵

Figure 25 also plots the §25.109 μ_{max} corresponding to 180 psi tires (Equation [25]), and the μ_{max} computed using a NASA method based on CFME measurements (described below). The §25.109 μ_{max} is in relatively good agreement with the average ESDU μ_{max} .

It is clear from the ESDU data presented in Figure 25 that the research data compiled in ESDU 71026 supports a wide range of μ_B values on any given wet runway, including values lower than those specified in §25.109(c).

⁶³ The μ_{max} values for these conditions were obtained by interpolation of the published ESDU data.

⁶⁴ The tire tread depth is not an input into the §25.109 or NASA CFME μ_{max} models, but is an input into the ESDU wet μ_{max} model. For the ESDU class A calculations shown in Figure 24, a tire tread depth of 3 mm was used (80% worn, based on a new tread depth of 7mm and fully-worn tread depth of 2 mm). The tread depths of the tires on N322QS were not measured after the accident, but the tires had 81 takeoff and landing cycles at the time. NJA informed NTSB that a set of tires typically needs replacement after 130-150 cycles. Based on 150 cycles, the N322QS tires were about 54% worn at the time of the accident.

⁶⁵ Note that the average values in the ESDU data are not simply the average of the maximum and minimum extents of the data range at each ground speed, but of all data points within the range at each groundspeed. Hence, the average lines do not necessarily pass through the middle of the data range.

NASA μ_B model based on Continuous Friction Measurement Equipment data

Appendix B of this *Study* is a paper prepared by Mr. Thomas Yager, Distinguished Research Associate at the NASA Langley Research Center (retired), documenting the details of the NASA method for computing μ_B for aircraft based on CFME data. This paper was prepared for NTSB in support of the investigation of the Hawker Beechcraft BAe 125-800A accident in Owatonna, MN, on July 31, 2008 (see Reference 27). The method is also presented in Reference 28.

As documented in Reference 24, friction measurements on the KCXO runway 1 were obtained using a Neubert Aero Corporation Dynamic Friction Tester (NAC DFT) trailer at 4 different speeds and at 4 different distances from the runway centerline (runway y-coordinates). The results of these measurements are presented in Figure 26 (taken from Reference 24).⁶⁶ The legends in the plots indicate the speed and runway y-coordinate of the run; for example, “R14 V60 Y-35” indicates Run #14, performed at 60 mph, at a y-coordinate of -35 ft. (i.e., 35 ft. left of the runway centerline).

The average μ over the length of the DFT runs for each speed and y-coordinate is presented in Figure 27. For the model used in this *Study*, the $y = -5$ ft. results in Figure 27 were used, since this y coordinate best matches the position of N322QS during the ground roll prior to the setting of the EPB (see Figure 6).

The NASA method for computing airplane μ_B values from the CFME data consists of computing the ratio of the wet-runway μ (μ_{wet}) to the dry-runway μ (μ_{dry}) based on the CFME μ (which measures μ_{wet}) and a characteristic μ_{dry} for the test vehicle, and assuming that this ratio also applies to the $\mu_{\text{wet}} / \mu_{\text{dry}}$ ratio of the braked airplane tires. The μ_{dry} of the airplane tires is a function of the tire inflation pressure (see Appendix B). The selection of μ_{dry} for the DFT trailer is discussed in Section D-VIII.

The airplane ground speed associated with each μ_{wet} value is similarly based on computing the ratio of the ground speed (V_G) to the spin-down hydroplaning speed ($V_{p,\text{spin down}}$) of the test vehicle, and then applying that same ratio to the spin-down hydroplaning speed of the aircraft tires. The $V_{p,\text{spin down}}$ of both the test vehicle and airplane tires are a function of each vehicle’s tire inflation pressure (see Equation [19a]).

One product of this method, which is based on similarity of the $\mu_{\text{wet}} / \mu_{\text{dry}}$ and $V_G / V_{p,\text{spin down}}$ ratios between the friction test vehicle and an airplane, is the maximum wet friction coefficient that the runway can provide (μ_{max}), as a function of V_G for an airplane. The μ_{max} computed from the $y = -5$ ft. DFT results plotted in Figure 27 is shown in Figure 25 as the brown line labeled “NASA CFME-based model.” The DFT speed range of 30 to 60 mph corresponds to an airplane V_G range from 65 to 130 knots; data below $V_G = 65$ kt. in Figure 27 are extrapolated. For the stopping distance calculated

⁶⁶ The lines in Figure 26 labeled “MIN LEVEL,” “MAINT LEVEL,” and “NEW LEVEL” indicate the μ values corresponding to friction levels defined in the FAA AC 150/5320-12C (Reference 29), and will be described further below.

using the NASA model presented in the top plot of Figure 24, μ_B for the full V_G range (including the extrapolated data) is used, as shown in the bottom plot of Figure 24. The extrapolation involves linearly extrapolating the CFME μ to a speed of 0 mph, and then computing the airplane μ_B per the NASA method. The resulting increase in μ_B at lower speeds is not as great as that in the §25.109 and ESDU models; if the actual μ_B increase below 65 kt. were greater, then the stopping distances corresponding to the NASA μ_B model would be shorter than those shown in Figure 24. However, at lower speeds an error in μ_B does not affect the total stopping distance as much as it would at higher speeds; as shown in Figure 24, the difference between the NASA CFME and ESDU class A stopping distances is only about 50 ft., though the differences in μ_B between these models below 25 knots is significant. The large differences between the NASA CFME and §25.109 stopping distances are the result of the large differences in the μ_B of these models at higher speeds.

As described in §25.109(c), the actual μ_B achieved by an aircraft is less than $\mu_{\max}$ because the braking systems of aircraft are not 100% efficient. In the NASA method, μ_B is computed from $\mu_{\max}$ using the following equations:

$$\text{For } \mu_{\max} < 0.7: \quad \mu_B = 0.2 \mu_{\max} + 0.7143 \mu_{\max}^2 \quad [26a]$$

$$\text{For } \mu_{\max} \geq 0.7: \quad \mu_B = 0.7 \mu_{\max} \quad [26b]$$

The computation of μ_B from $\mu_{\max}$ to account for the braking system efficiency of the airplane is similar to the method prescribed in §25.109 for the computation of μ_B by multiplying μ_{avgMAX} by η_{AS} (see Equation [24]). The η_{AS} implied in Equations [26a] and [26b] can be gleaned by dividing these equations by $\mu_{\max}$:

$$\text{For } \mu_{\max} < 0.7: \quad \eta_{AS} = \mu_B / \mu_{\max} = 0.2 + 0.7143 \mu_{\max} \quad [27a]$$

$$\text{For } \mu_{\max} \geq 0.7: \quad \eta_{AS} = \mu_B / \mu_{\max} = 0.7 \quad [27b]$$

Note that the η_{AS} defined by these equations is a function of $\mu_{\max}$ (and is never greater than 0.7), and does not depend on the type of anti-skid braking system, as does the anti-skid efficiency value defined in §25.109. Significantly, Equation [27a] indicates that η_{AS} deteriorates with $\mu_{\max}$; so, as the runway gets more slippery, the anti-skid system becomes less able to take advantage of the available friction that remains – in effect, a double penalty. The η_{AS} resulting from Equation [27a] is plotted vs. V_G in Figure 28, and compared to the η_{AS} for the three types of anti-skid systems identified in §25.109.

AC 25-7C (Reference 33) also indicates that the η_{AS} of “quasi-modulating” anti-skid systems may deteriorate on wet runways, if the anti-skid system has not been properly “tuned” for such a runway:

The effectiveness of quasi-modulating systems can vary significantly depending on the slipperiness of the runway and the design of the particular control system. On dry runways, these systems typically perform very well; however, on wet runways their performance is highly dependent on the design and tuning of the particular system.

Reference 27 indicates that η_{AS} may also deteriorate with decreasing μ_{max} even for “fully-modulating” anti-skid systems, such as that on the Boeing 737-200 ADV.⁶⁷ In analyzing the results of several wet-runway landing tests conducted at Roswell, NM, in 1973 with a Lockheed L-1011 airplane and a Boeing 737-200 ADV airplane (originally documented in Reference 36), Reference 27 concludes that the B737 landing data “indicate that the η_{AS} of even fully-modulating systems decreases as the runway becomes more slippery.”

The authors of Reference 36 arrived at a similar conclusion by examining the relationships between the μ measured by ground vehicles and the stopping performance of various aircraft during flight tests (including the L-1011 and 737 tested at Roswell):

The theoretical aircraft braking efficiency, η , lines ... are related to a μ_{max} value for a low friction wet surface and have been obtained from a current NASA/FAA digital computer simulation study. This comparison indicates a considerable reduction in braking efficiency of the aircraft as the wet runway surface exhibits lower friction values. This trend is confirmed by the data previously shown in [the Roswell B737-200 ADV μ_B data] wherein the aircraft effective braking friction coefficient was shown to be closer to the level of μ_{skid} than to μ_{max} . [Reference 36]

The final airplane μ_B values predicted by the NASA method using the DFT results are presented in Figure 24 as the dashed brown line labeled “ μ_B = NASA CFME model.” Note that this line lies well below the “ μ_B = §25.109” lines, but is a close match to the actual μ_B achieved during the landing, as computed from the FDR data.

Note also that, as shown in Figure 25, the NASA CFME model actually predicts a μ_{max} that is *higher* than the μ_{max} specified by §25.109 in Equation [25]. Hence, the reason that the final μ_B predicted by the NASA model is *lower* than that specified by §25.109 through Equations [24] and [25] is because the η_{AS} predicted by the NASA model is much lower than the $\eta_{AS} = 0.8$ value specified by §25.109 for fully-modulating anti-skid systems (such as the Meggitt system installed on the EMB-505). Figures 24 and 25 indicate that if $\eta_{AS} = 0.8$ is assumed, then the μ_{max} would have to be equivalent to the average μ_{max} on an ESDU class “A” runway, two classes down from the “C” that would be assigned to runway 1 based on its measured macrotexture depth of 0.017 inches, and near the lower bound of the ESDU μ_{max} data for a wet runway of this macrotexture depth. If the μ_{max} corresponding to the “KCXO runway 1 ESDU wet average, 80% worn tires” line in Figure 25 is assumed, then the η_{AS} would have to be about 0.58 in order to match the actual μ_B achieved during the landing roll.

Per Table 11, the runway 1 macrotexture depth of 0.017 inches is near the maximum depth for an class C runway, so the runway is closer to class D than class B (or class A). This fact, and the observation that the μ_{max} defined by Equation [25] is in relatively good agreement with the average ESDU μ_{max} for this runway, suggest that the μ_{max} specified in §25.109 is reasonable, but that the constant $\eta_{AS} = 0.8$ specified by §25.109 overestimates actual anti-skid system performance. The η_{AS} assumed in the NASA

⁶⁷ Per an email from Boeing to NTSB dated 12/08/2010, the B737-200 ADV is equipped with a Hydro-Aire Mark III anti-skid braking system, which is an analog, fully modulating system.

model, which is proportional to μ_{max} , results in better agreement with the actual performance of the airplane. As mentioned above, an η_{AS} of about 0.63 applied to the μ_{max} defined by Equation [25] would result in a μ_B that better matches the accident data.

Anti-skid system efficiency information in ESDU 71026

ESDU 71026 also addresses anti-skid system efficiency, and includes the chart duplicated here as Figure 29, which shows the range of η_{AS} values for “on-off” and “adaptive” type anti-skid systems. The chart indicates that, for values of μ_{max} from 0.25 – 0.30, “adaptive” systems have a “maximum likely value” of η_{AS} from 0.80 – 0.85, comparable to the η_{AS} specified by §25.109(c). However, these maximum values do “not allow for installation and undercarriage suspension effects.” In discussing this chart, ESDU 71026 states that

Values of μ_{eff} [equivalent to μ_B in this Study] and μ_{max} obtained or deduced from tests with a ground vehicle and aircraft are shown as the shaded areas in Figure [29]. The scatter indicated by these shaded areas reflects differences between types of brake system and also the differences resulting from the application of these systems to particular undercarriage and test vehicle configurations.

The efficiencies that may be expected from current automatic braking systems are represented in Figure [29] by the curves labelled, “adaptive system” and “on-off system”. These curves are derived principally from dynamometer tests and do not include any measure of the effects introduced when a brake system is incorporated as part of an aircraft undercarriage Where no further information is available, these curves should be used to estimate μ_{eff} once μ_{max} has been determined [emphasis in original].

ESDU 71026 goes on to include an equation for the effective braking force that is equivalent to modeling η_{AS} as follows:

$$\eta_{AS} = (k)(\eta_{AS, Fig. 29}) \quad [28]$$

Where $\eta_{AS, Fig. 29}$ is the η_{AS} determined from Figure 29, and

The factor k is included in Equation [[28]] to allow for possible reductions in braking efficiency due to, for example, normal load fluctuations, undercarriage vibration and suspension effects - none of which are usually simulated in dynamometer tests. Experience and the data presented as shaded areas in Figure [29], suggest that until values of η_{AS} based on aircraft trials are available, k should be assumed to lie in the range $0.8 \leq k < 1.0$ Where more precise information is available, either from aircraft braking trials or from brake manufacturers' tests, it should be used.

In allowing an η_{AS} of 0.80 for “fully-modulating” anti-skid systems, §25.109(c) effectively assumes that *both* terms in Equation [28] ($\eta_{AS, Fig. 29}$ and k) will achieve the maximum values contemplated in ESDU 71026, implying that these systems will always operate at the “maximum likely value” level shown in Figure 29, and that there will be no reduction in efficiency due to “normal load fluctuations, undercarriage vibration and suspension effects.” However, Figure 29 indicates that when these effects are taken into account, the resulting η_{AS} can be as low as 0.50 at $\mu_{max} = 0.3$. If the lower bound of k given in

ESDU 71026 (0.8) is applied to the §25.109(c) η_{AS} of 0.80, the overall η_{AS} is $(0.8)^2 = 0.64$, close to the $\eta_{AS} = 0.63$ value that makes the §25.109(c) μ_B match the actual μ_B achieved during the accident. This is further evidence that the $\eta_{AS} = 0.80$ value allowed by §25.109(c) may be unreasonably high.

Note that the $\eta_{AS} = 0.80$ value allowed by §25.109(c) is actually the *minimum* value allowed by the regulation, and applies in case an applicant for certification declines to determine a higher value of η_{AS} through flight tests on a wet runway (though even in this case, flight tests are still required to demonstrate proper anti-skid system function). Two acceptable methods for determining a higher value of η_{AS} from flight tests are outlined in AC 25-7C (Reference 33): the “torque method” and the “wheel slip method.” Both of these methods rely on determining an instantaneous η_{AS} during a stop based on recorded wheel speed, acceleration, and slip ratio and brake pressure or torque parameters, and then integrating this instantaneous η_{AS} over the stopping distance to obtain an overall η_{AS} . There is no requirement to demonstrate that the resulting overall η_{AS} , in combination with the μ_{max} defined in §25.109(c), results in a computed stopping distance (through the solution of Equations [13]-[17]) consistent with the actual stopping distance achieved during the flight tests. This lack of a “closed loop” between the computed η_{AS} and measured stopping distance during flight tests leaves uncertainty as to whether the combination of μ_{max} and η_{AS} prescribed in §25.109 is actually consistent with the capabilities of the airplane.

In any case, AC-25 7C states that “an anti-skid efficiency of 92% (i.e., a factor of 0.92) is considered to be the maximum efficiency on a wet runway normally achievable with fully modulating digital anti-skid systems.” Consequently, the $\eta_{AS} = 0.95$ required to make the §25.109 model match the EMB-505 unfactored wet landing distance is unrealistic, and is additional evidence that modeling the unfactored wet stopping distance as 25% greater than the dry unfactored distance is inadequate. The EMB-505 AFM wet runway stopping distances for the accident conditions are discussed further below.

To correctly predict airplane stopping performance, a model must generate a product of μ_{max} and η_{AS} that matches the actual μ_B (see Equation [24]). For the accident case, the NASA CFME model satisfies this requirement, while the §25.109 model overestimates the actual μ_B . This result is consistent with findings in other accidents and in flight tests (see References 27 and 30-32, and the discussion in Section D-VII below). Using the average μ_{max} in the range of ESDU data for the measured runway macrotexture, the ESDU model approximately matches the accident μ_B if the most conservative value of k (0.8) is used in Equation [28].

Industry statements on correlating CFME μ values to airplane μ_B

The good agreement between the μ_B predicted by the NASA CFME model and the μ_B actually achieved by the airplane, noted above for the KCXO accident, has also been observed in other accident investigations and in flight tests (see Sections D-VII and D-VIII). However, at times doubt has been expressed as to whether CFME measurements

can be reliably correlated to wet-runway airplane μ_B . For example, the final report on an EMB-145 landing overrun in Ottawa, Canada in 2010 (Reference 31)⁶⁸ states:

It is widely acknowledged that a wet runway may be slippery and require additional landing distance over and above that required for a dry runway. National and international efforts to closely correlate surface-friction measurements on wet runways to aircraft braking effectiveness have not been successful.

Reference 31 does not provide a reference for this statement, but it may be repeating information found in International Civil Aviation Organization (ICAO) document 9137, *Airport Services Manual, Part 2: Pavement Surface Conditions* (Reference 41):

3.1.1 There is an operational need for information on paved runways that may become slippery when wet. To this end, there is a need to measure periodically the friction characteristics of a paved runway surface to ensure that they do not fall below an agreed level. An indication of the friction characteristics of a wet paved runway can be obtained by friction-measuring devices; however, further experience is required to correlate the results obtained by such devices with aeroplane braking performance due to the many variables involved, such as runway temperature, tire inflation pressure, test speed, tire-operating mode (locked wheel, braked slip), anti-skid system efficiency, and measuring speed and water depth.

However, a later section in Reference 41 states that

5.4.2 In 1984, the United States undertook a five year programme to study the relationship between aeroplane tire braking performance and ground vehicle friction measurements. Several types of surface conditions were evaluated: dry, truck-wet, rain-wet and snow-, slush- and ice-covered The results of this investigation showed that the ground vehicle friction measurements did not directly correlate with the aeroplane tire effective braking friction on wet surfaces. However, agreement was achieved using the combined viscous/dynamic aquaplaning theory (see Appendix 1).

The “combined viscous/dynamic aquaplaning theory” presented in Appendix 1 of Reference 41 is precisely the NASA CFME μ_B model described above, and presented in detail in Appendix B and Reference 28. Consequently, while it is true that CFME μ values are not *directly* equivalent to wet-runway airplane μ_B , Reference 41 appears to agree with the observations in this *Study* that the two can be correlated using the NASA CFME method.⁶⁹

AMC 25.1591 flooded runway μ_B

As noted above, AMC 25.1591 provides one acceptable means of compliance with EASA regulation CS 25.1591, *Performance Information for Operations with Contaminated Runway Surface Conditions*. AMC 25.1591, paragraph 7.3.1 indicates that for runways contaminated with standing water, the “effective braking coefficient of an anti-skid controlled braked wheel/tyre” is given by

⁶⁸ This accident is discussed further in Section D-VII.

⁶⁹ Note that the good correlation between the NASA CFME method and the actual airplane μ_B noted throughout this *Study* concerns only *wet* runways. No observations or conclusions regarding the correlation between CFME devices and μ_B for *frozen* contaminants (ice, slush, snow) are made here.

$$\mu_B = -0.0632 \left(\frac{V}{100} \right)^3 + 0.2683 \left(\frac{V}{100} \right)^2 - 0.4321 \left(\frac{V}{100} \right) + 0.3485 \quad [29]$$

Where V is the groundspeed in knots.

Note: For V greater than the aquaplaning [hydroplaning] speed, use $\mu = 0.05$ constant.

Other paragraphs of AMC 25.1591 describe additional forces acting on the airplane during operations on contaminated runways, including contaminant drag (water displacement drag and water spray impingement drag).

The μ_B defined by Equation [29] is presented in the bottom plot of Figure 24 as the dashed magenta line labeled “ $\mu_B = \text{AMC 25.1591 standing water}$.” The stopping distance under the accident conditions associated with this μ_B is shown in the top plot of Figure 24. If the airplane had performed per this standing water model, it would have come to rest 5311 ft. from the runway threshold, or 311 ft. past the end of the runway (assuming that the forces on the tire past the end of the runway would have been consistent with the flooded-runway μ_B curve, which is not likely). It is more useful to note that Figure 32 (described further below) indicates that with μ_B given by Equation [29], airplane would have crossed the end of the runway at a groundspeed of about 39 knots.

Figure 24 indicates that the actual μ_B achieved during the accident was greater than what Equation [29] would predict, which is consistent with the finding above that the rainfall rate, runway macrotexture, and runway cross-slope do not support a conclusion that the runway could have been flooded at the time of the accident.

EMB-505 AFM stopping distances for the accident conditions

Perhaps the most relevant μ_B model, from an operational point of view, is that underlying the wet-runway stopping distances in the AFM. As described above, it is this information that operators use to ensure compliance with dispatch requirements and to perform a landing distance performance assessment.

The wet-runway landing distances in the AFM are not physics-based, but based on factors applied to the demonstrated dry landing distances. In the case of the EMB-505, the unfactored wet landing distances are equal to the unfactored dry distances multiplied by 1.25, per Embraer’s agreement with EASA. The factored wet landing distances are equal to the unfactored dry distances multiplied by 1.92. Consequently, the factored wet distances are equal to the unfactored wet distances multiplied by 1.53 (see Equation [18]).

Even though the unfactored wet distances are not the result of computations grounded in a μ_B model, an “equivalent” μ_B model can be inferred from the AFM distances, and expressed in terms of the same variables that define the §25.109 model. For a given set of landing conditions, this approach seeks to determine the η_{AS} (called $\eta_{AS,AFM}$) that

would have to be applied to the μ_{max} specified in §25.109(c) in order to generate a μ_B that results in a wet-runway stopping distance identical to that published in the AFM. As noted above, for the accident conditions, the resulting $\eta_{AS,AFM} = 0.95$, even higher than the $\eta_{AS} = 0.8$ specified in §25.109(c) that, as shown above, is already too high.

The landing distance is the sum of the air, transition, and ground roll distances. The air distance is the distance from a point 50 ft. above the threshold to touchdown; the transition distance is the distance from touchdown to the point where all three gear are on the ground and the all the deceleration devices are activated; and the ground roll distance is the distance travelled from the end of the transition distance to the point where the airplane stops. The AFM provides total landing distance for specified conditions, but does not break this distance into the air / transition and ground roll distances.

For this *Study*, the sum of the air and transition distances was estimated by subtracting the computed ground roll distance on a dry runway⁷⁰ from the AFM total landing distance on a dry runway, for the accident weight and ambient conditions (these conditions are specified in the text box in the middle of Figure 30). The dry ground roll distance was computed by assuming:

- The average dry μ_{max} specified by ESDU 71026 for a class C runway and 180 psi tires (essentially identical to the average dry μ_{max} plotted in Figure 25);
- An η_{AS} of 0.8 as specified in §25.109(c) (though too high for a wet runway, this should be an appropriate estimate for a dry runway);
- Airspeed over the threshold as specified by the AFM (V_{REF});
- A touchdown speed of 96% of the threshold speed (based on Reference 12);
- Immediate spoiler and brake application after touchdown.

The resulting sum of the air and transition distances is 1260 ft., so all subsequent ground roll calculations that are compared to the AFM wet runway landing distance start at a runway position of 1260 ft. from the threshold and a true airspeed of $0.96 \times (V_{REF}) = 109.4$ kt.⁷¹ Figure 30 indicates that using these values, the total dry landing distance matches the AFM dry landing distance (as designed).

From this initial condition, the η_{AS} required to match the AFM unfactored, wet landing distance using the μ_{max} defined by Equation [25] was determined by trial and error. As shown in Figure 30, $\eta_{AS} = 0.95$ resulted in a match of the AFM wet landing distance for the accident conditions.

The “OPERA results” plotted in Figure 30 are outputs from the Embraer *Optimized Performance Analyzer (OPERA)* computer program, which is essentially a computerized

⁷⁰ The ground roll distance is computed by solving Equations [13]-[17] for the deceleration of the airplane (n_x), and integrating over time (twice) to get speed and distance.

⁷¹ Note that the actual touchdown conditions for the accident are different; N322QS touched down about 903 ft. from the threshold, at a ground speed of about 118 kt.

version of the AFM performance data. Note that for wet runways, OPERA only outputs factored landing distances (1.92 x the unfactored dry distance). The OPERA output for dry runways matches the AFM distances determined “manually.”

The AFM distances in Figure 30 were “manually” computed two ways: first by using “density altitude,” and then by using the “temperature factor for landing distance” correction chart. The “density altitude” approach involves converting the pressure altitude and ambient temperature to a density altitude, and then looking up the AFM distances at the corresponding pressure altitude for standard day temperature (at standard temperature, pressure altitude equals density altitude). The “temperature factor” approach involves looking up the AFM landing distance at the current pressure altitude, and then correcting for non-standard temperature using the correction chart. Both methods give consistent results.

As noted above, both the “NASA CFME” and “ESDU class A, $\eta_{AS} = 0.80$ ” results in Figure 24 match the actual computed μ_B prior to the EPB being set. Figure 30 indicates that these models predict that if N322QS had matched the AFM touchdown conditions, it would have come to rest 3910 ft. (NASA CFME model) and 3958 ft. (ESDU class A model) from the threshold, compared to a distance of about 3168 ft. from the threshold corresponding to the AFM unfactored wet landing distance. Consequently, the actual distance required to stop on the wet runway on the day of the accident would have been at least 742 ft. (about 23%) greater than the AFM unfactored wet distance. This difference exceeds the 15% safety margin recommended by SAFO 06012 and NTSB recommendations A-07-057 and A-07-061, and required by NJA’s Operations Specifications.

For the AFM touchdown conditions, the landing distance predicted by the §25.109 model (with $\eta_{AS} = 0.8$) is 3474 ft. (see Figure 30). An actual landing distance of 3958 ft. exceeds this §25.109 distance by 484 ft., or about 14%. Consequently, even if the unfactored AFM wet landing distances were based on §25.109, they would underpredict the actual required distances required, and adding the recommended 15% safety margin to these distances would result in very little actual safety margin.

The results in Figures 24 and 30 indicate that modeling the unfactored wet landing distance as 25% greater than the unfactored dry distance is inadequate. In the accident case, the wet distance is actually about 56% greater than the dry distance (based on a dry distance of about 2534 ft., and a wet distance of 3958 ft.)

The wet runway landing distances based on the AFM data and various μ_B models described above is summarized in Table 12, for both the accident and AFM touchdown conditions. In both cases, the “ESDU class A, $\eta_{AS} = 0.8$ ” model (which is approximately equivalent to the §25.109(c) model with $\eta_{AS} = 0.63$, or an ESDU class C model with $\eta_{AS} = 0.58$) represents the best estimate of actual performance. For the accident touchdown conditions, the performance behind the AFM landing distance tables is best reflected by the “§25.109(c), $\eta_{AS} = 0.95$ ” model.

Table 12 also indicates the landing distance required per the Landing Performance Assessment (LPA) that NJA's Operations Manual would have required, as a result of the change from runway 14 to runway 1 for landing. The AFM unfactored wet landing distance, for the conditions listed in Figure 30, is 3168 ft.; the 15% safety margin required by the LPA makes the required distance 3643 ft. Hence runway 1, with an LDA of 5000 ft., satisfied the LPA requirements in the Operations Manual.

The planned landing weight in the dispatch release for the accident flight was 15830 lb. At this weight, the AFM unfactored wet landing distance is 3219 ft. The required runway length that NJA dispatchers plan for Part 91 flights is the AFM unfactored distance divided by 0.8, or 4023 ft., in this case; so the flight could have been dispatched to either runway 14 or runway 1.⁷²

Model or item	Accident touchdown conditions	Δ from §25.109(c), $\eta_{AS} = 0.95$ dist. (accident cond.)	AFM touchdown conditions	Δ from AFM unfactored wet (AFM cond.)
Touchdown x coordinate	903 ft.		1260 ft.	
Touchdown groundspeed	118 kt.		109.4 kt.	
AFM unfactored dry distance			2534 ft.	-634 ft. (-20%)
AFM unfactored wet distance			3168 ft.	0 ft. (0%)
AFM factored dry distance			4223 ft.	1055 ft. (33%)
AFM factored wet distance			4857 ft.	1689 ft. (53%)
AFM standing water landing distance			4875 ft.	1707 ft. (54%)
NJA OpsSpec Part 91 wet LPA (15% safety margin)			3643 ft.	475 ft. (15%)
AMC 25.1591 standing water landing distance	5311 ft.	1358 ft. (34%)	4634 ft.	1466 ft. (46%)
ESDU class A, $\eta_{AS} = 0.8$ landing distance	4669 ft.	716 ft. (18%)	3958 ft.	790 ft. (25%)
§25.109(c), $\eta_{AS} = 0.8$ landing distance	4210 ft.	257 ft. (6.5%)	3474 ft.	306 ft. (10%)
§25.109(c), $\eta_{AS} = 0.95$ landing distance	3953 ft.	0 ft. (0%)	3199 ft.	31 ft. (1%)
NASA CFME landing distance (extrapolated below 65 kt.)	4619 ft.	666 ft. (17%)	3910 ft.	742 ft. (23%)
$\mu_B = 0.160$ constant	5364 ft.	1411 ft. (36%)	4648 ft.	1480 ft. (47%)
$\mu_B = 0.218$ constant	4671 ft.	718 ft. (18%)	3921 ft.	753 ft. (24%)

Table 12. Summary of landing distances using various μ_B models, for conditions listed in Figure 30.

⁷² A data file error in NetJet's computerized performance program at the time of the accident resulted in the required runway length being computed as 3659 ft. instead of 4023 ft. The error was identified and corrected in November, 2014 (email from NJA to NTSB, dated 12/17/2015).

Plots of V_G , the body-axis longitudinal load factor (n_x), and μ_B vs. time and the runway 1 x-coordinate are shown in Figures 31 and 32. Note in these Figures that while the “ESDU class A, $\eta_{AS} = 0.8$ ” and “NASA CFME” μ_B match the computed accident μ_B well, the resulting n_x for these models is more negative than the n_x recorded on the FDR (in fact, the recorded n_x best matches the simulation n_x corresponding to the “AMC 25.1591 standing water” curve for a flooded runway). This difference is the result of small differences in pitch angle between the actual landing, and the simulations of the ground roll using the different μ_B models. The simulations assume a constant pitch angle of -1.7° , whereas the actual pitch angle gradually decreases over time, and only reaches -1.7° at about 08:47:27 (see Figure 10). The lower pitch angle for the simulations results in a larger component of gravity along the x-axis, which decreases n_x . More importantly, the lower pitch lowers the angle of attack and decreases lift, which results in a larger normal force on the main gear (N_M), and consequent larger braking force on the gear (F_M ; see Equation [14]). The larger F_M results in more negative n_x . If the simulation pitch angles matched the actual pitch angle exactly, then the simulation n_x solutions would shift upward (more positive n_x , or reduced deceleration), the “NASA CFME” and “ESDU class A, $\eta_{AS} = 0.8$ ” n_x lines would lie closer to the FDR n_x line, and the “AMC 25.1591 standing water” n_x line would move above the FDR n_x line.

A measure of the relative deceleration resulting from the various μ_B models is the n_x plotted in Figures 31 and 32. The deceleration associated with the unfactored wet-runway landing distances in the EMB-505 AFM is best represented by the “§25.109, $\eta_{AS} = 0.95$ ” lines in these plots.

VII. Other wet-runway landing accidents, and FAA actions

The NTSB has investigated or participated in the investigation of a number of other landing accidents or incidents on wet runways in which the airplane did not achieve the μ_B implied in the manufacturer’s AFM landing distances, or that would be predicted by the §25.109 model. Five of these events are summarized below, along with relevant conclusions from the airplane performance studies or final reports of the investigations.

In addition, the FAA has taken several actions relevant to wet-runway braking performance, including:

- Adding a wet-runway stopping performance task to the Transport Airplane Performance and Handling Characteristics Aviation Rulemaking Advisory Committee (ARAC) in March 2008;
- Requesting comments on draft ACs 25-31 & 25-32 in January 2015; and
- Issuing SAFO 15009 in August 2015 (see Reference 16 or Appendix C).

These actions are also discussed below.

The BAe 125-800A accident in Owatonna, MN (NTSB #DCA08MA085)

On July 31, 2008, a Hawker Beechcraft BAe 125-800A, registration N818MV crashed while attempting to go around after landing on runway 30 at Owatonna Degner Regional Airport (KOWA). The two pilots and six passengers died, and the airplane was destroyed (see References 27 and 35). The NTSB determined that the probable cause of this accident was

the captain's decision to attempt a go-around late in the landing roll with insufficient runway remaining. Contributing to the accident were (1) the pilots' poor crew coordination and lack of cockpit discipline; (2) fatigue, which likely impaired both pilots' performance; and (3) the failure of the Federal Aviation Administration (FAA) to require crew resource management (CRM) training and standard operating procedures (SOPs) for 14 CFR Part 135 operators (Reference 35).

Among the conclusions of the *Aircraft Performance Study Addendum #1* to the KOWA accident (Reference 27) are:

- Given the measured rainfall on the day of the accident, the KOWA runway cross-slope gradient and surface macrotexture do not support a conclusion that the runway could have been flooded at the time of the accident, or that the airplane could have experienced dynamic hydroplaning during the landing roll.
- As indicated in the *Performance Study* [of the KOWA accident], simulations of the accident landing using the [BAe 125-800A landing performance computer] program required flooded runway conditions to match the performance data available for this accident, assuming sufficient braking to take full advantage of the available friction on the runway. Flooded runway conditions are inconsistent with the weather and runway evidence.
- The wet runway landing distances published in the BAe 125-800A AFM and computed by the ... performance program are based on μ_B wet / μ_B dry ratios specified in [European Joint Aviation Regulations (JAR)] [Advisory Material Joint (AMJ)] 25X1591. The wet – runway μ_B values that result from these ratios correspond roughly to half the value of the braking coefficients obtained on a dry runway, and do not decrease significantly with increasing groundspeed.
- §25.109, which considers the accelerate-stop distance during rejected takeoffs, indicates that the μ_B on a wet runway is a strong function of both ground speed and the efficiency of the anti-skid braking system (η_{AS}). A wet-runway μ_B corresponding to about half of a dry-runway μ_B can only be obtained with anti-skid systems with efficiencies of 0.8 or higher, and at relatively low groundspeeds.
- The Dunlop Maxaret anti-skid braking system used on the BAe 125-800A is an “on-off” type system, which can have an η_{AS} in the range of 0.3 to 0.75, though §25.109 requires an assumption of 0.3 for this type of system unless higher values can be demonstrated. Assuming sufficient braking effort on a wet runway, the braking performance of N818MV during the accident is consistent with an η_{AS} of about 0.475.
- The wet – runway μ_B values based on the §25.109 μ_B model and an η_{AS} of 0.475 are significantly lower at high groundspeeds than the wet – runway μ_B values based on the JAR AMJ 25X1591 μ_B wet / μ_B dry ratios.
- Landing distance flight tests of a Boeing 737-200ADV airplane on a wet runway at Roswell, NM, in 1973 indicate that the η_{AS} of even fully-modulating systems decreases as the runway becomes

more slippery. This finding is consistent with the behavior of η_{AS} used in the NASA prediction of the effective braking coefficient available on the KOWA runway, based on CFME tests performed after the accident. These observations suggest that models of braking performance may be improved by modeling η_{AS} as a function of the maximum available friction coefficient (μ_{max}), rather than as a constant, as currently specified in §25.109.

- The Roswell B737 tests also indicate that the actual braking performance achieved on some ungrooved, wet runways may be below that produced by the combination of μ_{max} and η_{AS} specified in §25.109. These results underscore the importance of testing the actual η_{AS} achieved on a wet, ungrooved runway during certification, and ensuring that the values of μ_{max} and η_{AS} determined from the tests are consistent with the actual landing distances achieved by the airplane during the tests.
- Given that the §25.109 μ_B model provides a better representation of N818MV's performance during the accident (as indicated by the simulations), the [performance] program (and the AFM) under-predict the actual, unfactored landing distances on some wet, ungrooved runways by a significant amount. The difference between the AFM and §25.109 μ_B – based distances examined in this Addendum are much greater than the minimum 15% safety factor to be applied to AFM advisory data when performing the en-route landing distance assessments envisioned by FAA SAFO 06012 and NTSB recommendation A-07-057. Consequently, for this airplane (and potentially all aircraft with wet landing distances based on the AMJ 25X1591 μ_B model) the use of the AFM data for en-route landing distance assessments on wet runways may not be advisable, unless additional correction and / or safety factors are applied to the data.

These conclusions indicate that the airplane performance concerns described in the present *Study* of the KCXO accident were previously identified in the KOWA accident.

Specifically:

- AFM data can underestimate the landing distance required on wet runways.
- A constant $\eta_{AS} = 0.8$ is specified in §25.109(c) for fully-modulating anti-skid systems, when research and flight test data indicate that η_{AS} decreases with μ_{max} , even for these systems.
- The §25.109(c) model can overestimate μ_B on wet runways.
- There is no requirement to demonstrate consistency between the μ_B model used to develop AFM wet-runway performance data, and actual wet-runway stopping performance.

Strictly speaking, the deficiency of the §25.109(c) μ_B model is the result of the *combination* of the modeled μ_{max} and η_{AS} , and a deficiency in either term (or both) will result in a deficiency in μ_B (see Equation [24]). It can be difficult to identify which term is more in error (μ_{max} or η_{AS}) when a shortfall in μ_B is identified. While Figure 25 indicates that the range of ESDU data includes values of μ_{max} lower than those specified in §25.109(c), the use of a constant $\eta_{AS} = 0.8$ in §25.109(c) demands the closest scrutiny. AC 25-7C, the NASA CFME model, ESDU 71026, and the flight test results cited in Reference 36 agree that η_{AS} deteriorates with μ_{max} , even for adaptive anti-skid systems. Consequently, the $\eta_{AS} = 0.8$ assumption in §25.109(c) must remain suspect until it is demonstrated that the μ_B resulting from this value is consistent with the μ_B computed from flight tests on a wet runway, per the method described in Equations [13]-[17].

One of the recommendations issued by the NTSB as a result of the KOWA accident was A-11-029, to the FAA:

Inform operators of airplanes that have wet runway landing distance data based on the British Civil Air Regulations Reference Wet Hard Surface or Advisory Material Joint 25X1591 that the data contained in the Aircraft Flight Manuals (and/or performance supplemental materials) may underestimate the landing distance required to land on wet, ungrooved runways and work with industry to provide guidance to these operators on how to conduct landing distance assessments when landing on such runways. (A-11-029)

A-11-029 is currently classified “Open – Unacceptable Response.” The correspondence between the NTSB and the FAA concerning this recommendation is summarized in Table 13. Note that the disagreement between the FAA and NTSB reflected in the correspondence mainly concerns the water depth on the runway, and whether the runway could have supported dynamic hydroplaning. The NTSB conclusion that the runway could not have been flooded (and that dynamic hydroplaning was not possible) is based on the TTI model described above, with results similar to those in Figure 23.

Also note that the witness reports of a “rooster tail” of water behind the airplane, which the FAA takes as evidence of a flooded runway and hydroplaning, is in fact evidence of the opposite. As described above, in dynamic hydroplaning conditions, the tires would lose contact with the runway and spin down, reducing the spray behind the airplane. Tom Yager (retired from NASA) advised NTSB at the time of the KOWA investigation that because of this phenomenon, rooster tails are evidence *against* hydroplaning.

As in the present case, in the KOWA accident the NASA CFME μ_B model matched the computed airplane performance, while the AFM data overestimated the performance.

Date From/To	Summary of actions re: A-11-029	Recommendation Status
03/29/2011 NTSB/FAA	Original recommendation transmittal letter, issued after the conclusion of the KOWA investigation.	Open- Await Response
06/10/2011 FAA/NTSB	FAA is reviewing the <i>Aircraft Performance Study</i> and other reports for this accident, and plans to evaluate which airplanes base wet runway landing distance on AMJ 25X1591. Following the reviews, the FAA will determine how best to address the recommendation.	Open- Await Response
09/06/2011 NTSB/FAA	NTSB acknowledges; pending completion of recommended action classifies A-11-026 Open – Acceptable Response (OAR).	OAR
08/21/2012 FAA/NTSB	FAA believes BAe 125-800A wet runway AFM data correct, because validated by flight tests in Hatfield, UK, and as evidenced by successful operation of the airplane for 50 years. FAA notes that the <i>Performance Study Addendum</i> indicates that while the limited information for the accident introduces elements of uncertainty in the analysis, the stopping performance was most consistent with the AFM data for a flooded runway. FAA points to a picture of a puddle in a parking lot a mile from the accident, the fact that there were thunderstorms in the area, and to witness reports of a “rooster tail” of water behind the airplane to reject the <i>Study</i> conclusion that the runway could not have been flooded. FAA did its own stopping calculations and also found that the AFM data for a flooded runway best fit the accident scenario, supporting the conclusion that the runway must indeed have been flooded. FAA concludes that there are too many uncertainties in the accident to justify questioning the AFM data, and states that more testing would be required to make the case that the distances are underestimated. FAA material, including the Airman’s Information Manual and SAFO 09015, advise pilots how to evaluate landing on “less than ideal runway conditions,” including wet runways. FAA considers its actions complete.	OAR
11/13/2012 NTSB/FAA	NTSB and FAA agree that the airplane performance is most consistent the AFM data for a flooded runway, and dynamic hydroplaning. Hence, whether or not the runway was flooded, leading to dynamic hydroplaning, is key to this recommendation. The <i>Addendum</i> examined this question, and rather than relying on a picture of a parking lot taken a mile from the runway, relied on measurements of the runway cross slope, macrotexture, and recorded rainfall rate, together with a model for runway drainage provided by the Texas Transportation Institute (TTI) to compute the likely depth of water on the runway. The maximum TTI water depth was only about 1 mm, significantly less than the 3 mm of water necessary for hydroplaning. Further, per a NASA expert, “rooster tails” are evidence <i>against</i> hydroplaning, because they indicate spinning tires in contact with the runway. Further, the <i>Addendum</i> indicates that the AMJ 25X1591 wet runway μ_B are substantially higher than those of the TALPA ARC’s recommendations, which are based on § 25.109. NTSB agrees that more testing is needed; however, the FAA does not plan to perform testing, or otherwise to address the safety problem documented in the <i>Addendum</i> . NTSB asks the FAA to reconsider; in the meantime, A-11-029 is classified OPEN—UNACCEPTABLE RESPONSE (OUR). Mounting evidence suggests that the §25.109 standard may not be representative, and consequently NTSB may issue more recommendations.	OUR

Table 13. Summary of NTSB/FAA correspondence re: A-11-029. For full correspondence, see: <http://www.nts.gov/safety/safety-recs/ layouts/ntsb.recsearch/Recommendation.aspx?Rec=A-11-029>.

The American Airlines flight 331 accident in Kingston, Jamaica (NTSB #DCA10RA017)

On December 22, 2009, American Airlines Flight 331, a Boeing 737-823, overran runway 12 after landing at Norman Manley International Airport in Kingston, Jamaica (MKJP). According to the final report issued by the Civil Aviation Authority of Jamaica (JCAA) (Reference 32),

The aircraft landed ... on runway 12 in the hours of darkness at 22:22 EST (03:22 UTC) in Instrument Meteorological Conditions (IMC) following an Instrument Landing System (ILS) approach flown using the heads up display (HUD) and becoming visual at approximately two miles from the runway. The aircraft touched down at approximately 4,100 feet on the 8,911 foot long runway in heavy rain and with a 14 knot left quartering tailwind.

The crew was unable to stop the aircraft on the remaining 4,811 feet of runway and it overran the end of the runway at 62 knots ground speed. The aircraft broke through a fence, crossed above a road below the runway level and came to an abrupt stop on the sand dunes and rocks between the road and the waterline of the Caribbean Sea.

There was no post-crash fire. The aircraft was destroyed, its fuselage broken into three sections, while the left landing gear collapsed. The right engine and landing gear were torn off, the left wingtip was badly damaged and the right wing fuel tanks were ruptured, leaking jet fuel onto the beach sand.

One hundred and thirty four (134) passengers suffered minor or no injury, while 14 were seriously injured, though there were no life-threatening injuries. None of the flight crew and cabin crew was seriously injured, and they were able to assist the passengers during the evacuation.

Section 1.18.6 of the JCAA report, titled "Estimated Water Depth and Braking Action," states:

The depth of water on MKJP runway 12 during the flight 331 ground roll can be estimated using empirically-based models to calculate water depth as a function of rainfall intensity and the runway 12/30 width, transverse slope, and pavement macro-texture characteristics. Based on the NASA rainfall rate/flooding exposure model and the Texas Transportation Institute (TTI) accumulated water depth model data presented to the JCAA at the Aircraft Performance Group Briefing in August 2010, no evidence supports a runway 12/30 water depth accumulation close to 3 millimeters (mm) of water.

These models indicate that, depending on the pavement macro-texture and airplane lateral position, there was at most a 0.5 to 1.0 mm water depth in the calculated main gear braked wheel path. A similar conclusion holds (at most 0.75 to 1.5 mm water depth) for all possible pavement macro-textures, even if the measured rainfall rate at the time of the accident is doubled to 1.0 inch/hour and the calculated airplane lateral position is artificially and significantly biased toward the runway shoulder.

An independent Boeing analysis of the existing rainfall precipitation and runway 12/30 factual data is consistent with the TTI model results described here.

...

The estimated depth of water in the airplane braked wheel paths during the runway 12 ground roll was less than 3 mm (less than .125 in.), which corresponds to an equivalent stopping performance level better than that expected for either a runway covered with standing water or a flooded runway

Independent of the above models for estimating water depth, the airplane deceleration observed during the flight 331 ground roll is consistent with B737NG (-700/900) flight test data on an artificially wet (no active rainfall; water applied to pavement prior to airplane touchdown using a fleet of tanker trucks), un-grooved runway with pavement macro-texture characteristics similar to or better than MKJP runway 12. These Boeing flight test data benefit from explicit knowledge that less than 25 percent of the runway surface was subject to standing water 1/8 inch deep or greater. In other words, the AA 331 braking performance level has been achieved on a wet, un-grooved runway with no active rainfall and less than 1/8 inch depth of water.

Analysis of the AA flight 331 event indicates the achieved airplane braking coefficient value was less than that traditionally considered to be associated with a wet runway (0.2), but better than what Boeing associates with a flooded runway (0.05). The factual evidence indicates that the airplane/ runway stopping performance interaction for AA flight 331 was essentially consistent with AA Fair/Medium braking action.

In other words, the AA flight 331 stopping performance level is inconsistent with the Boeing model for standing water or flooded runway.

Quoted performance is based on Wet/Good braking action, maximum manual braking, without reverse thrust and landing at about 1,000 feet from the threshold.

Section 1.11.2.2 of the JCAA report, titled “Information from Flight Data Recorder,” includes the following bullets resulting from an examination of the FDR data:

- Boeing FDR graphs showed aircraft ground speed at end of runway was 62 knots, in accordance with runway condition between Wet Smooth and Standing Water.
- Boeing FDR graphs showed actual rate of deceleration from braking on the wet runway to be less than defined by §25.109 for a Wet-Smooth runway, but more than defined by the NASA Standing Water Runway model.

The JCAA report refers to the μ_B computed by Boeing in order to match the deceleration recorded on the FDR.⁷³ Boeing provided the results of these calculations to the NTSB in Reference 44, and indicated that the required μ_B was equal to a 27% factor between the Boeing wet-smooth μ_B and the Boeing standing-water μ_B , where 0% = wet-smooth, and 100% = standing-water. The resulting μ_B is plotted in Figure 35 and discussed further below.

The JCAA report contains findings similar to those reported in the KOWA *Aircraft Performance Study Addendum*, and in the present *Study* concerning N322QS at KCXO: an evaluation of the water depth on the runway indicates that the runway could not have been flooded or have supported dynamic hydroplaning; yet the μ_B achieved during the landing roll was less than assumed in the AFM for a wet runway, and less than that predicted by the §25.109(c) model. Moreover, the JCAA indicates that these same observations follow from B737-700/900 flight test data on an *artificially wetted runway*, with no active rainfall. This is additional evidence of the inadequacy of the §25.109(c) model for predicting μ_B reliably on smooth, wet runways.

⁷³ The Boeing μ is actually expressed in terms of the total airplane μ , which is less than the wheel-braking μ_B used throughout this *Study*. The difference between these terms is explained below. The Boeing airplane μ has been converted to μ_B for the purposes of this discussion, and in the plot in Figure 35.

The United Express flight 8050 accident in Ottawa, Ontario (NTSB # DCA10RA069)

On June 16, 2010, United Express flight 8050, an Embraer EMB-145LR operated by Trans States Airlines LLC, overran runway 07 after landing at the Ottawa/MacDonald-Cartier International Airport in Ottawa, Ontario (CYOW). According to the final report issued by the Transportation Safety Board of Canada (TSB) (Reference 31),

The aircraft came to rest 550 feet off the end of Runway 07 and 220 feet to the left of the runway centreline. The nose and cockpit area were damaged when the nose wheel collapsed. There were 33 passengers and 3 crew members aboard. Two of the flight crew and 1 passenger sustained minor injuries.

...

When the aircraft descended through approach minimums, 200 feet agl and 0.3 nm from the threshold, the airspeed was 144 KIAS. The aircraft crossed the threshold of Runway 07 at 49 feet agl, at a speed of 139 KIAS. The aircraft did a very smooth touchdown, and the weight on wheels (WOW) switch momentarily activated at 1430:15, 1740 feet from threshold. At that point, the nose was still in the air, and the aircraft floated. Two seconds later, 2270 feet from the threshold and at a speed of 132 KIAS, the second WOW activated and the nose wheel came down Video recordings at the time of landing showed that the runway was wet.

The first officer was depressing the brake pedals during the second WOW activation; all spoilers automatically deployed after the nose wheel was lowered to the ground. The first officer continued to apply brakes until maximum braking was commanded. Sensing a lack of deceleration, the first officer informed the captain, who then took control of the aircraft and applied maximum braking as well. The aircraft could not be slowed during brake application.

The aircraft was on the centreline until approximately 200 feet before the end of the runway, where it veered left. The aircraft exited the paved surface of the runway at approximately 62 KIAS. It continued through the grass for approximately 120 feet, at which point there was a sharp downward change in elevation of about 2 feet. The nose gear collapsed rearward, but the aircraft continued to skid. It came to a rest 550 feet from the end of the runway and 220 feet left of centreline. The flight attendant initiated the evacuation procedure for the passengers.

Section 1.6.6 of the TSB report, titled "Aircraft Braking Coefficient," states

For the occurrence landing, the brake-pedal position went from 0% to 95%, while the braking coefficient and brake pressure remained constant at 0.07 and 200 psi, respectively

The aircraft braking coefficient of friction calculated for the occurrence ground roll was compared with the wet runway braking coefficient of friction (adjusted for a fully modulated antiskid system) used by Embraer as per §25.109(c). The comparison showed that the occurrence aircraft had a braking coefficient significantly lower than that predicted by the smooth wet runway equations in §25.109(c)(1).

Another comparison was made between the FDR data from the occurrence ground roll and brake-system test data obtained from Honeywell for the ground-roll phase of wet runway landing. The test was conducted in an aircraft under the same conditions and with the same configuration as the occurrence aircraft. The test showed that braking performance by the occurrence aircraft was as expected, and that the brake system on the occurrence aircraft performed as designed. The test also indicated that the braking coefficients of friction for both landings were similar and significantly lower than that predicted by the smooth wet runway equations in §25.109(c)(1).

Section 2.6 of the TSB report, titled “Hydroplaning,” states

In this particular occurrence, the factors exhibited during the landing roll are indicative of viscous and not dynamic hydroplaning. These factors were smooth touchdown, slower-than-normal wheel spin-up with no lockup, and supply of very low brake pressures by the brake control unit (BCU) until very low speeds. The friction between the tire and runway was reduced, but not to a level that impeded the wheel rotation. Dynamic hydroplaning did not occur, as wheel rotation did not stop, and the water depth was calculated to be less than the 3 mm normally associated with the onset of dynamic hydroplaning. Once hydroplaning begins, it will continue to speeds well below that required to initiate hydroplaning. Although the pedals of both pilots were deflected to the right during the latter part of the landing roll, the aircraft veered to the left, indicating the lack of friction and lack of directional control that are associated with hydroplaning.

During a post-accident examination, no reverted-rubber burns were found on the aircraft's main landing-gear tires. The aircraft exited the runway before the rubber reached reversion temperature; hence there was no reverted-rubber hydroplaning. However, there were steam-cleaned marks at the end of the runway, indicating the temperature had reached that at which steam is formed.

Notably, TSB report concludes that the μ_B achieved on this wet (but not flooded) runway is “significantly lower” than that predicted by §25.109(c); and that the same result was observed during a flight test “under the same conditions and with the same configuration as the occurrence aircraft.”

The Southwest Airlines flight 1919 incident in Chicago, IL (NTSB #DCA11SA047)

On April 26, 2011, Southwest Airlines flight 1919, a Boeing 737-7Q8, exited the left side near the end of runway 13C after landing at Chicago Midway International Airport, Chicago IL (KMDW). The airplane had minor damage and there were no injuries (see References 30 and 37).

The NTSB determined that the probable cause of this incident was

The flight crew's delayed deployment of the speedbrakes and thrust reversers, resulting in insufficient runway remaining to bring the airplane to a stop.

Contributing to the delay in deployment of these stopping devices was the flight crew's inadequate monitoring of the airplane's configuration after touchdown, likely as a result of being distracted by a perceived lack of wheel braking effectiveness.

Contributing to the incident was the flight crew's omission of the Before Landing checklist, which includes an item to verify speedbrake arming before touchdown, as a result of workload and operational distractions during the approach phase of flight (Reference 37).

The crew of a Southwest Airlines B737 that had landed prior to the incident flight reported that the runway was “wet with fair braking action.” Reference 37 states that

The airplane touched down within 500 feet of the runway threshold. After touchdown, the captain perceived a lack of braking effectiveness and quickly applied full manual brakes. Speedbrakes did not deploy upon touchdown, nor were thrust reversers deployed. About 16 seconds after touchdown, thrust reversers were manually deployed, which also resulted in speedbrake deployment per system design, when the airplane had about 1,500 feet of runway remaining. As

the airplane neared the end of the pavement, the captain attempted to turn onto the connecting taxiway but was unable. The airplane struck a taxiway light and rolled about 200 feet into the grass.

FDR data and component examination revealed that all airplane systems operated as expected. The automatic speedbrakes were not armed and, therefore, would not deploy upon touchdown without crew action. Extending the speedbrakes after landing increases aerodynamic drag and reduces lift, which increases the load applied to the main gear tires and makes the wheel brakes more effective. A lack of speedbrake deployment results in severely degraded stopping ability. According to the flight operations manual, braking effectiveness is reduced by as much as 60 percent. The flight crew's delay in applying reverse thrust also contributed to the amount of runway used.

Simulation studies concluded that the airplane would have stopped with about 900 feet of runway remaining if the speedbrakes had been deployed at touchdown (without reverse thrust) or with about 1,950 feet remaining if both speedbrakes and reverse thrust had been deployed at touchdown, per standard procedures. The calculated braking coefficient of the incident airplane was consistent with a "fair" braking action report, as given by the preceding Southwest Airlines 737 arrival. The braking coefficient is also in accordance with the [Onboard Performance Computer] calculations.

Reference 37 makes it clear that the flight 1919 incident resulted from a number of serious operational mistakes; nonetheless, the "fair" braking action reported by the previous Southwest crew, and the simulation studies performed during the investigation, indicate that the §25.109 μ_B model can over-predict the μ_B available on wet *grooved* runways (such as those at KMDW), as well as on wet *smooth* runways.

The *Aircraft Performance Study* for this incident (Reference 30) states:

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 §25.109 Wet Smooth Runway curve (0% corresponds to NASA Convair 880 and 100% corresponds to §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 Furthermore, the resulting simulation ground speed agrees with the incident deceleration

Note that the KMDW *Study* refers to both the "wheel braking coefficient" and the "airplane braking coefficient." The KMDW *Study*, following Boeing convention, primarily uses the latter quantity, and describes the difference between these coefficients as follows:

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.

The μ_B term used throughout the present *Study* is what the KMDW *Study* calls the “wheel braking coefficient” (see Equation [14]). Note that the KMDW *Study* indicates that the *wheel* braking coefficient (i.e., μ_B) required to match the airplane performance in the KMDW event is less than the μ_B defined by §25.109(c) for a *smooth* (ungrooved) runway,⁷⁴ and that KMDW runway 13C is *grooved*. Per Table 11, a grooved runway is an ESDU class E runway, with the highest macrotexture depth and corresponding μ_{max} .

§25.109(d) specifies 5th-order polynomials defining μ_B as a function of V_G for a grooved or “porous friction course” runway, similar to the 3rd-order polynomials defined in §25.109(c) for a smooth runway. As in §25.109(c), the polynomial coefficients in §25.109(d) are functions of tire inflation pressure (p). For a given V_G and p , the μ_{max} defined in §25.109(d) is greater than that defined in §25.109(c). For example, for $p = 200$ psi and $V_G = 100$ kt., §25.109(c) specifies $\mu_{max} = 0.2529$ and §25.109(d) specifies $\mu_{max} = 0.3478$, which is about 38% higher. As in §25.109(c), the μ_{max} defined in §25.109(d) must be multiplied by η_{AS} to obtain μ_B (see Equation [24]).

The Boeing airplane braking coefficient required to match the deceleration on the FDR, provided in the KMDW *Study*, is converted into μ_B and plotted in Figure 35.⁷⁵ Note that since this μ_B is lower than that defined in §25.109(c), it will be even lower than the larger μ_B defined in §25.109(d) corresponding to a grooved runway. Since the KMDW runway is grooved, this points to a significant discrepancy between the achieved performance and that assumed in §25.109(d). However, as shown in Figure 35, the achieved μ_B at 90 kt. is consistent with the NASA CFME model based on a CFME test run at 40 mph. This CFME test and Figure 35 in general will be discussed further in Section D-VIII.

The EMB-500 accident in Sugar Land, TX (NTSB #CEN15LA057)

The investigations of the four events described above are complete, and the final reports for each issued. The NTSB is currently investigating another wet-runway landing overrun accident that has circumstances very similar to the KCXO accident that is the subject of this *Study*.

On November 21, 2014, an Embraer Phenom EMB-500 airplane, registration N584JS, overran the runway after landing at the Sugar Land Regional Airport (KSGR) in Sugar

⁷⁴ The NASA Convair 880 Standing Water μ_B referred to in the KMDW *Study* is less than the μ_B defined by §25.109(c), and the μ_B that matches the KMDW airplane performance lies *between* these two models.

⁷⁵ The conversion from airplane braking coefficient to μ_B involves an algebraic combination of the airplane braking coefficient, the nose wheel rolling friction coefficient, and airplane geometric terms.

Land, Texas. The airline transport rated pilots were not injured but the airplane was substantially damaged. The NTSB preliminary report for this event⁷⁶ states

According to the crewmembers, the purpose of the flight was to reposition the airplane from [William P. Hobby Airport (KHO)] to KSGR. After departing KHO the flight received vectors from air traffic control, who also told the pilots to expect the ILS 35 approach at KSGR. The first officer reported that the KSGR tower controller cleared the flight to land and that there was no standing water on the runway. During the approach, the first officer noted that there was a tailwind of 15 knots that decreased to 9 knots on touch down.

After landing, the captain, who was flying the airplane, applied the brakes which were unresponsive. She then pulled the emergency brakes twice, but the airplane continued past the end of the runway and onto a grassy area. The airplane then crossed a service road and came to rest in a drainage ditch. The airplane's empennage section was partially submerged by water and the airplane faced the opposite direction of travel.

This investigation of this event is still ongoing, but an examination of the KSGR runway, and a computation of the μ_B achieved during the landing roll have been completed. The results are similar to those for the KCXO event: the depth of water on the runway computed using the TTI model could not have supported dynamic hydroplaning, which is consistent with the spin-up and slip ratio of the tires after touchdown; and the μ_B developed during the ground roll is below that implied by the wet-runway landing distances in the AFM, and below that predicted by the §25.109(c) model. However, the maximum μ_B achieved is consistent with the predictions of the NASA CFME model.

Transport Airplane Performance and Handling Characteristics ARAC Task 2b

As stated above, the FAA has recognized that the actual μ_B achieved on some wet runways may be less than that specified in §25.109(c), and that the runway length required to stop on these runways may exceed the lengths specified in AFMs. On March 8, 2013, the FAA assigned an additional task addressing wet runway stopping performance to the Transport Airplane Performance and Handling Characteristics Aviation Rulemaking Advisory Committee (ARAC). The notice in the *Federal Register* announcing this assignment (Reference 17) states:

The FAA tasked ARAC to consider several areas within the airplane performance and handling qualities requirements of the 14 CFR part 25 airworthiness standards and guidance for possible revision. The task includes prioritizing the list of topic areas provided in this notice based on prioritization criteria established by the [Flight Test Harmonization Working Group (FTHWG)]. The prioritization criteria should consider harmonization of regulatory requirements and associated guidance material for airworthiness certification of airplane designs. Recommendations may result in subsequent ARAC taskings for standards recommendations in follow-on phases. ARAC may also recommend additional topics in the general area of airplane performance and handling qualities that are not on the list provided in this notice.

The working group will provide a draft report to ARAC recommending focus areas and work plans to address those areas the FTHWG identified as high priorities for airworthiness standards

⁷⁶ The preliminary NTSB report for this event can be found at http://www.nts.gov/layouts/ntsb.aviation/brief.aspx?ev_id=20141123X91658&key=1&queryId=4da7f04a-b899-472e-b998-44e3228c7f41&pgno=1&pgsize=50.

development relative to new airplane designs. This report will provide the rationale for the priority recommended as well as identify those items for which coordination with other working groups or experts outside the FTHWG may be needed. The report will also include a proposed schedule for accomplishment of the plan, including whether multiple topics can be worked simultaneously. If there is disagreement within the working group, those items should be documented, including the rationale from each party and the reasons for the disagreement. The following subject areas should be considered:

1. *Fly-by-wire (FBW) Flight Controls.* ...

2. *Takeoff and Landing Performance.* Regulatory requirements and associated guidance material for airworthiness certification in the following areas listed below. (Note: This topic area excludes items addressed by the Takeoff and Landing Performance Assessment Aviation Rulemaking Committee.)

a. Flight test methods used to determine maximum tailwind and crosswind capability. ...

b. Wet runway stopping performance. Recent landing overruns on wet runways have raised questions regarding current wet runway stopping performance requirements and methods. Analyses indicate that the braking coefficient of friction in each case was significantly lower than expected for a wet runway (i.e., lower than the level specified in FAA regulations). Consideration should also be given to the scheduling of landing performance on wet porous friction course and grooved runway surfaces. Recommendations may include the need for additional data gathering, analysis, and possible rulemaking.

The TALPA ARC recommendations include amending Part 25 certification standards to require that the landing distances on wet runways be based on a μ_B computed using the methods defined in §25.109 (see below). Since the ARAC Task 2b is focused on wet-runway μ_B models specifically, it would not seem that the statement in Reference 17 that “this topic area excludes items addressed by the [TALPA ARC]” is intended to exclude examination of the μ_B models, even though those were addressed by the TALPA ARC. In fact, the ARAC started its review of wet runway stopping performance and associated μ_B models in September, 2015.⁷⁷

The Part 25 TALPA ARC recommendations, and AC 25-32

As stated in Section D-V, the regulatory changes proposed by the most groups in the TALPA ARC would introduce a new “Runway Condition and Braking Action Reports” table that would provide a mapping between a six-level runway “code” and corresponding runway contaminant type and depth, CFME measured μ values, airplane μ_B values, and pilot braking action reports. Aircraft manufacturers would have to supply data from which “operational” (i.e., unfactored) landing distances could be calculated for runway codes 6 through 1, and operations would be prohibited on code “0” runways. The methods and assumptions to be used for generating this data would be specified in new regulations added to Part 25. Specifically, the new rules would require that the μ_B on wet, ungrooved runways (runway code 5) be computed per the §25.109(c) method.

⁷⁷ Per telephone conversations between NTSB and FAA staff, November 2015.

In its October 28, 2014 letter to the NTSB regarding NTSB safety recommendation A-07-061, the FAA stated that “we are no longer considering rulemaking related to TALPA or regulating performance data” (see Table 8). Instead, “as a result of the TALPA ARC recommendations, many document changes will be forth coming,” including the incorporation of the information contained in SAFO 06012 into ACs and other documents. The FAA also indicated that it was developing the Runway Condition Assessment Matrix (RCAM) tool:

The RCAM takes a known assessment criteria provided from the airport and provides the pilot with a downgrade assessment criterion. This downgrade assessment criterion is based on the reported runway conditions, such as the reported runway friction expressed in mu (μ) values and reported braking action. This information will provide the pilot with an expected braking ability to slow or stop the airplane during the landing roll. The RCAM is still under final development ... (from FAA 10/28/2014 letter).

The RCAM is the outgrowth of the “Runway Condition and Braking Action Reports” table proposed by the TALPA ARC. The current version of the RCAM is contained in Table 2 of AC 25-32, “Landing Performance Data for Time-of-Arrival Landing Performance Assessments” (Reference 38), and is presented here as Figure 33.

Note in Figure 33 that runway condition code 5 includes a runway surface that is “wet (includes damp $\frac{1}{8}$ ” (3 mm) depth or less of water),” and is associated with a pilot-reported braking action of “good.” This runway surface condition would describe the runways associated with the overrun events described in this *Study*, in the absence of pilot braking reports. The surface condition also describes the KMDW runway, although in that event, the previous Southwest crew reported a braking action of “fair” (which translates to “medium” in the RCAM), and so the associated runway condition code would be 3, corresponding to a “wet (‘Slippery When Wet’)” runway.

A flooded runway (i.e., greater than $\frac{1}{8}$ inch (3 mm) of water), on which dynamic hydroplaning is possible, is an RCAM code 2, and is similar to the AMC 25.1591 flooded runway model given in Equation [29].

For a code 5 runway, Figure 33 indicates that the μ_B should be computed “per [the] method defined in §25.109(c).” For the code 3 runway, the μ_B should be a constant 0.16, which is consistent with the maximum μ_B achieved during the KCXO event. However, a constant μ_B of 0.16 for the KCXO event may be too conservative, if the actual μ_B increases as the airplane slows down, per the ESDU class A model (see Figure 24). Per Table 12, the stopping distance for the accident conditions assuming $\mu_B = 0.16$ constant is 5364 ft., 795 ft. longer than that obtained with the ESDU class A model. The ESDU class A model distance can be approximately matched assuming $\mu_B = 0.218$ constant (see Table 12).

In any case, a practical operational difficulty with the “slippery when wet” designation is determining whether a wet (but not flooded) runway corresponds to condition code 5 or

3, in the absence of a prior CFME test⁷⁸ or a current pilot braking report. This difficulty was addressed in the NTSB comments on the draft versions of ACs 25-31 and 25-32 (Reference 14). The NTSB comments also express concern with the use of the §25.109(c) μ_B model for code 5 runways, given the evidence from multiple events that this model is insufficiently conservative:

One technical problem that should be addressed within the ACs is their reliance, in part, on the wheel braking coefficient model codified in Section 25.109(c) for wet runway stopping performance calculations. However, the Section 25.109(c) model has never been validated by flight test data. To its credit, the FAA has recognized that the wheel braking coefficient model in Section 25.109(c) might be insufficiently conservative, as evidenced by the recent FAA Aviation Rulemaking Advisory Committee (ARAC) tasked to provide recommendations regarding new or updated standards for airplane performance and handling qualities. Under the subject area of Takeoff and Landing Performance, subtask (b) addresses wet runway stopping performance: [see excerpt from Reference 17 above]

The NTSB encourages the FAA to perform flight tests on representative domestic and international runways that support turbine-powered airplane operations in order to validate the wet-ungrooved and wet-grooved wheel braking coefficient models in Section 25.109(c). The NTSB believes that issuing these draft ACs relying on the untested and potentially insufficiently conservative models in Section 25.109(c) is premature. The suggested ARAC flight test validation work should be used to update the wheel braking coefficients appropriate for wet runway operations.

Another technical problem within the ACs arises for certain runway surface conditions characterized as Wet. The ACs define a Wet runway surface condition with good braking action and a wheel braking coefficient calculated by the method in Section 25.109(c), as well as a Wet ("Slippery When Wet") runway surface condition with medium braking action and a wheel braking coefficient of 0.16. Designating a runway as "Slippery When Wet" requires that it be tested using a calibrated Continuous Friction Measuring Equipment (CFME) device, and the resulting friction coefficient found to be below some threshold value. However, because the wet runway friction coefficients specified in Section 25.109(c) have never been validated by flight test, the association of these coefficients with airplane stopping performance capability on runways with CFME friction measurements above a target threshold is unproven. Furthermore, many international runways and smaller domestic runways that support turbojet operations will not have a friction maintenance program, and might therefore not get tested. The NTSB believes that untested runways should be designated as "Slippery When Wet" until and unless (1) the runways have been tested and shown to meet the minimum CFME friction coefficient threshold, and (2) the CFME measurements have been shown to correlate to a minimum wheel braking coefficient developed by airplanes on wet runways deemed to be adequately maintained. This procedure would result in more conservative estimates of airplane stopping distance required on runways with undocumented friction characteristics until a proper CFME friction survey could be conducted and the results could be reliably correlated to airplane stopping performance.

The FAA's response to these comments are contained in Reference 51, as follows:

The FAA tasked an ARAC working group to investigate wet runway issues.

The FAA will react to the recommendations of this body when they have been formulated. However, we do not agree with delaying the implementation the TALPA ARC recommendations until that working group has completed its tasking.

⁷⁸ The CFME values used to designate a runway "slippery when wet" are presented in Section D-VIII.

As to the inclusion of “Slippery when Wet,” the FAA agrees with many of the NTSB’s specific points. However, the TALPA ARC felt, and the FAA concurs, that it is better at a minimum to supply some guidance that has the potential of identifying a worse than nominal wet runway and, therefore, have operators take actions to mitigate the possible worse than expected wheel braking on a wet runway. We recognize the tools to do this are less than optimal and are optimistic the ARAC working group will be able to determine a better course of action for the future.

FAA Flight Standards (AFS-200) has also addressed this topic to some degree in SAFO 15009, dated 8/11/15.

The NTSB comments note the difficulty, in the absence of test data, of identifying the minimum CFME-measured μ required to achieve the μ_B level specified in 25.109(c). Section D-VIII of this *Study* presents an alternative μ_B model that can more reliably predict the minimum μ_B that can be reasonably expected from a wet runway, even in the absence of CFME data for that particular runway.

SAFO 15009

In addition to adding the wet runway stopping performance task to the Transport Airplane Performance and Handling Characteristics ARAC in March 2013, on August 11, 2015 the FAA issued SAFO 15009 concerning “Turbojet Braking Performance on Wet Runways” (see Reference 16 or Appendix C). The SAFO “warns airplane operators and pilots that the advisory data for wet runway landings may not provide a safe stopping margin under all conditions,” and states that

Landing overruns which occur on wet runways typically involve multiple contributing factors such as long touchdown, improper use of deceleration devices, tailwind and less available friction than expected. Several recent runway landing incidents/accidents have raised concerns with wet runway stopping performance assumptions. Analysis of the stopping data from these incidents/accidents indicates the braking coefficient of friction in each case was significantly lower than expected for a wet runway as defined by the Federal Aviation Administration (FAA) in Federal Air Regulation (FAR) 25.109 and Advisory Circular (AC) 25-7C methods. These incidents/accidents occurred on both grooved and un-grooved or non-Porous Friction Course overlay (PFC) runways. The data indicates that applying a 15% safety margin to wet runway time-of-arrival advisory data, as recommended by SAFO 06012, may be inadequate in certain wet runway conditions.

This statement summarizes the findings in this *Study* concerning the KCXO event, and the other wet-runway overrun events described above. The SAFO states that there are typically “multiple contributing” factors to wet-runway overruns, only one of which is “less available friction than expected.” The other contributors include a long touchdown, tailwind, and “improper use of deceleration devices.” In the KCXO event, the touchdown was not long, nor downwind, nor overly fast. However, the engagement of the EPB contributed to the overrun, because it put the airplane into a locked-wheel skid, thereby reducing μ_B to μ_{SKID} ; and Figure 24 and Table 12 indicate that had the airplane continued to perform per the “ $\mu_B = \text{ESDU class A, } \eta_{AS} = 0.80$ ” μ_B curve, it would have stopped on the runway with about 330 ft. remaining. In this sense, the engagement of the EPB could be considered an “improper use” of a deceleration device.

Significantly, the SAFO notes that “the braking coefficient of friction in each case was significantly lower than expected for a wet runway as defined by ... §25.109 and AC 25-7C methods,” which is also a key finding in the KCXO and KSGR events.

SAFO 15009 goes on to say that

The root cause of the wet runway stopping performance shortfall is not fully understood at this time; however issues that appear to be contributors are runway conditions such as texture (polished or rubber contaminated surfaces), drainage, puddling in wheel tracks and active precipitation. Analysis of this data indicates that 30 to 40 percent of additional stopping distance may be required in certain cases where the runway is very wet, but not flooded.

Based on examinations of the runways involved, rubber contamination, drainage, and puddling in wheel tracks were *not* contributors to the KOWA, Kingston, KMDW, KCXO, or KSGR events, though precipitation was present or recent in each case.⁷⁹ As discussed in the preceding sections, the shortfall in μ_B may not be solely the result of a shortfall in μ_{max} (which will decrease as a result of the items listed in the SAFO), but may also result from a lower than assumed η_{AS} . As argued above, the constant $\eta_{AS} = 0.80$ specified in §25.109 is likely overly optimistic in light of research and flight test data, and the overrun events themselves.

The SAFO indicates that the FAA agrees with the NTSB’s concern expressed in safety recommendation A-11-029 that “data contained in the Aircraft Flight Manuals (and/or performance supplemental materials) may underestimate the landing distance required to land on wet, ungrooved runways,” and appears to contradict the FAA’s own statement in its last response to this recommendation (in August 2012) that “more testing would be required to make a case that [the] landing distances [in the BAe 125-800A AFM] are underestimated.”

SAFO 15009 recommends that

Directors of safety and directors of operations (Part 121); directors of operations (part 135, and 125), program managers, (Part 91K), and Pilots (Part 91) should take appropriate action within their operation to address the safety concerns with landing performance on wet runways discussed in this SAFO.

The SAFO also suggests some ways of taking “appropriate action” to address the safety concerns, such as “assuming a braking action of medium or fair when computing time-of-arrival landing performance or increasing the factor applied to the wet runway time-of-arrival landing performance data.” The wet-runway stopping performance issues discussed in this *Study* confirm that this is good advice.

⁷⁹ Based on information in Reference 31, it is not possible to exclude drainage and puddling problems or rubber deposits on the runway as contributors to the Ottawa event, though Reference 31 excludes the possibility of dynamic hydroplaning in that event.

VIII. μ_B model combining §25.109, NASA CFME, and AC 150/5320-12C methods

Overview

This section of the *Study* presents an alternative μ_B model based on:

- The observation that the NASA method for correlating CFME measurements to actual airplane μ_B on wet runways correctly predicts the μ_B achieved in the KOWA, KMDW, KCXO, and KSGR events, and is therefore the most reliable μ_B model of those examined in this *Study*;
- The CFME-measured μ values defined in existing FAA advisory material (Reference 29) as the basis for runway maintenance practices; and
- The observation that the §25.109 μ_B model mirrors the non-linear shape of the μ_B vs. V_G curves in the ESDU 71026 data, and hence serves to extrapolate CFME-based data to V_G values outside of the range measured by a CFME device.

The alternative model (hereafter referred to as the “combined μ_B model”) relies on CFME μ values that can be reasonably expected on actual runways, and converts these to airplane μ_B based on a proven method. As shown below, this model can accurately predict the μ_B achieved in the KOWA, KMDW, KCXO, and KSGR events, without the actual CFME data from the runways involved. In addition, the model is in relatively good agreement with the results of wet-runway flight and CFME tests conducted by Transport Canada using both a Falcon 20 jet and a De Havilland Dash 8 turboprop.

FAA Advisory Circular AC 150/5320-12C, *Measurement, Construction, and Maintenance of Skid-Resistant Airport Pavement Surfaces* (Reference 29) provides guidance to airport operators for evaluating and maintaining runway friction characteristics. The AC specifies minimum CFME μ values for newly constructed runways, and the μ values at which maintenance (such as rubber deposit removal) must be either planned for or taken immediately in order to improve the runway friction. These CFME μ values are used in the combined μ_B model in lieu of actual CFME measurements on a particular runway.

Reference 29 specifies CFME μ values for different maintenance actions at two different CFME vehicle speeds: 40 mph and 60 mph. The two speeds are intended to determine the condition of the runway microtexture and macrotexture:

All of the approved CFME ... can be used at either 40 mph (65 km/h) or 60 mph (95 km/h). The lower speed determines the overall macrotexture/contaminant/drainage condition of the pavement surface. The higher speed provides an indication of the condition of the surface's microtexture. A complete survey should include tests at both speeds.

In the combined μ_B model, these vehicle speeds and associated μ values are converted into V_G and μ_B for a particular aircraft (using the aircraft tire inflation pressure p) per the NASA CFME method described in Section D-VI. This provides the aircraft μ_B at two values of V_G .

Finally, the μ_B vs. V_G curve for the aircraft across the V_G range of interest is determined by finding the factor that should be applied to the μ_{max} specified in §25.109(c) in order to approximately match the μ_B at the two V_G speeds computed from the CFME μ values specified in Reference 29. The factor accounts for the efficiency of the anti-skid braking system (η_{AS}), as well as any adjustment that must be made to the §25.109(c) μ_{max} in order to make it match the μ_{max} that results from applying the NASA conversion method to the Reference 29 CFME μ values.

These steps are described in further detail below.

CFME μ values defined in AC 150/5320-12C

Reference 29 notes that the μ_{max} on a given runway will deteriorate over time, and recommends that airports that support turbojet traffic monitor the μ_{max} on the runways through the use of CFME:

Over time, the skid-resistance of runway pavement deteriorates due to a number of factors, the primary ones being mechanical wear and polishing action from aircraft tires rolling or braking on the pavement and the accumulation of contaminants, chiefly rubber, on the pavement surface. The effect of these two factors is directly dependent upon the volume and type of aircraft traffic. Other influences on the rate of deterioration are local weather conditions, the type of pavement ([Hot Mix Asphalt or Portland Cement Concrete]), the materials used in original construction, any subsequent surface treatment, and airport maintenance practices.

...

All airports with turbojet traffic should own or have access to use of CFME. Not only is it an effective tool for scheduling runway maintenance, it can also be used in winter weather to enhance operational safety (see AC 150/5200-30). Airports that have few turbojet traffic operations may be able to borrow the CFME from nearby airports for maintenance use, share ownership with a pool of neighboring airports, or hire a qualified contractor.

The CFME μ values corresponding to runway friction levels that warrant specific maintenance actions are defined in Section 3 of Reference 29. Three friction levels are defined, corresponding to the “NEW LEVEL,” “MAINT LEVEL,” and “MIN LEVEL” lines shown in Figure 26. Reference 29 describes these friction levels as follows:

3-20.EVALUATION AND MAINTENANCE GUIDELINES. The following evaluation and maintenance guidelines are recommended based on the friction levels classified in [Figure 34]. These guidelines take into account that poor friction conditions for short distances on the runway do not pose a safety problem to aircraft, but long stretches of slippery pavement are of serious concern and require prompt remedial action.

a. Friction Deterioration Below the Maintenance Planning Friction Level [MAINT LEVEL] (500 ft). When the average μ value on the wet runway pavement surface is less than the Maintenance Planning Friction Level but above the Minimum Friction Level [MIN LEVEL] in [Figure 34] for a distance of 500 feet (152 m), and the adjacent 500 foot (152 m) segments are at or above the Maintenance Planning Friction Level, no corrective action is required. These readings indicate that the pavement friction is deteriorating but the situation is still within an acceptable overall condition. The airport operator should monitor the situation closely by conducting periodic friction surveys to establish the rate and extent of the friction deterioration.

b. Friction Deterioration Below the Maintenance Planning Friction Level (1000 ft). When the averaged μ value on the wet runway pavement surface is less than the Maintenance Planning Friction Level in [Figure 34] for a distance of 1000 feet (305 m) or more, the airport operator should conduct extensive evaluation into the cause(s) and extent of the friction deterioration and take appropriate corrective action.

c. Friction Deterioration Below the Minimum Friction Level [MIN LEVEL]. When the averaged μ value on the wet pavement surface is below the Minimum Friction Level in [Figure 34] for a distance of 500 feet (152 m), and the adjacent 500 foot (152 m) segments are below the Maintenance Planning Friction Level, corrective action should be taken immediately after determining the cause(s) of the friction deterioration. Before undertaking corrective measures, the airport operator should investigate the overall condition of the entire runway pavement surface to determine if other deficiencies exist that may require additional corrective action.

d. New Design/Construction Friction Level for Runways [NEW LEVEL]. For newly constructed runway pavement surfaces (that are either saw cut grooved or have a PFC overlay) serving turbojet aircraft operations, the averaged μ value on the wet runway pavement surface for each 500 foot (152 m) segment should be no less than the New Design/Construction Friction Level in [Figure 34].

The DFT trailer used during the CFME testing at KCXO and KSGR is represented by the “Mu meter” (MM) device entry in Figure 34, and the Saab 9-5 vehicle used at KOWA (see below), is represented by the “Airport Surface Friction Tester” (SFT) device entry. The DFT trailer and Saab vehicle have similar operational characteristics: a 30 psi measurement tire inflation pressure, operated at a slip ratio between 10% (for the Saab vehicle) and 12% (for the DFT trailer). However, the μ values in Figure 34 for the MM and SFT devices are different, and therefore comparing the friction levels of different runways (e.g., KCXO runway 1 and KOWA runway 30), measured with different devices, is not straightforward.

The friction levels of different runways measured with different devices can be compared if the device measurements, and the μ values defined in Figure 34, are converted into airplane μ_B using the NASA CFME method. As noted above, the method requires the “characteristic dry” μ_{cd} of each device. Table I of Appendix B lists the μ_{cd} for the SFT as 1.1, and does not have a specific entry for the DFT, though the entry for the MM is 0.9. Since the DFT vehicle shares the MM friction classification levels, it is reasonable to assume that it will also share the MM μ_{cd} value.

This assumption can be verified by estimating the DFT μ_{cd} based on the data in Figure 34. For each friction classification level in Figure 34, the resulting μ_B for an airplane should be the same, regardless of the CFME device used to measure μ . The μ_B is given by Equation [24], with μ_{max} from the NASA CFME model given by

$$\mu_{max} = \frac{\mu_{CFME}}{\mu_{cd,CFME}} \mu_{cd,airplane} \quad [30]$$

Where:

μ_{CFME} = runway μ measured by the CFME device;

$\mu_{cd,CFME}$ = characteristic dry μ_{cd} of the CFME device; and

$\mu_{cd,airplane}$ = characteristic dry μ_{cd} of the airplane (a function of the airplane tire p).

Since the μ_{max} computed from DFT and SFT measurements should be the same, we can write

$$\frac{\mu_{DFT}}{\mu_{cd,DFT}} \mu_{cd,airplane} = \frac{\mu_{SFT}}{\mu_{cd,SFT}} \mu_{cd,airplane} \quad [31]$$

Where:

μ_{DFT} = runway μ measured by the DFT device;
 $\mu_{cd,DFT}$ = characteristic dry μ_{cd} of the DFT device;
 μ_{SFT} = runway μ measured by SFT device; and
 $\mu_{cd,SFT}$ = characteristic dry μ_{cd} of the SFT device.

From Equation [31] it follows that

$$\mu_{cd,DFT} = \frac{\mu_{DFT}}{\mu_{SFT}} \mu_{cd,SFT} \quad [32]$$

Equation [32] can be used to compute $\mu_{cd,DFT}$ based on the μ_{DFT} and μ_{SFT} values in Figure 34, and $\mu_{cd,SFT} = 1.1$. The results vary from 0.84 to 0.98, with an average of 0.92. This *Study* uses $\mu_{cd,DFT} = 0.92$, which compares well with the MM μ_{cd} of 0.9 listed in Table I of Appendix B.

CFME measurements following KCXO, KSGR, KOWA, CYOW, MKJP, & KMDW events

During the investigation of the KCXO and KSGR accidents, the NTSB conducted CFME and other measurements on the accident runways. CFME measurements on the accident runways at KOWA, CYOW, KMJP, and KMDW were also conducted during the investigation of those events.

As shown in Figure 27, on KCXO runway 1 the average DFT μ values measured at $y = -5$ ft. and at 40 mph and 60 mph were 0.50 and 0.36, respectively. These values lie between the MAINT LEVEL and MIN LEVEL for the MM device in Figure 34.

On KSGR runway 35, the average DFT μ values measured at $y = -5$ ft. and at 40 mph and 60 mph were 0.51 and 0.47, respectively. The 40 mph value is between the MAINT LEVEL and MIN LEVEL for the MM device in Figure 34, and the 60 mph value is between and MIN LEVEL and NEW LEVEL in Figure 34.

CFME measurements taken on KOWA runway 30 following the accident there are documented in Reference 40:

The MAC [Minneapolis/St. Paul Metropolitan Airport Commission] vehicle was driven the length of the runway, 10 feet to the right and left of the centerline at 40 mph and at 60 mph to measure the macro and micro (respectively) μ value friction of the runway while its water tank sprayed 1mm of continuous water onto its friction measuring tire. The first and last 500 feet of the runway friction is

not measured because this distance is used to accelerate and decelerate the speed of the vehicle therefore, the test measures 4,500 feet of runway 30. The following [average] μ friction values were measured on runway 30:

- 10 ft right of centerline at 40 mph = .53 μ
- 10 ft left of centerline at 40 mph = .51 μ
- 10 ft right of centerline at 60 mph = .40 μ
- 10 ft left of centerline at 60 mph = .38 μ

These μ values lie between the Reference 29 MIN LEVEL and MAINT LEVEL for the SFT device at both 40 mph and 60 mph, though closer to the MIN LEVEL in both cases.

SFT measurements at 40 mph were taken on CYOW runway 7 in April 2010 and on June 25, 2010 (the accident occurred on June 16).⁸⁰ The average μ values measured were 0.55 and 0.63, respectively. The 0.55 value is below the MAINT LEVEL for the SFT (0.60), while the 0.63 value is above it. However, for these tests the SFT device was run with 0.5 mm of water applied in front of the measuring tire, as opposed to the 1 mm specified by the FAA for CFME measurements in the USA, and as recommended by International Civil Aviation Organization (ICAO). Reference 31 notes that

The results of [post-accident] coefficient-of-friction testing conducted from April to August 2011 indicate that, when using 0.5 mm, the friction values are above the specified [Transport Canada (TC)] guidelines for programming corrective action. However, when using 1.0 mm, the friction values are below those specified in ICAO Airport Services Manual (DOC 9137) Part 2, and immediate corrective action would have to be taken. The investigation was unable to determine the reason for the differences in published minimum friction values and testing methodology between TC and ICAO/FAA This difference may result in reduced runway friction levels at Canadian airports.

Consequently, it is likely that if the SFT device had been run with 1 mm of water during the April and June 2010 tests, the results would have been lower (and possibly below the MAINT LEVEL for *both* runs).

CFME measurements at 40 and 60 mph on runway 12 at MKJP were performed on January 7, 2010 as part of the American Airlines flight 331 accident investigation, using a Findlay Irving Mark 2 Griptester Friction device (one of those listed in Figure 34).⁸¹ At 40 mph 10 ft. to the left of the runway centerline, the average μ values measured were 0.66, 0.60, and 0.54 on the first, second, and third thirds of the runway, respectively. The corresponding values measured at 60 mph were 0.61, 0.63, and 0.54, respectively. These measurements are all between the MAINT LEVEL and NEW LEVEL for the Griptester, as listed in Figure 34. Curiously, except for the first third of the runway, the Griptester results do not show the reduction in μ with increased speed that is reflected in the friction level classifications of Figure 34, and that would be expected based on the physics of wet-runway braking.

As noted above, CFME tests at 40 mph were conducted on KMDW runway 13C after the Southwest Airlines flight 1919 incident. The results of the tests conducted 10 ft. left and

⁸⁰ See Reference 31.

⁸¹ See Reference 46.

right of the runway centerline are presented in Figure 36, and show considerable variation in μ over the length of the runway. A CFME μ value of 0.54, corresponding to about the average μ measured in the first 3000 ft. of the runway, is used to compute the “KMDW μ_B from SFT run & NASA model” point plotted in Figure 35. An estimate of the airplane μ_B over the length of the runway, using the combined μ_B model and the CFME data in Figure 36, is presented below.

Based on the available CFME measurements from the KCXO, KSGR, KOWA, CYOW, and KMDW runways, a reasonable estimate for the μ values for a “representative” runway that could well be encountered in service is an average between the MIN LEVEL and MAINT LEVEL values specified in Figure 34 (i.e., 0.47 at 40 mph and 0.33 at 60 mph, for the MM device). This “REP LEVEL” will be added to the three levels specified in Reference 29 in the further development of the combined μ_B model discussed below.

Scaling the §25.109 μ to the AC 150/5320-12C μ using the NASA CFME model

Consideration of the μ values associated with the different runway friction levels specified in Reference 29 yields four μ values at each of two CFME vehicle speeds: the MIN LEVEL, REP LEVEL, MAINT LEVEL, and NEW LEVEL μ values, at both 40 mph and 60 mph. We now seek to transform both the speeds and the μ values into corresponding parameters applicable to airplanes, that is, to V_G and μ_B , using the NASA CFME model presented in Section VI (and described in detail in Appendix B). The results of the transformation will define scale factors that must be applied to the §25.109(c) μ_{max} and μ_B in order to approximately match the μ_{max} and μ_B resulting from the transformed CFME μ values. For simplicity, these scale factors are determined for CFME measurements at a single CFME device speed: at 50 mph, with the corresponding μ taken as the average of the 40 and 60 mph μ values.

The NASA method uses the tire p of both the CFME device and the airplane as inputs, as well as the μ_{cd} for the CFME device. For both the DFT and SFT, $p = 30$ psi. As discussed above, for the DFT, $\mu_{cd,DFT} = 0.92$, and for the SFT, $\mu_{cd,SFT} = 1.1$. Values of the airplane p considered in §25.109(c) (i.e., 50, 100, 200, and 300 psi) are also considered here, as well as the EMB-505 p of 180 psi.

Tables 14a-14g present the CFME μ values at 50 mph transformed to airplane μ_{max} and μ_B , and the CFME speed of 50 mph transformed to airplane V_G , for the four runway friction levels and four airplane p values considered in this development.⁸² The μ_{max} specified by §25.109(c) at each V_G , and the factors required to scale the §25.109(c) μ_{max} to the CFME-based μ_{max} and CFME-based μ_B , are also listed. The scale factors are defined as follows:

⁸² See Appendix B for details about the NASA CFME transformation method.

$$\mu_{max}|_{CFME:50} = (k_{max})(\mu_{max}|_{25.109}) \quad [33]$$

$$\mu_B|_{CFME:50} = (k_B)(\mu_{max}|_{25.109}) \quad [34]$$

Where:

$\mu_{max}|_{CFME:50}$ = CFME μ at 50 mph transformed into runway μ_{max} by the NASA model;
 $\mu_{max}|_{25.109}$ = μ_{max} specified by §25.109(c), at the airplane V_G corresponding to the CFME device speed of 50 mph, and the airplane p ; and
 $\mu_B|_{CFME:50}$ = CFME μ values at 50 mph transformed into airplane μ_B by the NASA model.

k_{max} indicates how closely the μ_{max} from the NASA and the §25.109(c) models compare, and k_B is equivalent to the anti-skid efficiency η_{AS} that should be applied to the §25.109(c) μ_{max} in order to match the final μ_B predicted by the NASA model. The η_{AS} corresponding to the NASA model itself (i.e., Equations [27a] and [27b]) is given by

$$\eta_{AS} = \frac{\mu_B|_{CFME:50}}{\mu_{max}|_{CFME:50}} = \frac{k_B}{k_{max}} \quad [35]$$

The η_{AS} computed using Equation [35] is listed in Table 14g.

CFME μ		CFME speed, mph		
		40	50	60
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.42	0.34	0.26
	REP	0.47	0.40	0.32
	MAINT	0.52	0.45	0.38
	NEW	0.72	0.69	0.66

Table 14a. “Mu meter” μ values defined in AC 150/5320-12C for different friction level classifications. Shaded values are defined in the AC; others are interpolated. The 50 mph values are used in the development of the combined μ_B model.

$\mu_{max} _{CFME:50}$		Airplane tire pressure, psi				
		50	100	180	200	300
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.323	0.303	0.271	0.262	0.222
	REP	0.376	0.352	0.314	0.305	0.258
	MAINT	0.428	0.401	0.358	0.347	0.293
	NEW	0.656	0.615	0.549	0.533	0.450

Table 14b. AC 150/5320-12C μ at 50 mph transformed into runway μ_{max} by the NASA CFME model.

$\mu_B _{CFME:50}$		Airplane tire pressure, psi				
		50	100	180	200	300
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.139	0.126	0.106	0.102	0.079
	REP	0.176	0.159	0.133	0.127	0.099
	MAINT	0.216	0.195	0.163	0.156	0.120
	NEW	0.439	0.393	0.325	0.309	0.235

Table 14c. AC 150/5320-12C μ at 50 mph transformed into runway μ_B by the NASA CFME model.

	Airplane tire pressure, psi				
	50	100	180	200	300
Airplane spin-down V_p , kt.	63.6	90.0	120.7	127.3	155.9
V_G for CFME speed of 50 mph, kt.	56.1	79.3	106.4	112.2	137.4
$\mu_{max} _{25.109}$	0.496	0.345	0.241	0.224	0.167

Table 14d. Airplane spin-down hydroplaning speed (V_p) and ground speed (V_G) corresponding to a CFME device speed of 50 mph, for various airplane tire inflation pressures.

k_{max}		Airplane tire pressure, psi				
		50	100	180	200	300
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.652	0.878	1.122	1.170	1.328
	REP	0.758	1.021	1.303	1.359	1.543
	MAINT	0.863	1.163	1.484	1.549	1.758
	NEW	1.324	1.783	2.276	2.375	2.695

Table 14e. Factor k_{max} for scaling $\mu_{max}|_{25.109}$ to $\mu_{max}|_{CFME:50}$.

k_B		Airplane tire pressure, psi				
		50	100	180	200	300
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.281	0.366	0.441	0.453	0.476
	REP	0.355	0.461	0.553	0.568	0.592
	MAINT	0.437	0.566	0.677	0.694	0.720
	NEW	0.885	1.140	1.348	1.378	1.405

Table 14f. Factor k_B for scaling $\mu_{max}|_{25.109}$ to $\mu_B|_{CFME:50}$.

η_{AS}		Airplane tire pressure, psi				
		50	100	180	200	300
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.431	0.416	0.393	0.387	0.358
	REP	0.468	0.451	0.424	0.418	0.384
	MAINT	0.506	0.486	0.456	0.448	0.410
	NEW	0.669	0.639	0.592	0.580	0.521

Table 14g. NASA CFME model anti-skid braking system efficiency $\eta_{AS} = k_B / k_{max}$.

Figure 35 plots the μ_B resulting from multiplying $\mu_{max}|_{25.109}$ by the k_B from Table 14f, for $p = 180$ psi (corresponding to the EMB-505) and the four runway friction classification levels, as a function of airplane ground speed (V_G). The Figure also plots $\mu_{max}|_{25.109}$ multiplied by η_{AS} values of 0.80 and 0.95, corresponding to the value in §25.109(c) for fully-modulating anti-skid braking systems, and the value required to match the EMB-505 unfactored wet runway landing distances, respectively. Note that as scaling factors on the μ_{max} defined in §25.109(c), k_B and η_{AS} operate equivalently.

Figure 35 also plots the results of converting the CFME μ and speed measured in the accident investigations discussed above to airplane μ_B and V_G using the NASA CFME model. For the MKJP measurements with the Griptester, a $\mu_{cd,Griptester} = 0.91$ was used, based on a method similar to that used to determine $\mu_{cd,DFT}$. The p of the Griptester is 20.3 psi, per Reference 41.⁸³ For a proper comparison with the μ_B runway classification levels plotted in Figure 35, a k_B corresponding to each of the airplane p involved should be used, rather than the 180 psi used for the EMB-505 (though this value is appropriate for the KCXO and KSGR comparisons). The p of the CYOW EMB-145 was 160 psi, and the p of the MKJP B737 was 200 psi.⁸⁴ Nonetheless, Figure 35 places the resulting μ_B and V_G in the same runway pavement classifications that would result from comparing the original CFME μ measurements to the values in Figure 34.

Figure 35 indicates that the μ_B predicted by the NASA CFME model based on the CFME measurements taken during several accident investigations are below that predicted by the §25.109(c) model, and below the MAINT LEVEL classification. Further, the Figure indicates that the §25.109(c) μ_B lies between the AC 150/5320-12C NEW and MAINT friction classification levels, when the μ values corresponding to those levels are converted to μ_B over a large range of V_G , per the combined model presented here.

It should be noted that while the μ_B actually achieved by the airplanes in the KCXO, KSGR, KOWA, and KMDW accidents match the μ_B predicted by the NASA CFME model well, the airplanes in the CYOW and MKJP accidents achieved μ_B levels *lower* than those predicted by both the §25.109(c) *and* the NASA CFME models. The MKJP μ_B based on the Griptester measurements is above the §25.109(c) μ_B , but the Boeing simulation match indicates that the actual μ_B achieved was far below that level, and even less than the AC 150/5320-12C MIN LEVEL, until V_G dropped below 44 kt. Reference 42 indicates that the airplane braking coefficient achieved over a large portion of the runway at CYOW oscillated about a constant value of approximately 0.07, much lower than the values based on the SFT measurements and NASA model (even considering that the

⁸³ For an airplane tire pressure of 200 psi, the Griptester runs at 60 mph correspond to an airplane groundspeed of 164 knots, which is off the scale of Figure 35. Hence, the airplane μ_B corresponding to these points (0.257, 0.271, and 0.211 for the 1st, 2nd, and 3rd thirds of the runway, respectively) are not shown. Note that two of these values are in the NEW LEVEL area of Figure 35, even at 140 kt.

⁸⁴ See References 31 and 32, respectively. The tire pressure of the KMDW B737 is assumed to match the 200 psi measured on the MKJP B737.

airplane braking coefficient is by definition less than μ_B).⁸⁵ Consequently, the μ_B predicted by the NASA CFME model should be considered *maximum* likely values for a given airplane and runway combination; other factors could make the actual μ_B achieved lower.

The results shown in Figure 35 indicate that unfactored wet-runway stopping distances based on the §25.109(c) model μ_B values (or greater) likely overestimate the μ_B available on runways that do not achieve CFME μ values about 18% better than the MAINT LEVEL values in Figure 34, and consequently underestimate the runway length required to stop on these runways. The μ_B values resulting from the REP LEVEL k_B factors in Table 14f (and illustrated in Figure 35 for $p = 180$ psi), which are about 30% below the §25.109(c) values, are more representative of the airplane performance that may well be encountered on actual, operational wet runways.

Figure 35 also suggests that the μ_B that can be expected on many runways will likely be between the μ_B values specified by the RCAM runway condition codes 5 (wet) and condition code 3 (slippery when wet) shown in Figure 33. AC 25-32 (Reference 38) defines “slippery when wet” as follows:

A wet runway where the surface friction characteristics would indicate diminished braking action as compared to a normal wet runway.

This definition is less specific than the one that was contained in the draft version of AC 25-32, for which the NTSB provided comments (noted above). The draft version defined a runway as “slippery when wet”

When a friction survey, conducted for pavement evaluation/friction deterioration in accordance with AC 150/5320-12C (or current version), indicates that at least 1,000 consecutive feet (304 meters) of runway length (per test run) does not meet the minimum friction level classification specified in table 3-2 of that AC.

The reason for removing this definition from the final AC 25-32 was because it more properly belonged in Advisory Circulars addressing airport field condition assessments (AC 150/5200-30, specifically).⁸⁶ The term “slippery when wet” is currently defined in draft Advisory Circular 150/5200-30D (Reference 52):

Slippery When Wet Runway

A wet runway where the surface friction characteristics would indicate diminished braking action as compared to a normal wet runway.

Note: Slippery When Wet is only reported when a pavement maintenance evaluation indicates the averaged μ value on the wet pavement surface is below the Minimum Friction Level classification specified in Table 3-2 of AC 150/5320-12, *Measurement, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces*. Some contributing factors that can create this condition include: Rubber buildup, groove failures/wear, pavement macro/micro textures.

⁸⁵ The EMB-500 involved in the KSGR accident also achieved μ_B values much lower than those predicted by the NASA CFME model for a portion of its ground roll, though the μ_B subsequently increased to levels more consistent with the DFT measurements. The reasons for the lower μ_B are still under investigation.

⁸⁶ Per telephone conversations between NTSB and FAA staff.

Note that this definition is less conservative than that contained in the draft AC 25-32, since it requires that the “averaged μ value on the wet pavement surface” be below the AC 150/5320-12C MIN LEVEL, while the draft AC 25032 definition only requires the averaged μ to be below the MIN LEVEL for any consecutive 1000 ft. or more (as opposed to the average over the entire “wet pavement surface”). By either definition, however, AC 150/5320-12C would require that for such a runway “corrective action should be taken immediately after determining the cause(s) of the friction deterioration.”

The only runway discussed in this *Study* that would have met the definition of “slippery when wet” (by either the draft AC 25-32 or draft AC 150/5200-30D definitions), and therefore could have been classified as RCAM code 3, was KMDW runway 13C. Figure 36 shows that for the SFT Lane 2 Run 1 test, the average μ over the run was 0.49, which is below the 0.50 value corresponding to the 40 mph MIN LEVEL for the SFT shown in Figure 34.⁸⁷ The other runways discussed above would be classified as RCAM code 5, implying that the μ_B that could have been achieved on these runways is that defined by the §25.109(c) model. However, as shown in Figure 35 and discussed above, the actual μ_B achieved in each case was well below the §25.109(c) level.

The μ_B predicted by the combined μ_B model for the entire ground roll of Southwest Airlines flight 1919, computed as a function of distance from the KMDW runway 13C threshold using the SFT μ shown in Figure 36, is presented below. The agreement between the combined μ_B model and the results of wet-runway flight and CFME tests conducted by Transport Canada with two different airplane types is also considered.

Comparison of the combined μ_B model with wet-runway flight and CFME test results

In September 2006, the National Research Council of Canada (NRC-CNRC) published a report titled *Evaluation of Falcon 20 Turbojet and DHC-8 Series 100 and 400 Turbopropeller Aircraft Safety Margins for Landings on Wet Runway Surfaces* (Reference 47). The *Introduction* section of this report states:

Aircraft landing incidents and accidents have occurred consistently each year on wet, slippery runway surfaces. These occurrences have included either overruns or excursions off the side of the runway, with cause factors usually including any or all of the following: a rushed, unstable approach; a slippery runway surface due to water and/or rubber contaminant, a tailwind and/or crosswind, or an excessive touchdown speed or distance. An apparent increase in such incidents has prompted Transport Canada to initiate a research program to evaluate the braking performance of selected aircraft on wet runway surfaces. Previous research conducted by other agencies has provided a relatively large database of information on factors influencing wet runway friction levels. These factors include aircraft speed, braking slip ratio, water film depth, surface texture, tire pressure, and the presence of contaminants In addition, hydroplaning has been studied extensively. The most significant gap in the information database is the relationship between aircraft friction and ground vehicle measured friction on wet runways, and the effect of basic pavement parameters such as texture and condition.

⁸⁷ For the μ_B calculation based on the KMDW SFT measurements shown in Figure 35, the SFT μ in the first 3000 ft. was used (assumed to average about 0.54).

Over the last three years, Transport Canada has led a collaborative project to evaluate current operational dispatch factors for landings on wet runways for both turbojet and turbopropeller aircraft. Research has focused primarily on determining the variation of aircraft braking performance as a function of wet runway texture, with the texture being quantified by ground vehicle friction measurements. If a correlation could be shown between aircraft braking coefficients and wet runway texture, then the dispatch factors, or safety margins, for landing on wet runways could be tailored to the specific runway texture and condition. This would enhance operational safety, by increasing dispatch factors on low texture or rubber contaminated runways, and would improve efficiency by enabling dispatch factors to be reduced on higher texture, well maintained runways.

Project collaborators have included Transport Canada (TC), the National Research Council (NRC), Nav Canada, Bombardier Aerospace (BA) and the Airport Authorities for the Montreal Mirabel, Ottawa and North Bay airports. The three aircraft used for these tests were the NRC operated Falcon 20 research aircraft, the Bombardier DHC-8-400 aircraft and the Nav Canada operated DHC-8-100 flight inspection aircraft.

The *Conclusions* section of Reference 47 states:

Aircraft braking performance tests were conducted on wet runway surfaces with the NRC Falcon 20 at the Mirabel, Ottawa and North Bay airports, and with the Nav Canada DHC-8-100 and BA DHC-8-400 aircraft at the Mirabel airport. Saab SFT ground friction vehicles were used to measure the friction on the wet runway surfaces for comparison with the aircraft data. Since the surfaces tested all had a similar degree of wetness ("wet," as opposed to damp or flooded), the SFT measurements proved to be a good indication of surface texture and condition.

Runway texture varied considerably for the four runways on which tests were conducted, with SFT friction values ranging from less than 0.40 to above 0.90. The Falcon 20 braking coefficients also varied considerably on the different wet runway surfaces, and at a given groundspeed, correlated well with the mean SFT measured friction. The DHC-8-100 and DHC-8-400 aircraft braking coefficients were measured only on runway 11/29 at Mirabel; thus, their variation over a wide range of runway textures could not be ascertained. However, it is expected that their variation with texture would be similar to that of the Falcon 20.

An analysis of Falcon 20 landing distances, using the braking coefficients obtained during the tests on wet surfaces, indicates that the current operational dispatch factor of 1.92 for turbojet aircraft does not provide an adequate safety margin for landings on wet runways, particularly those with low texture or rubber contamination. A similar analysis for the DHC-8-100 and DHC-8-400 aircraft indicates that the current operational dispatch factor of 1.43 for turbopropeller aircraft does not provide an adequate safety margin for landings on wet runways. These conclusions are identical to those made in a separate statistical study done by Transport Canada.⁸⁸

In addition, Reference 47 notes that the wet-runway μ_B achieved by all three aircraft during the flight tests was well below that specified in §25.109(c), consistent with the findings in the wet-runway overrun events described above. Reference 47 states that

the reduced Falcon 20 data [relative to §25.109(c)] is likely due to a combination of an antiskid braking system efficiency somewhat below 80%, and a runway surface that is considerably smoother than the moderate texture assumed by ESDU.

References 48 and 49 are reports specific to the Falcon 20 and DHC-8-400 tests, respectively. Referring to the DHC-8-400 report, Reference 47 states

⁸⁸ The Transport Canada statistical study is documented in References 55 and 56.

The results for the DHC-8-400 ... are attributed ... to the smooth concrete surface combined with a runway condition which showed “heavy rubber deposits.” It is also stated that some periods of “heavy rain” may have contributed to the lower braking coefficients, although the water depth measured no greater than 3 mm to 4 mm. In any case, the reduction in aircraft μ_B for the DHC-8-400 was consistent with the results of the Falcon 20 on rain wet runway 11 at Mirabel.

References 48 and 49 present the results of the SFT runs on the test runways, as well as the actual μ_B achieved by the airplanes during the tests. This information can be used as additional validation of the combined μ_B model described above.

Falcon 20 tests

Figure 37a, from Reference 48, presents the results of the SFT μ runs on the Montreal Mirabel airport (CYMX) runway 11 test section performed in support of the Falcon 20 flight testing. Reference 48 attributes the different results for the Tradewinds Scientific, Inc. (TW) and Transport Canada (TC) devices during the October 2003 tests to

a problem with the test tires, which was discovered on the first day of testing ... the problem was likely due to one of the tires being close to the minimum tread depth, since friction readings tend to become higher as the minimum tread depth is reached. The test tires were replaced on both TW and TC SFTs prior to continuing the tests. This reduced the output differences, but discrepancies of up to 20 percent remained, as shown in Figure 6. Issues relating to test tire quality control and calibration should be addressed.

Reference 48 summarizes the results of the μ_B achieved by the Falcon 20 airplane itself, based on recorded flight data, as the black line plotted in Figure 37b labeled “Falcon 20 flight-test (Reference 48).” Reference 48 compares this performance to the §25.109(c) μ_B model, and analyses the results as follows:

[The §25.109(c)] requirement is based on the ESDU (Engineering Sciences Data Unit) International definition of maximum tire-to-ground braking coefficient, multiplied by an efficiency factor applicable to the anti-skid system in use. An efficiency factor of 50% is applied to a “quasi-modulating” anti-skid system, whereas an efficiency factor of 80% is applied to a “fully-modulating” anti-skid system. Even though the Falcon 20 anti-skid system was designed and built in the 1960s, when the Mark II modulating rate type system was being produced, the Falcon 20 system has many of the features of the more advanced Mark III closed-loop feedback control system developed in the early 1970s. The efficiency rating of the Falcon 20 anti-skid system is therefore estimated to be between 50% and 80%, probably closer to 80% considering the modulation characteristics shown consistently in the brake pressure time histories of [the test results].

The first order plot of the Falcon $[\mu_B]$ on wet runway surfaces is shown in Figure [37b] compared to the ESDU 50% and 80% efficiency levels. This plot essentially overlays the ESDU 50% efficiency level for values of $[\mu_B]$ between about 30 knots and 120 knots, and is well below the certification requirement of 80% efficiency for a fully modulating anti-skid braking system.

The reduced Falcon $[\mu_B]$ data shown in Figure [37b] could be due to an anti-skid braking system efficiency below 80% (either by design or a faulty system), or a runway surface that is considerably smoother than the moderate texture assumed by ESDU, or a combination of both. Considering the fact that no braking system anomalies were evident during the tests, it is reasonable to assume that the smooth concrete surface of runway 11 at Mirabel is part of the problem. Given this assumption, the minimum average SFT friction profile of 0.50 for maintenance

action may need to be adjusted upwards, at least for concrete runways, since the reduced braking performance occurred on a runway with an average friction profile of 0.54. Additional aircraft tests at Mirabel and/or Falcon tests on asphalt runways would be beneficial in confirming these data.

The tire pressure p of the Falcon 20 is 136 psi (see Reference 48, p. 8). With this value of airplane p , and the CFME p and μ_{cd} for the SFT cited above (30 psi and 1.1, respectively), the NASA CFME model predicts that an SFT μ reading of 0.54 at 40 mph represents an airplane μ_B of 0.18 at an airplane V_G of 74 knots. These airplane μ_B and V_G values are plotted in Figure 37b as the red circle labeled “NASA CFME model with SFT $\mu = 0.54$ @ 40 mph.” Note that this point lies very close to the line representing the actual Falcon 20 μ_B results.

The combined μ_B model described above uses the CFME μ at 50 mph (computed as the average μ of SFT runs at 40 mph and 60 mph) to determine k_B , the scaling factor (or equivalently, the η_{AS}) applied to the §25.109(c) μ_{max} to compute the airplane μ_B as a function of V_G . The SFT runs described in Reference 48 were only performed at one speed (40 mph), so the SFT μ at this speed will be used to compute the k_B for the combined μ_B model for the Falcon 20 tests.

As noted, the SFT speed of 40 mph corresponds to an airplane V_G of 74 knots for an airplane p of 136 psi. At this V_G and p , the §25.109(c) μ_{max} is 0.35. From Equation [34], the resulting k_B for the combined μ_B model is therefore

$$k_B = \frac{\mu_B|_{CFME:40}}{\mu_{max}|_{25.109}} = \frac{0.18}{0.35} = 0.51 \quad [36]$$

Where $\mu_B|_{CFME:40}$ is the SFT μ measured at the vehicle speed of 40 mph. The $k_B = 0.51$ value compares well with the analysis in Reference 48, which noted that the actual Falcon 20 μ_B “essentially overlays the ESDU 50% efficiency level for values of μ_B between about 30 knots and 120 knots.” Since the combined μ_B model correctly predicts the Falcon 20 actual μ_B based on SFT runs alone, the tests described in Reference 48 provide additional validation of the combined model.

DHC-8-400 tests

Reference 49, which describes the wet-runway braking tests conducted with the DHC-8-400 airplane, provides SFT and airplane μ_B data on a run-by-run basis. This information is more detailed than that provided for the Falcon 20, and allows a more thorough check of the NASA CFME and combined μ_B models.

The braking tests described in Reference 49 consist of both full-stop landing tests, and accelerate-stop tests (in which the airplane remains on the ground). Before and after each test, an SFT run was conducted. For each test, Reference 49 plots the actual airplane μ_B achieved as a function of V_G , and compares the result with the §25.109(c) model, assuming $\eta_{AS} = 0.80$. Reference 49 states that

The relationship between brake friction coefficient and true groundspeed has been determined for each of the six braking test points. All test points show a similar characteristic with groundspeed; however, the aircraft derived wet braking friction for runway 11/29 at Mirabel was only about 50% of the braking coefficient levels of FAR 25.109 Amendment 92/JAA AMJ 25.1591.

...

This [performance] is attributed to the smooth concrete surface and the condition of the runway throughout the test sections which showed heavy rubber deposits. These findings for the Dash 8 Series 400 are in line with those found during the Falcon 20 tests of Reference A on this runway.

The heavy rain present for some of the test points may have also contributed to the lower braking coefficients; however, the maximum observed water depth was measured to be no greater than 3 mm to 4 mm. The poor wet surface characteristic of runway 11/29 at Mirabel was also supported by pilot comments. The flight crew noted that greater deceleration was felt before the heavy rain started; leading to not a very pronounced braking effect during the rain.

As discussed above and noted in Figure 33, a water depth of (just over) 3 mm is considered sufficient to support dynamic hydroplaning, and classify a runway as RCAM Code 2, with μ_B values no greater than 0.05 above $V_{p,spin up}$, and no greater than 0.16 below $V_{p,spin up}$.⁸⁹ Reference 49 does not indicate where on the runway the 3 mm water depths were measured, or provide rainfall rate, runway cross-slope, or macrotexture depth information with which to compute the water depth as a function of distance from the runway centerline, per the TTI model (Reference 22). Reference 49 does note that “the crown on the runway provided good drainage despite the heavy rain.” However, the μ_B values achieved by the airplane at speeds above the hydroplaning speed during some test points are on the order of 0.05, and at lower speeds the actual μ_B achieved is somewhat lower than the μ_B predicted by the combined μ_B model. Consequently, it is reasonable to conclude that the water depth in the wheel tracks of the airplane during some of these tests was in the neighborhood of 3 mm, making the runway closer to an RCAM code 2 than to an RCAM code 5. Nonetheless, as will be seen below, the combined μ_B model does match the actual airplane μ_B well for long stretches of runway for several test points (particularly for the landing tests, vs. the accelerate/stop tests), and in any case matches the actual μ_B much better than the §25.109(c) model.

Appendix E of Reference 49 contains plots of “the aircraft measured runway friction as a ratio of the [§25.109(c)] wet runway model” vs. distance down the runway. The plots also present the average of the TC and TW SFT μ measurements taken before and after each airplane test point, as a function of distance down the runway. Hence, these plots can be used to determine both the actual μ_B achieved by the airplane, and the μ_B that would be predicted by the combined μ_B model based on the SFT measurements, as functions of distance down the runway, for each of the six test points presented. This represents a large number of “validation points” for the combined μ_B model.

An equivalent way of comparing the combined μ_B model prediction to the actual μ_B achieved is to compare the k_B at each point predicted by the model (computed from Equation [36]) to the ratio of the actual μ_B to the §25.109(c) μ_{max} . The §25.109(c) μ_B

⁸⁹ Figure 33 defines the “hydroplaning speed” as $V_{p,spin down}$. $V_{p,spin up} \approx (0.85) V_{p,spin down}$; see Equations [19a-b]. The DHC-8-400 tire p is 134 psi, resulting in $V_{p,spin up} = 89$ kt. and $V_{p,spin down} = 104$ kt.

used to compute ratios plotted in Appendix E of Reference 49 assumes $\eta_{AS} = 0.8$; hence, these ratios must be multiplied by 0.8 in order to compare them to the k_B resulting from the combined μ_B model:

$$k_{Ref49} = \frac{\mu_B}{(0.8)(\mu_{max}|_{25.109})} \rightarrow \frac{\mu_B}{\mu_{max}|_{25.109}} = k_B = (0.8)(k_{Ref49}) \quad [37]$$

Where k_{Ref49} is the μ ratio plotted in Reference 49.

The resulting comparisons are shown in Figure 38. This Figure presents, as a function of distance from the CYMX runway 11 threshold, k_{Ref49} multiplied by 0.8 (the red lines labeled “Based on airplane test data”), and k_B from the combined μ_B model, based on the SFT runs before and after each airplane test point. Since all the SFT runs were conducted at 40 mph, the k_B was computed using Equation [36], with $\mu_{max}|_{25.109}$ at each point equal to 0.356, corresponding to a tire p of 134 psi (the DHC-8-400 p cited in Reference 49) and a V_G of 73.5 kt. (the airplane V_G corresponding to an SFT speed of 40 mph and an airplane p of 134 psi, per the NASA CFME model).

Figure 38 also notes the type of test for each test point (landing or accelerate/stop), the runway used (CYMX runway 11 or 29), and the weather conditions before and after each SFT run. Note that for test points 5.1 and 5.5, only the SFT data for the run taken after the test point is presented; Reference 49 explains that for these test points, “too much time had elapsed between the SFT runs before the aircraft test and the aircraft test.”

Figure 38 indicates generally good agreement between the k_B computed from the airplane test data, and from the SFT data using the combined μ_B model, for the landing tests. The k_B based on the airplane data is lower than that based on the SFT data at the higher groundspeeds for test points 4.1 and 4.2 (nearer the runway threshold), indicating worse braking performance than that predicted by the combined μ_B model (this may be due to water depths in the neighborhood of 3 mm, as discussed above). For test point 4.1, the k_B lines based on the SFT runs are initially slightly higher than that based on the airplane data, but then bracket the airplane-based k_B for the majority of the length of the runway. For test point 4.2, the SFT-based k_B again is initially higher than the airplane-based result, but then shows slightly worse performance (though the black line based on the SFT run performed before the airplane test matches the airplane-based data fairly well). The degraded performance shown by the blue line for the SFT run after the airplane test may be due to the heavier rain and increased water depths during that run.

For the accelerate-stop tests, Figure 38 shows that the actual braking performance is consistently worse than that predicted by the combined μ_B model, though the difference diminishes at lower groundspeeds (for test point 5.2, the solutions are essentially the same by the end of the test). The SFT-based k_B remains relatively constant at about 0.5, whereas the airplane-based data for test points 5.5 and 5.7 peak at about 0.40 to 0.45, or 10% to 20% lower. However, it should be noted that the combined μ_B model approximates the actual performance much better than the §25.109(c) model, for which $k_B = 0.8$ constant. The actual maximum k_B of 0.40 to 0.45 is 43% to 50% lower.

The method used here to compare the μ_B predicted by the combined μ_B model with the actual μ_B achieved by the airplane, as a function of distance from the runway threshold, can also be used to examine the Southwest Airlines flight 1919 incident at KMDW in more detail, since the actual airplane μ_B and the SFT μ at each point on the runway are available for that event.

k_B & μ_B along the runway for the Southwest Airlines flight 1919 incident

As noted above, the results of SFT runs conducted on KMDW runway 13C following the Southwest Airlines flight 1919 incident are shown in Figure 36. These runs were all performed with a target speed of 40 mph (though the achieved speed varied slightly from the target; see Figure 36). The SFT speed and μ data for each of the SFT runs can be used in the NASA CFME model to compute an associated airplane μ_B and V_G at every point along the runway. The §25.109(c) model μ_{max} corresponding to these V_G values and the assumed airplane tire p of 200 psi can then be determined. The combined μ_B model k_B values can then be computed as the ratio of the airplane μ_B from the NASA CFME model, to the §25.109(c) model μ_{max} computed at the airplane V_G values derived from the NASA CFME model (see Equation [36]).

Finally, the combined μ_B model μ_B prediction at each point along the runway can be computed as the §25.109(c) model μ_{max} corresponding to the *actual* airplane V_G at each point along the runway (as recorded in the flight data), multiplied by the k_B values computed at each point. This estimated μ_B can then be compared to the *actual* μ_B computed from the flight data.

The results of these calculations are shown in Figure 39. The top plot of Figure 39 compares the μ_B values resulting from:

- §25.109(c) for a smooth runway, with $\eta_{AS} = 0.8$;
- §25.109(d) for a grooved runway, with $\eta_{AS} = 0.8$ (KMDW runway 13C is grooved);
- The μ_B computed from the recorded airplane data;⁹⁰
- The μ_B used in the Boeing simulation to match the airplane's deceleration;⁹¹
- The combined μ_B model for each of the three SFT runs shown in Figure 36.

Note that between 1000 and 2700 ft. from the threshold, the μ_B from the combined μ_B model for all three SFT runs matches the μ_B required in the simulation to duplicate the airplane's deceleration very well. This is consistent with the "KMDW μ_B from SFT run & NASA model" point plotted in Figure 35, which is based on an average SFT μ of 0.54 and an SFT speed of 40 mph.

⁹⁰ This μ_B is derived from the airplane braking coefficient computed by Boeing, based on an algebraic combination of the airplane braking coefficient, the nose wheel rolling friction coefficient, and airplane geometric terms.

⁹¹ This μ_B is derived from the airplane braking coefficient used in the simulator.

Between 2700 and 3400 ft. from the threshold, both the μ_B computed from the airplane data, and the measured SFT μ , show a large rise.⁹² The airplane μ_B increases above the §25.109(d) level for a grooved runway (assuming $\eta_{AS} = 0.8$), while the μ_B computed from the SFT data and the combined μ_B model increases to about the §25.109(d) level. Following this peak, both the actual and modeled μ_B drop significantly, though the modeled μ_B drops further and indicates worse performance than both the actual μ_B and the Boeing simulation μ_B . The modeled μ_B remains below the actual and simulation μ_B until about 5300 ft. from the threshold, when the modeled μ_B climbs back up to the actual and simulation μ_B levels.

The large drop in the modeled μ_B starting at 3400 ft. from the threshold reflects the drop in the SFT μ measured in the same area; the SFT μ drops to about 0.25, or half of the MIN LEVEL value defined in AC 150/5320-12C for the SFT device at 40 mph (see Figure 34). The airplane μ_B , on the other hand, generally follows the trend indicated by the simulation μ_B , which is based on monotonic functions of V_G (i.e., the simulation μ_B increases monotonically as V_G decreases).⁹³ In other words, in this area the airplane μ_B trend appears to be driven primarily by decreasing V_G , without significant influences from other factors (such as a dramatic change in the runway surface condition). Since the actual μ_B does not decrease notably below the simulation μ_B , it appears that (for unknown reasons) the airplane did not experience the increased runway “slipperiness” between 3400 and 5300 ft. from the threshold measured by the SFT device.

The μ_B behavior depicted in the top plot of Figure 39 is reflected in the plots of k_B and η_{AS} at the bottom of the Figure (k_B and η_{AS} are essentially equivalent in this analysis, since both of these are factors applied to μ_{max} to produce μ_B). The differences between the solid and dashed lines in this plot result from using either the μ_{max} from §25.109(d) for a grooved runway, or the μ_{max} from §25.109(c) for a smooth runway, in the calculation of k_B and η_{AS} (see Equation [36]). Note that if μ_{max} for a grooved runway is assumed (KMDW runway 13C is grooved), then the η_{AS} computed from the actual airplane μ_B drops as low as 40% to 50%. Even if the μ_{max} for a smooth runway is assumed, the resulting η_{AS} is only about 60%. This is further evidence that the combination of μ_{max} and η_{AS} assumed in §25.109 can greatly overestimate the actual μ_B achievable on some wet runways, even grooved runways at large commercial airports certified under 14 CFR Part 139.

On the other hand, the good agreement between the achieved μ_B and the μ_B resulting from the combined μ_B model between 1000 and 2700 ft. from the threshold provides further evidence that the combined μ_B model, and the NASA CFME model it employs, are reliable predictors of the actual μ_B that can be achieved on a wet runway, if the CFME characteristics of that runway are known or can be estimated.

⁹² The runway position of the SFT data was adjusted by about 81 ft. towards the threshold so as to align the rise in the SFT μ with the rise in the computed airplane μ_B . The rise in μ coincides with the intersection of runway 13C with runway 4R, approximately 350 ft. to each side of the centerline of runway 4R.

⁹³ As discussed above, the simulator μ_B lies between the “NASA Convair 880 Standing Water curve” and the §25.109(c) model.

E. CONCLUSIONS

The material in this *Study* supports a number of observations and conclusions regarding the performance of N322QS during its approach and landing on KCXO runway 1. In addition, this accident confirms several observations and conclusions drawn from other accidents regarding airplane stopping performance on wet runways, and the modeling of μ_B on these runways in particular. These observations and conclusions are outlined below.

Approach, touchdown, and ground roll performance

N322QS was dispatched to KCXO runway 14 assuming that the runway would be wet at arrival. However, several Notices to Airmen (NOTAMs), which were overlooked by the dispatcher, indicated that because of construction, on the day of the accident the runway 14 LDA was reduced, and the ILS and RNAV instrument approaches to runway 14 were not available. CVR information indicates that the crew first became aware of this information during their approach to KCXO, and decided to use runway 1 instead. Since the runway 1 LDA was shorter than that planned for in the flight release package, the NJA FOM required an LPA, but the CVR does not indicate whether the crew performed an LPA for runway 1. Nonetheless, runway 1 would have satisfied the requirements of an LPA.

Below 1200 ft. MSL during the final approach, the airplane was aligned with the vertical and horizontal RNAV approach path, and the airspeed and rate of climb complied with the stabilized approach criteria defined in the NJA AOM. The AOM specified a V_{AP} of $V_{REF} + 10$ kt., and required that below 1000 ft. above the TDZE, $V_{REF} \leq V_{KIAS} \leq V_{REF} + 20$ kt., and that $\dot{h} \leq 1000$ ft./min. However, the AOM also specified that the airspeed should be reduced to V_{REF} by 50 ft., and in this case the airspeed exceeded the target V_{REF} speed of 112 kt. by about 9 kt., resulting in a longer landing distance than would have been needed otherwise. Nonetheless, the airplane should have been able to stop on the runway even considering the higher threshold crossing speed and touchdown speed, had it performed in a manner consistent with the braking performance implied in the AFM wet-runway landing distances.

The airplane touched down about 903 ft. from the threshold, at a groundspeed of about 118 kt., with negligible headwind. The FDR brake pedal and brake pressure parameters indicate that the pilot started applying the brakes immediately upon touchdown, and progressively demanded full braking performance from the system. The speedbrake surfaces operated normally, deflecting shortly after touchdown.

The airplane achieved a maximum deceleration (negative n_x) of about -0.17 G's and a maximum μ_B of about 0.16. The crew expressed concern about the airplane's deceleration and applied the EPB, putting the airplane into a full, locked-wheel skid. During the skid, the μ_B dropped to 0.065 and the n_x increased to -0.09 G's just before the airplane passed the end of the runway. This decrease in stopping performance is consistent with the known decrease in μ_B during skids; the decrease in μ_B , white scrub

marks on the runway, and observed tire damage are also consistent with reverted-rubber hydroplaning during the skid. The airplane exited the runway about 27 seconds after touchdown, at a groundspeed of about 61 knots, and came to rest about 400 ft. past the end of the runway.

The maximum μ_B of 0.16 achieved during the portion of the ground roll before the EPB was applied, but during which maximum braking performance was commanded through the brake pedals, is significantly less than the μ_B that would be expected given the unfactored wet-runway landing distances published in the EMB-505 AFM, or even the μ_B predicted by the §25.109(c) model (which is more conservative than the μ_B implied by the AFM distances). This apparent “deficit” in μ_B is consistent with the poorer-than-expected braking performance observed in other accidents investigated by the NTSB and foreign accident investigation agencies.

The μ_B that was actually achieved in the N322QS accident was consistent with that modeled by an ESDU class “A” runway, with an η_{AS} of 80% (or equivalently, an ESDU class “C” runway, with an η_{AS} of 58%). If the EPB had not been set and if the airplane had continued to perform in a manner consistent with this model, then it should have been able to stop on the runway with about 300 ft. of runway remaining.

Significant events during N322QS’s landing and ground-roll are summarized in Table 15.

Time (CDT)	Event	Distance from KCXO runway 1 threshold, ft.	Distance to end of runway, ft.	Ground speed, kt.
08:47:05.8	Threshold crossing	0	5000	123.2
08:47:10.2	Touchdown (wheel spin-up)	903	4097	117.9
08:47:13.6	Speedbrakes fully deployed	1556	3444	114.2
08:47:13.8	[CAM] [sound similar to aircraft touchdown].	1600	3400	113.8
08:47:17.2	n_x reaches -0.17	2229	2771	105.0
08:47:18.8	Start of temporary n_x drop	2507	2493	100.4
08:47:20.4	[HOT-1] Comment 1 concerning aircraft speed.	2772	2228	96.2
08:47:21.0	Brake pedals reach 35 mm (full deflection)	2869	2131	94.8
08:47:21.1	[HOT-2] Comment 2 concerning aircraft speed.	2885	2115	94.5
08:47:22.0	End of temporary n_x drop	3027	1973	92.1
08:47:23.0	[HOT-2] Comment 1 concerning braking action.	3180	1820	89.4
08:47:23.3	Start of final n_x drop	3225	1775	88.5
08:47:23.7	Recorded brake pressures drop	3282	1718	87.5
08:47:23.7	Wheel speeds drop to zero	3291	1709	87.4
08:47:24.9	EPB discrete = 1 (set)	3452	1548	84.7
08:47:25.4	[HOT-2] Comment 2 concerning braking action.	3529	1471	83.4
08:47:26.5	[HOT-2] Comment 3 concerning braking action.	3682	1318	81.1
08:47:26.7	Brake pressures 3000 psi	3707	1293	80.8
08:47:28.9	[HOT-2] Comment 4 concerning braking action.	4002	998	76.8
08:47:35.7	[HOT-1] Comment concerning aircraft alignment with runway.	4816	184	64.6
08:47:37.4	Airplane departs runway	5000	0	61.1

Table 15. Summary of significant events during N322QS’s landing and ground roll.

Need for more conservative μ_B models for computing AFM wet-runway landing distances

The μ_B deficit observed in this and other accidents makes the stopping performance of the airplanes involved more consistent with AFM landing distances for runways contaminated with standing water, than for runways that are merely “wet.” For this reason, observers may be (understandably) quick to conclude that the runways involved must be more contaminated (contain a greater depth of water) than assumed in the wet runway models underlying the AFM distances. However, in this accident and in the others mentioned in this *Study*, examination of the runways involved, including an examination of their macrotexture and cross-slope, do not support a conclusion that the runways could have been flooded given the rainfall rates during the accidents in question. Furthermore, the μ_B actually achieved in a number of these accidents (including N322QS) is consistent with the NASA CFME model for a wet – not flooded – runway. In other words, the NASA CFME model for a wet runway is more conservative than those underlying the airplane AFMs, and moreover, matches the actual airplane performance achieved during the accidents better than those underlying the AFMs.

The NASA CFME model is also more conservative than the §25.109(c) model. The analysis presented in Section D-VIII of this *Study* illustrates why: the §25.109(c) model assumes a runway that achieves a friction classification level between the MAINT LEVEL and NEW LEVEL specified in AC 150/5320-12C, while the NASA CFME method relies on actual CFME measurements on the runway – which can be lower than the MAINT LEVEL.

The FAA has recognized the reality of this μ_B deficit, and the need to address it, in several documents and actions. SAFO 15009 warns operators that “the advisory data for wet runway landings may not provide a safe stopping margin under all conditions,” and advises them to assume “a braking action of medium or fair when computing time-of-arrival landing performance or [increase] the factor applied to the wet runway time-of-arrival landing performance data.” Moreover, the Transport Airplane Performance and Handling Characteristics ARAC was given a new task to address “wet runway stopping performance.”

In addition, AC 25-32, *Landing Performance Data for Time-of-Arrival Landing Performance Assessments*, incorporates many of the recommendations of the TALPA ARC, including the RCAM. However, wet (not flooded) runways can either be classified as RCAM code 5 (associated with μ_B levels defined by the §25.109(c) model), or as RCAM code 3 “slippery when wet” (for which $\mu_B = 0.16$ constant). The “slippery when wet” designation applies when the average CFME μ of the runway falls below the AC 150/5320-12C MIN LEVEL – a condition that only one of the runways examined in this *Study* met. The actual μ_B levels achieved on the other runways was *between* those specified by RCAM codes 5 and 3. Consequently, the RCAM as currently specified in Reference 38 will likely overestimate the μ_B that can actually be achieved on operational, wet runways.

Need for “closed-loop” demonstration of μ_B

The *Study* notes that for a μ_B model to be correct, the product of μ_{max} and η_{AS} must be correct. The NASA CFME model produces an accurate estimate of μ_B with μ_{max} values that are somewhat higher than those assumed in §25.109(c), and with η_{AS} values that are substantially lower than the 0.80 allowed in §25.109(c) for fully-modulating braking systems (and not considering that manufacturers may choose to “demonstrate” higher values using the torque and wheel-slip methods defined in Reference 33). The resulting NASA CFME μ_B values are significantly lower than those predicted by §25.109(c), but match the μ_B values actually achieved during the N322QS accident, other landing overrun events, and the Falcon 20 and DHC-8-400 flight tests relatively well.

Given these results, either the assumption of $\eta_{AS} = 0.80$ in §25.109(c) (and the adequacy of the torque and wheel-slip methods for computing higher values of η_{AS}), the μ_{max} specified in §25.109(c) (rooted in the ESDU 71026 models), or both, must be considered suspect. The reduced μ_B documented in the events considered in this *Study* can be explained by:

- A wet-runway η_{AS} that is significantly less than 80% (even for fully-modulating anti-skid systems);
- A wet-runway μ_{max} that is significantly less than what ESDU 71026 would predict based on the pavement macrotexture and airplane tire p (e.g., KCXO runway 1 would have to perform like an ESDU Class A runway, instead of the ESDU Class C runway indicated by its average macrotexture depth);
- A combination of these factors.

NTSB staff discussions with staff at airplane and brake system manufacturers indicate that these organizations are very confident that the wet-runway η_{AS} of fully-modulating anti-skid systems is at least 80%, and that the torque and wheel-slip methods outlined in AC 25-7C for demonstrating η_{AS} are valid. It is likely that these organizations would be skeptical of the suggestion that η_{AS} could be significantly lower than 80%, as it is modeled in the NASA CFME model (see Equations [27a-b]). On the other hand, the NASA CFME and ESDU models, reflecting research results, indicate that η_{AS} decreases as μ_{max} decreases, even for fully-modulating systems; this behavior is not reflected in the §25.109(c) model. Furthermore, while §25.109(c) requires a demonstration that the anti-skid braking system operates as expected, there is no requirement to demonstrate that the μ_{max} specified by §25.109(c), when combined with the η_{AS} assumed (or “demonstrated”) by the manufacturer, is consistent with the stopping distance actually obtained during flight tests on wet runways.

The μ_{max} available from a wet but non-flooded runway at a given V_G depends on its surface macrotexture and microtexture, as well as the presence of rubber and loose surface deposits, such as sand or grit. ESDU 71026 classifies runway surfaces with regard to macrotexture, but the effect of microtexture is reflected simply in the very large range of possible μ_{max} for a particular runway class (see Figure 25). Microtexture has a

strong influence on μ_{max} , but the research reviewed in this *Study* does not identify a means for measuring this quantity directly. If the reduced μ_B documented in this *Study* is the result of fine microtextures on the runway surfaces involved, then this too indicates the inadequacy of the §25.109(c) model, since that model does not account for the range of microtextures that are possible on existing runways.

The combined μ_B model, and the NASA CFME model it employs, avoid the need to quantify the runway macrotexture and microtexture directly because they are rooted in a measurement of μ on the runway in question (via a CFME device), or an assumption of the minimum CFME μ the runway can provide (based on the AC 150/5320-12C friction classification levels and maintenance standards). Factors that act to reduce or increase the CFME μ will affect μ_{max} in a similar way; for example, reductions in macrotexture and microtexture, and greater rubber contamination, all act to reduce both the CFME μ and the runway μ_{max} . Furthermore, AC 150/5320-12C indicates that CFME runs at different speeds can help identify the effects of both macrotexture (from 40 mph runs) and microtexture (from 60 mph runs).

As shown in this *Study*, the combined μ_B model provides a reliable means for estimating the final airplane μ_B , even when the details of the runway macrotexture, microtexture, and rubber contamination are unknown. Nonetheless, measurements of runway macrotexture, cross-slope, and rubber contamination are always useful, in order to estimate water depths using the TTI model (so as to evaluate the possibility of dynamic hydroplaning), and to help understand the surface condition that produced the CFME measurements. Indeed, if a method for measuring microtexture directly is ever developed, the potential for understanding poor μ_B performance on wet runways will be significantly improved.

As the Transport Airplane Performance and Handling Characteristics ARAC continues its work, the requirement for a “closed-loop” validation of the μ_B models underlying AFM wet-runway landing distances should be seriously considered. This validation would consist of demonstrating that the landing distances computed from the assumed μ_{max} and η_{AS} match the landing distances actually achieved on a wet runway. In particular, the behavior of η_{AS} as μ_{max} decreases should be tested and modeled, so as to correctly predict the performance of the system over a range of CFME runway friction classifications.

Range of μ_B levels on wet runways

The runway friction classification levels in AC 150/5320-12C, and the transformation of these levels into airplane μ_B as presented in Section D-VIII of this *Study*, indicate that μ_{max} can vary widely across different runways, and deteriorate over time on any given runway. Consequently, the validation of any μ_B model by flight testing (as advocated above) should also include an evaluation of μ_{max} on the runway used for testing. CFME and macrotexture measurements should be a part of such an evaluation.

CFME measurements converted to μ_{max} using the NASA CFME model, and the actual μ_B attained on the runway (determined using the method outlined in Section D-IV of this *Study*), can be used to determine the actual η_{AS} achieved on that runway. This in turn can be a means of investigating the dependence of η_{AS} on μ_{max} .

In general, the wet runway landing distances published in airplane AFMs are not functions of different CFME friction levels, even though the actual distances required will vary as the slipperiness of the wet runway varies. If a single “slipperiness level” is chosen to be representative of the range of possible wet runways, the REP LEVEL described in Section D-VIII, which lies halfway between the AC 150/5320-12C MAINT LEVEL and MIN LEVEL, would be more appropriate than the level defined by §25.109(c). An “average” friction level is not adequate, since by definition half of the runways would perform below that average. A conservative estimate of μ_B is particularly important for airplanes that do not have thrust reversers (like the EMB-505), and that therefore depend on effective wheel braking for decelerating from high touchdown speeds.

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G. GLOSSARY

Acronyms

AA	American Airlines
AC	Advisory Circular
AOM	Airplane Operations Manual
AFM	Airplane Flight Manual
AIR	SAE Aerospace Information Report
AMC	Acceptable Means of Compliance (EASA)
AMJ	Advisory Material Joint (Europe)
ANAC	<i>Agência Nacional de Aviação Civil</i> (Brazil)
ARAC	Aviation Rulemaking Advisory Committee
ASOS	Airport Surface Observation System
ATIS	Automatic Terminal Information Service
BA	Bombardier Aerospace
BCU	Brake Control Unit
CDT	Central Daylight Time
CFME	Continuous Friction Measurement Equipment
CFR	Code of Federal Regulations
CG	Center of Gravity
CS	Certification Specification (EASA)
CUA	Closed – Unacceptable Action (NTSB recommendation classification)
CVR	Cockpit Voice Recorder
CYMX	Montreal Mirabel Airport, Montreal, Canada
CYOW	Ottawa/MacDonald-Cartier International Airport, Ottawa, Ontario
DAAP	Destination Airport Analysis Program
DFT	Neubert Aero Corporation Dynamic Friction Tester CFME device
EASA	European Aviation Safety Agency
EPB	Emergency / Parking Brake
ESDU	Engineering Science Data Unit
EU OPS	European operational regulation(s)
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
FOM	Flight Operations Manual
FTHWG	Flight Test Harmonization Working Group
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
JAR	European Joint Aviation Regulations
JCAA	Civil Aviation Authority of Jamaica
KBNA	Nashville International Airport, Nashville, Tennessee
KCXO	Lone Star Executive Airport, Conroe, Texas
KMDW	Chicago Midway Airport, Chicago, Illinois
KOWA	Owatonna Degner Regional Airport, Owatonna, Minnesota
KROW	Roswell International Air Center, Roswell, New Mexico
KSGR	Sugar Land Regional Airport, Sugar Land, Texas

LDA	Landing Distance Available
LEMAC	Leading Edge of the Mean Aerodynamic Chord
LPA	Landing Performance Assessment
MAC	Mean Aerodynamic Chord
MAINT LEVEL	AC 150/5320-12C Maintenance Planning Friction Level
METAR	Meteorological Terminal Air Report
MIN LEVEL	AC 150/5320-12C Minimum Friction Level
MKJP	Norman Manley International Airport, Kingston, Jamaica
MM	Mu meter CFME device
MPD	Mean profile depth
MSpec	Management Specification(s)
MWL	NTSB Most Wanted List
NAC	Neubert Aero Corporation
NASA	National Aeronautics and Space Administration
NEW LEVEL	AC 150/5320-12C New Design/Construction Friction Level
NJA	NetJets Aviation, Inc.
NOTAM	Notice To Airmen
NRC	National Resource Council of Canada
NTSB	National Transportation Safety Board
OAR	Open – Acceptable Response (NTSB recommendation classification)
OPERA	Embraer <i>Optimized Performance Analyzer</i> computer program
OpsSpec	Operations Specification(s)
OUR	Open – Unacceptable Response (NTSB recommendation classification)
POH	Pilot's Operating Handbook
RBHA	<i>Regulamento Brasileiro de Homologação Aeronáutica</i> (Brazil)
RCAM	Runway Condition Assessment Matrix
REP LEVEL	Average of AC 150/5320-12C MIN LEVEL and MAINT LEVEL
RNAV	Area Navigation (instrument approach)
SAE	Society of Automotive Engineers
SAFO	Safety Alert For Operators
SPECI	Special meteorological report or forecast
SRN	Subframe Reference Number
SRTM	Shuttle Radar Topography Mission
SFT	Airport Surface Friction Tester CFME device
STC	Supplemental Type Certificate
TALPA ARC	Takeoff/Landing Performance Assessment Aviation Rulemaking Committee
TC	Type Certificate or Transport Canada (depending on context)
TDZE	Touchdown Zone Elevation
TSB	Transportation Safety Board of Canada
TTI	Texas Transportation Institute
TW	Tradewinds Scientific, Inc.
USA	United States of America
USGS	United States Geological Survey
UTC	Universal Coordinated Time
WOW	Weight On Wheels

English symbols

C_Y	Side force coefficient
d	Average water depth above the top of the runway macrotexture
ETD	Estimated texture depth, converted from MPD using Equation [21]
ETD'	Estimated texture depth, converted from MPD using Equation [22]
F_N	Longitudinal reaction force at nose gear
F_M	Longitudinal reaction force at main gear
F_x	Force along body x-axis
F_z	Force along body z-axis
$\dot{h}$	Rate of climb
I	Rainfall intensity
k	Factor on η_{AS} to account for installation and undercarriage effects
k_B	$= (\mu_B _{CFME:50}) / (\mu_{max} _{25.109})$
k_{max}	$= (\mu_{max} _{CFME:50}) / (\mu_{max} _{25.109})$
L	Runway drainage path-length (distance from runway centerline)
M_y	Moment about body y-axis
n_x	Longitudinal load factor
n_y	Lateral load factor
N_N	Vertical reaction force at nose gear
N_M	Vertical reaction force at main gear
p	Tire pressure
r_{TIRE}	Effective tire radius
s	Wheel slip ratio
$s_{\mu,MAX}$	Wheel slip ratio for $\mu_{B,MAX}$
S	Wing reference area, or runway cross slope (depending on context)
T	Average runway macrotexture depth
u	Component of airspeed along body x-axis
v	Component of airspeed along body y-axis
V	Airplane speed (airspeed or groundspeed depending on context)
$\vec{V}$	Airspeed vector
V_1	Takeoff decision speed
V_{AP}	Approach speed
V_G	Groundspeed
$\vec{V}_G$	Groundspeed vector
V_p	Hydroplaning speed (for dynamic hydroplaning)
$V_{p,spin\ down}$	Spin-down hydroplaning speed (rotating tire)
$V_{p,spin\ up}$	Spin-up hydroplaning speed (nonrotating tire)
$\vec{V}_W$	Wind speed vector
V_{WHEEL}	Tangential speed of tire
V_{REF}	Landing reference speed
w	Component of airspeed along body z-axis
W	Airplane weight
W_x	Component of airplane weight along body x-axis
W_z	Component of airplane weight along body z-axis
Y	Side force

Greek symbols

α	Angle of attack
β	Sideslip angle
δr	Rudder deflection
γ	Flight path angle
η_{AS}	Anti-skid braking system efficiency
θ	Pitch angle
μ	Friction coefficient
μ_B	Wheel braking friction coefficient
$\mu_{B,av}$	Average μ_B in the range of $0.1 \leq s \leq 0.5$
$\mu_B _{CFME:50}$	CFME μ values at 50 mph transformed into airplane μ_B by NASA model
$\mu_{B,MAX}$	Maximum wheel braking friction coefficient (at $s_{\mu,MAX}$)
$\mu_{B,SKID}$	Wheel braking friction coefficient with locked wheels (i.e., at $s = 1$)
$\mu_{cd,airplane}$	Characteristic dry μ_{cd} of an airplane
$\mu_{cd,CFME}$	Characteristic dry μ_{cd} of a CFME device
$\mu_{cd,DFT}$	Characteristic dry μ_{cd} of the NAC DFT CFME device
$\mu_{cd,Griptester}$	Characteristic dry μ_{cd} of the Findlay Griptester CFME device
$\mu_{cd,SFT}$	Characteristic dry μ_{cd} of the SFT CFME device
μ_{CFME}	Runway μ measured by a CFME device
μ_{DFT}	Runway μ measured by the NAC DFT CFME device
μ_{dry}, μ_{cd}	Dry-runway (or “characteristic dry”) friction coefficient
μ_N	Rolling friction coefficient at nose gear
$\mu_{max}, \mu_{t/gMAX}$	Maximum μ available on runway
$\mu_{max} _{25.109}$	μ_{max} specified by §25.109(c), at the airplane V_G corresponding to the CFME device speed of 50 mph, and the airplane p
$\mu_{max} _{CFME:50}$	CFME μ at 50 mph transformed into runway μ_{max} by NASA model
μ_{SFT}	Runway μ measured by the SFT CFME device
μ_{wet}	Wet-runway friction coefficient
ρ	Air density
ϕ	Roll angle
ψ_T	True heading angle
ω_{WHEEL}	Wheel angular velocity

FIGURES

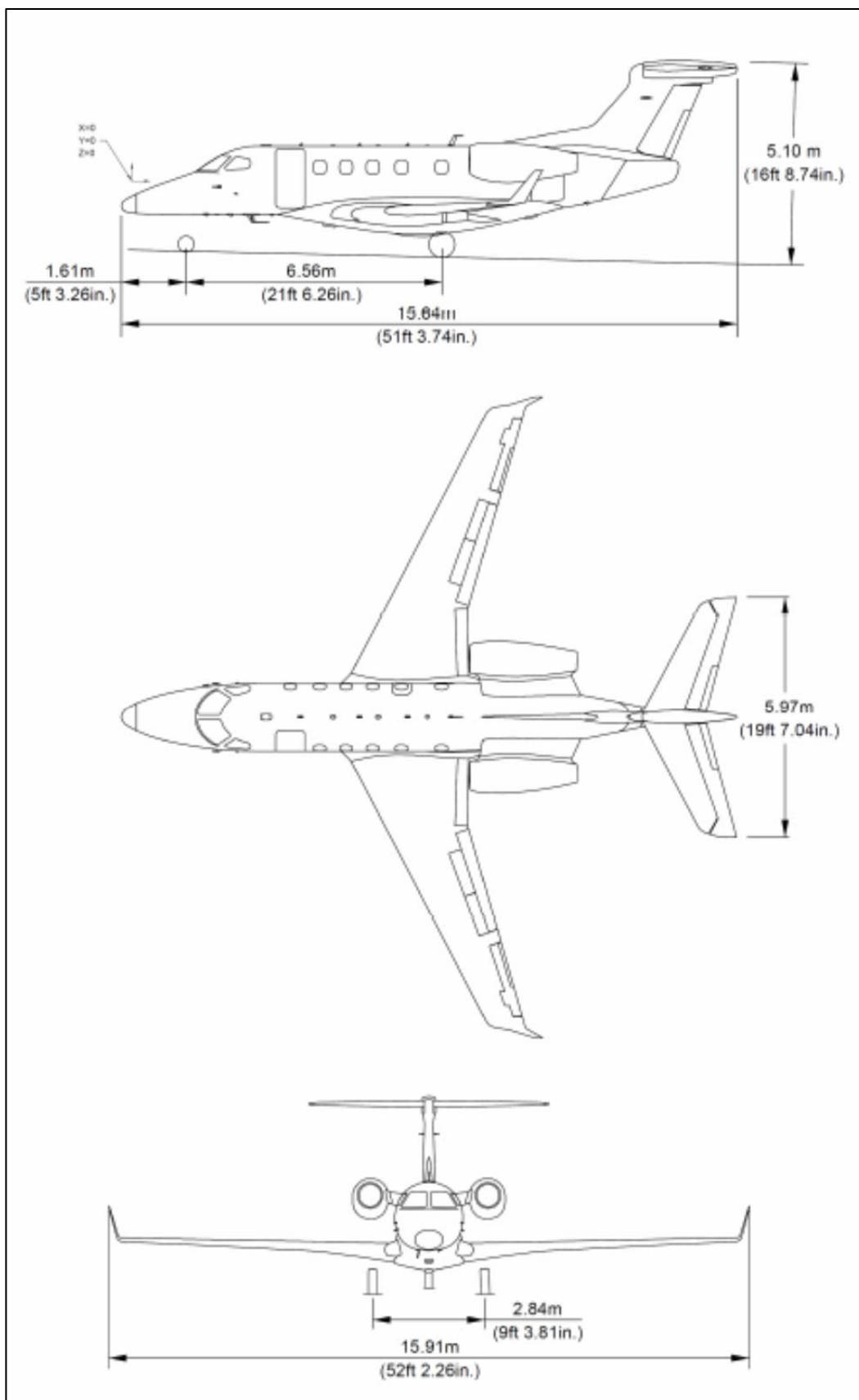


Figure 1. 3-view of Embraer EMB-505 airplane (from Reference 1).

Altitude during final approach

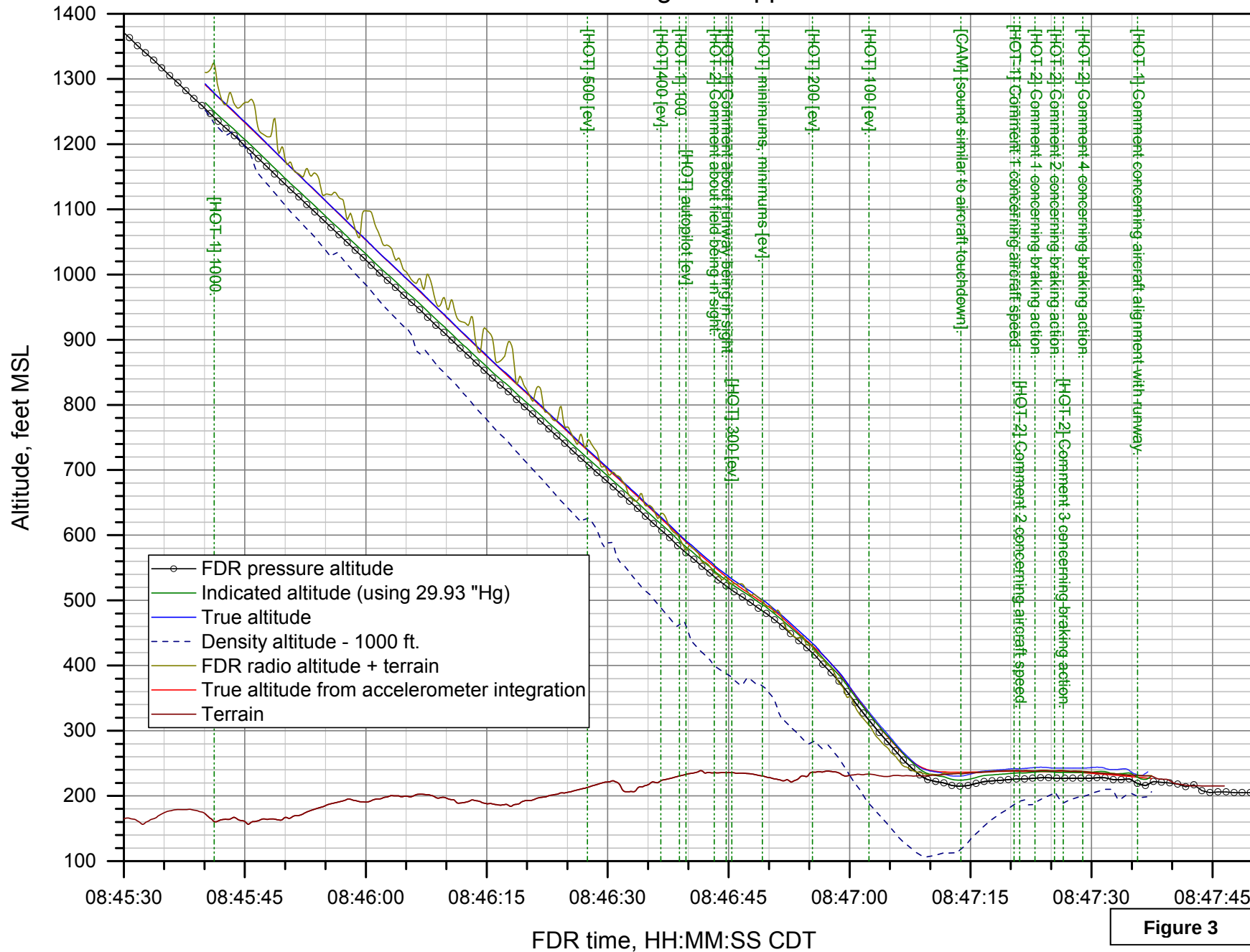


Figure 3

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

115

Plan view of ground track during landing and rollout

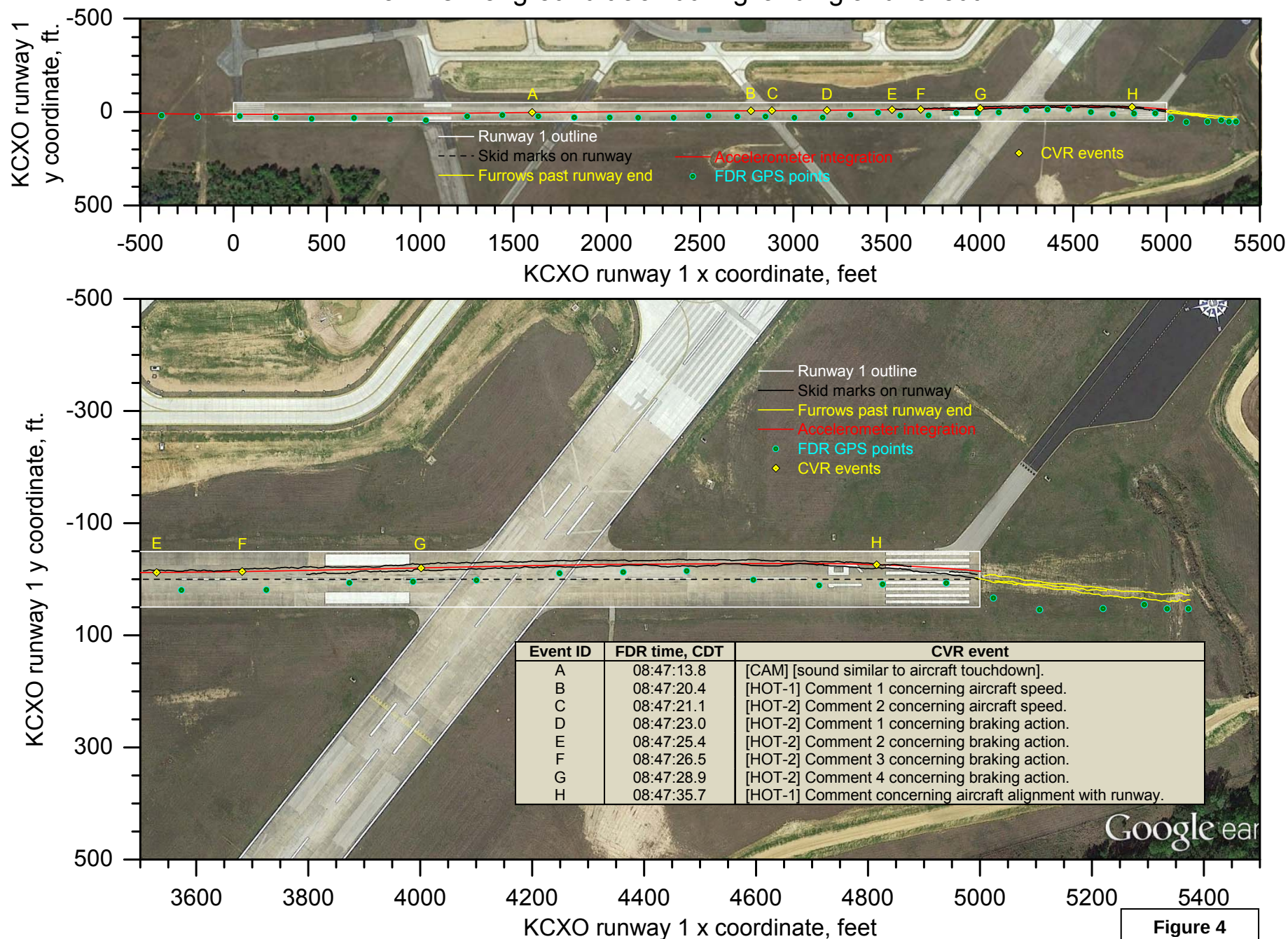


Figure 4



(a)



(b)



(c)



(d)



(e)

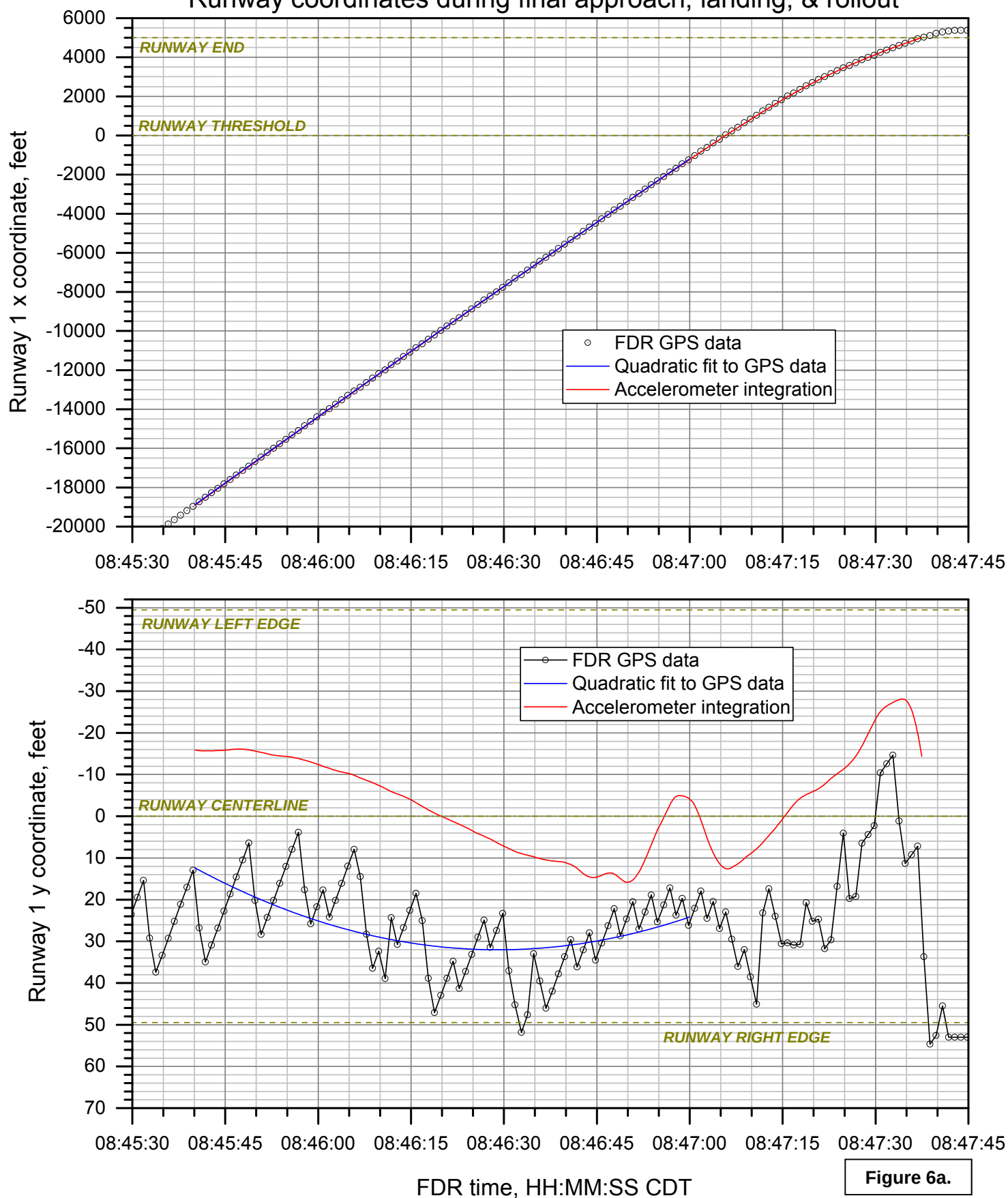


(f)

Figure 5. Photographs of tire scrub marks and furrows, and of airplane at rest past the end of the runway.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Runway coordinates during final approach, landing, & rollout



CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Runway coordinates during final approach, landing, & rollout (detail)

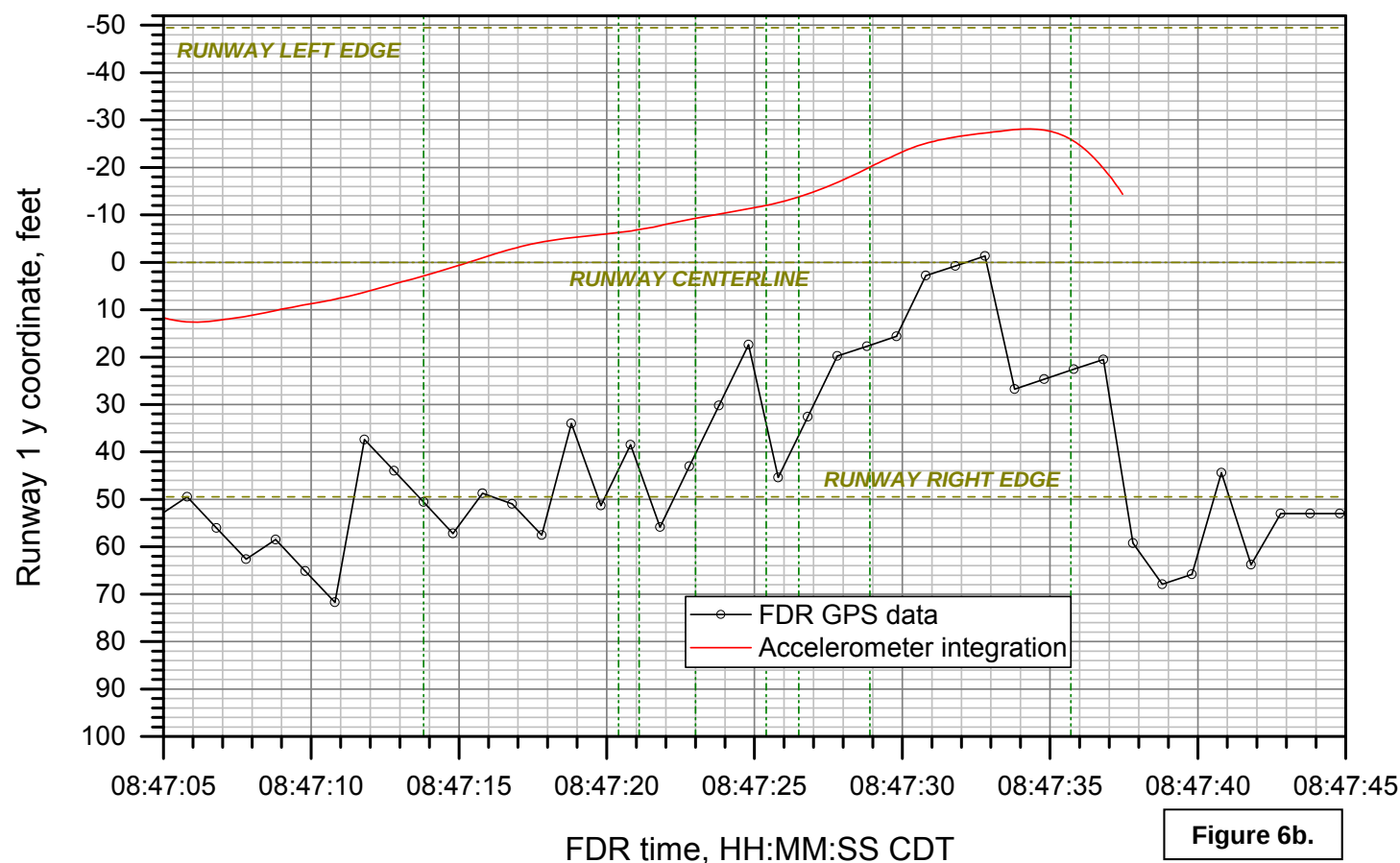
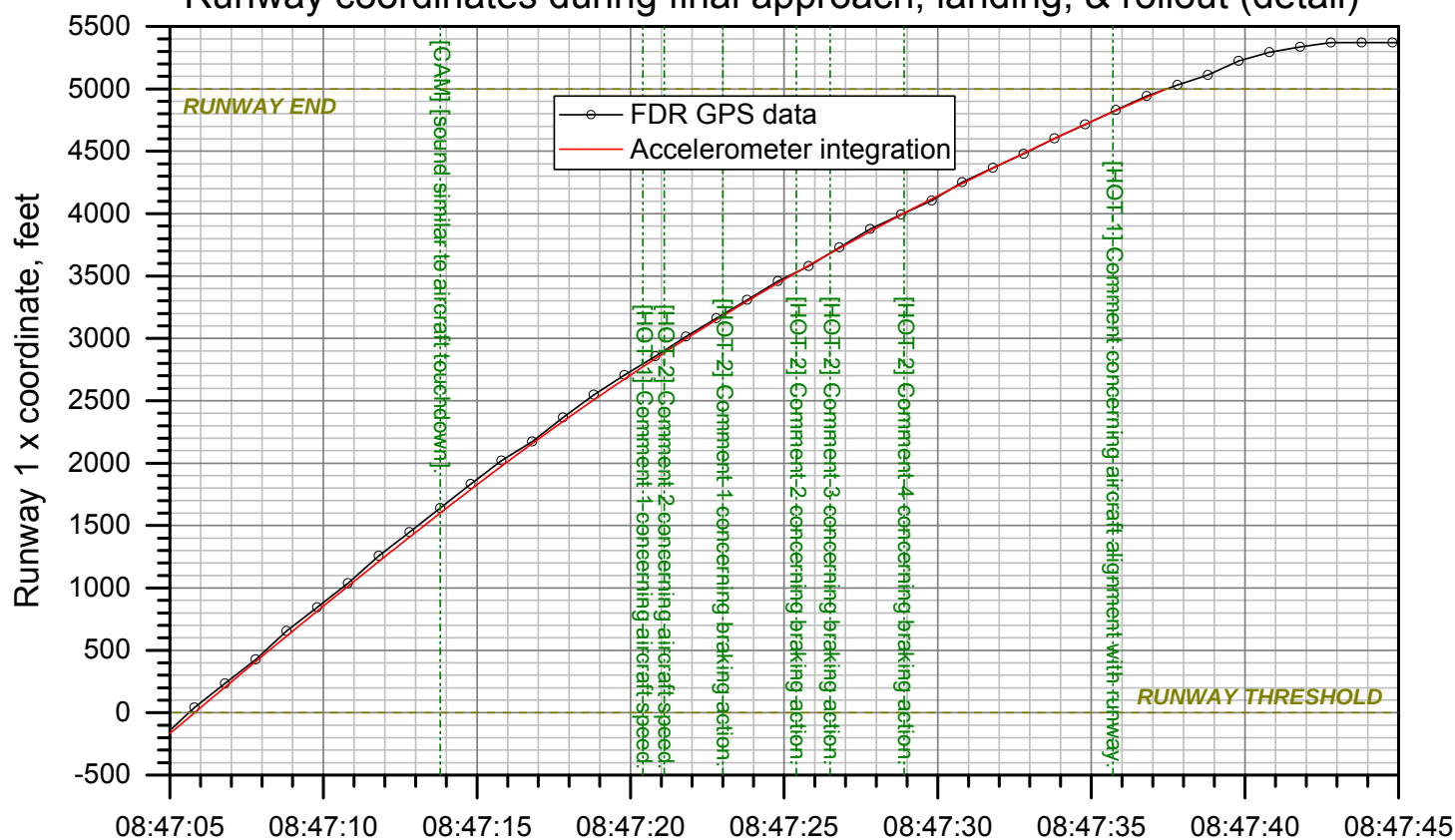


Figure 6b.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Speed & rate of climb during final approach, landing, & rollout

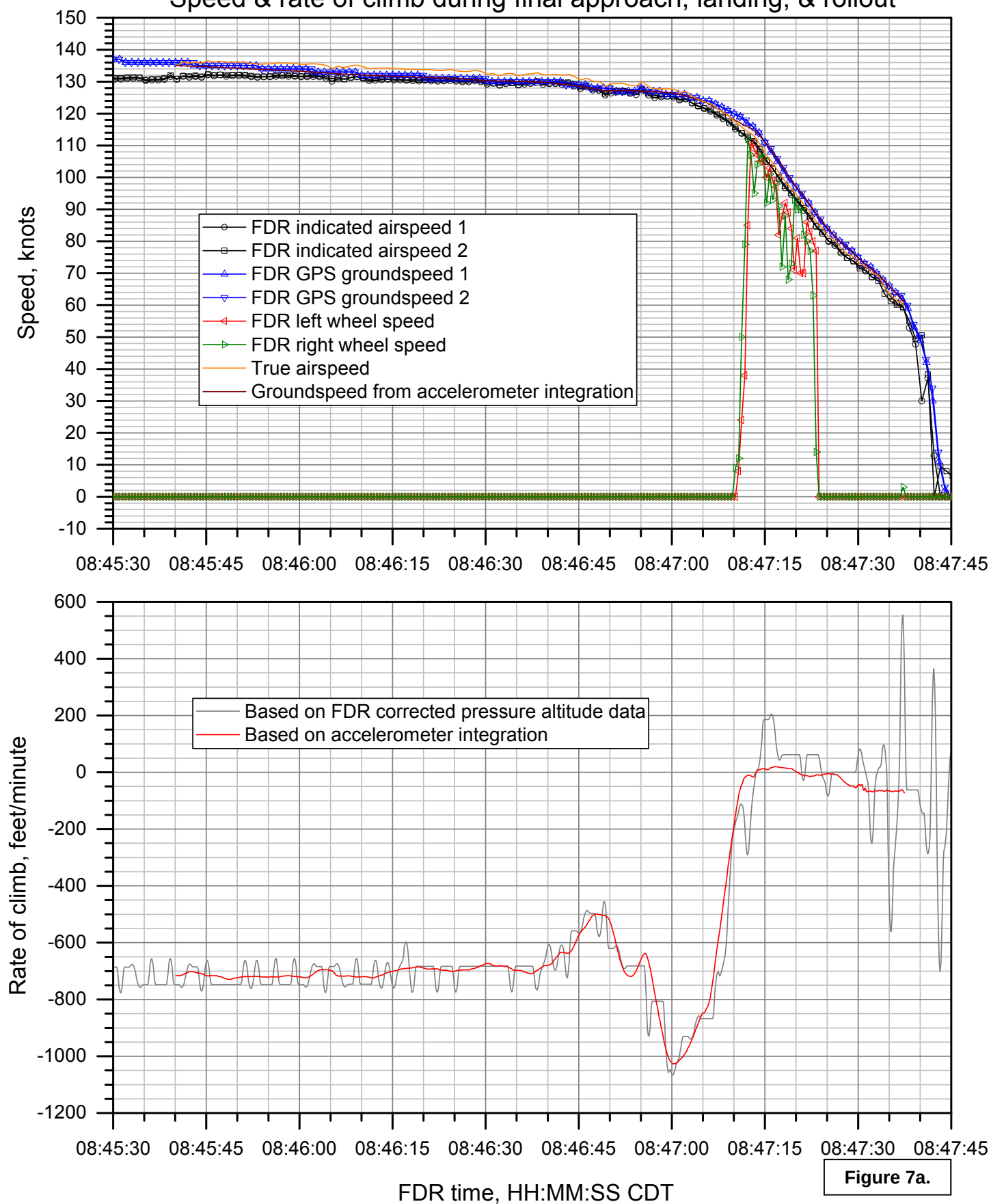


Figure 7a.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Speed & rate of climb during final approach, landing, & rollout (detail)

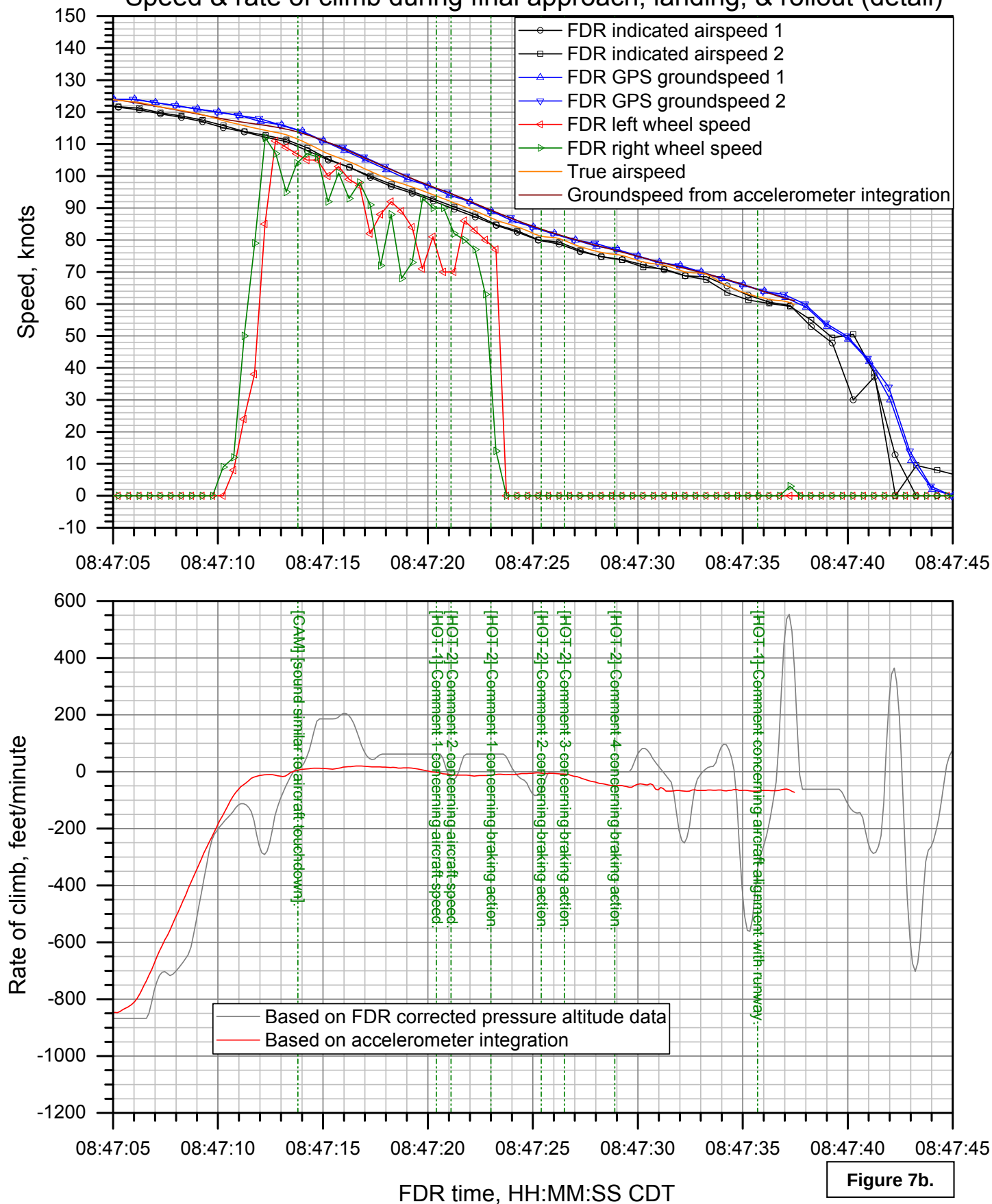
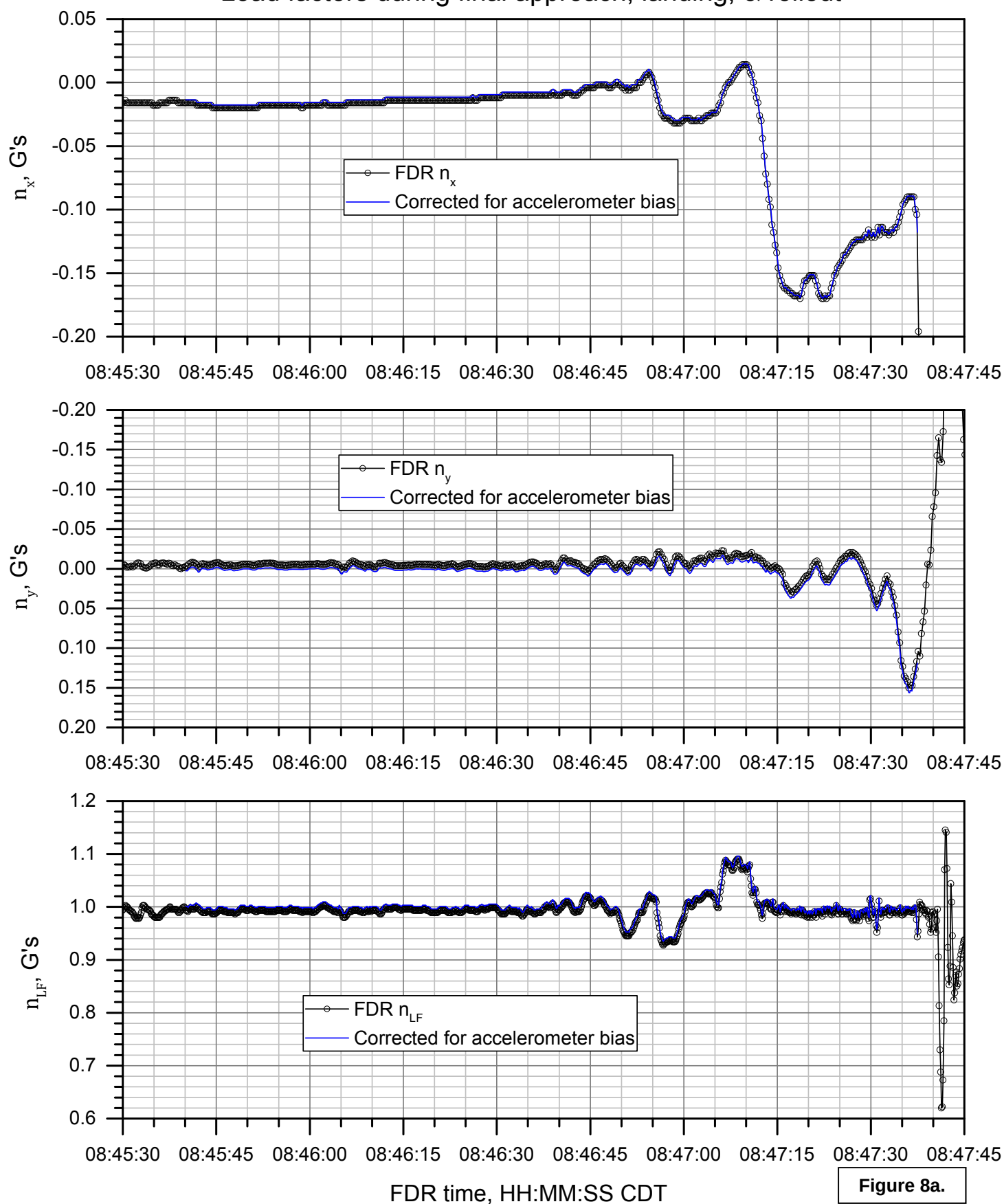


Figure 7b.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Load factors during final approach, landing, & rollout



CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Load factors during final approach, landing, & rollout (detail)

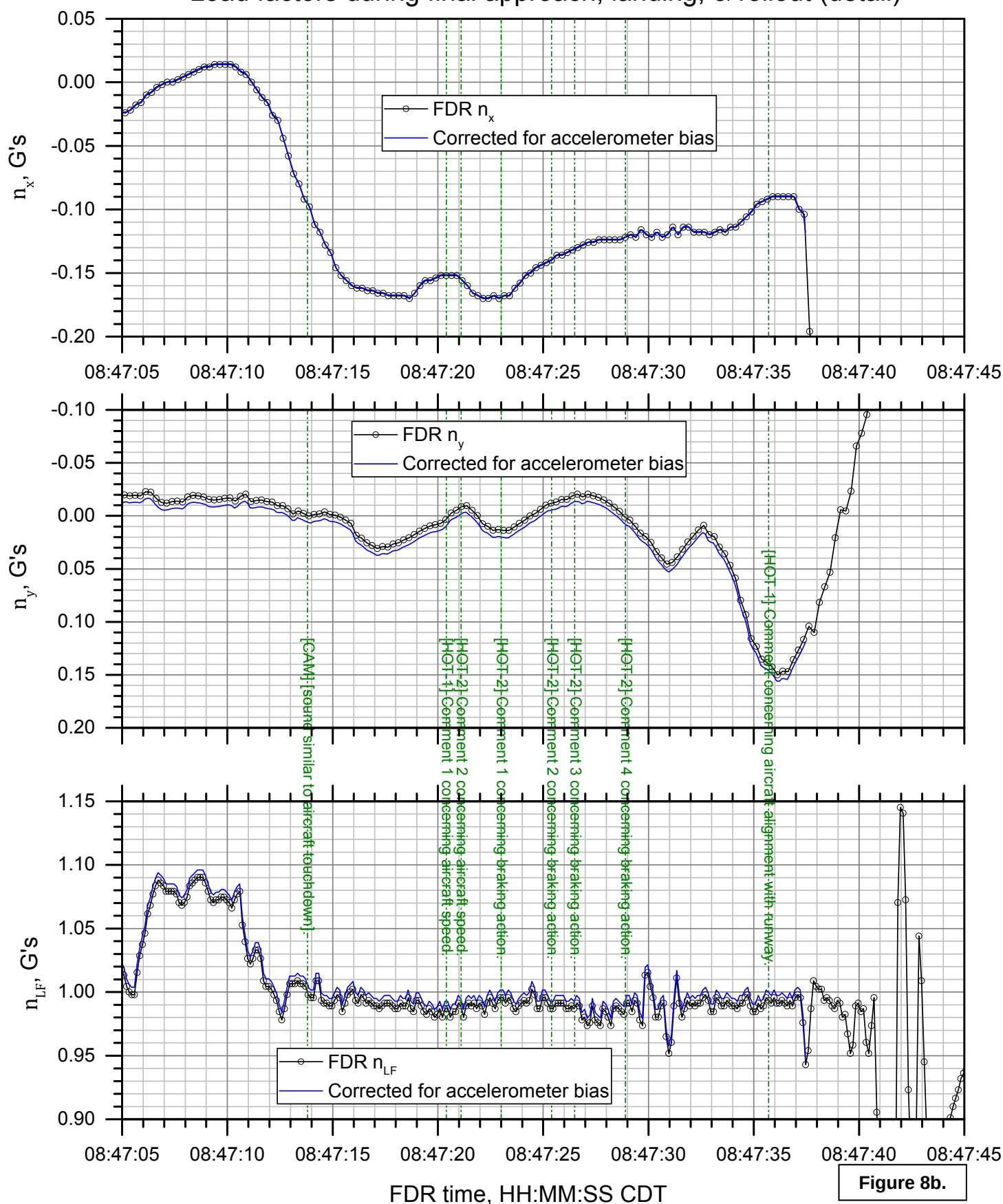
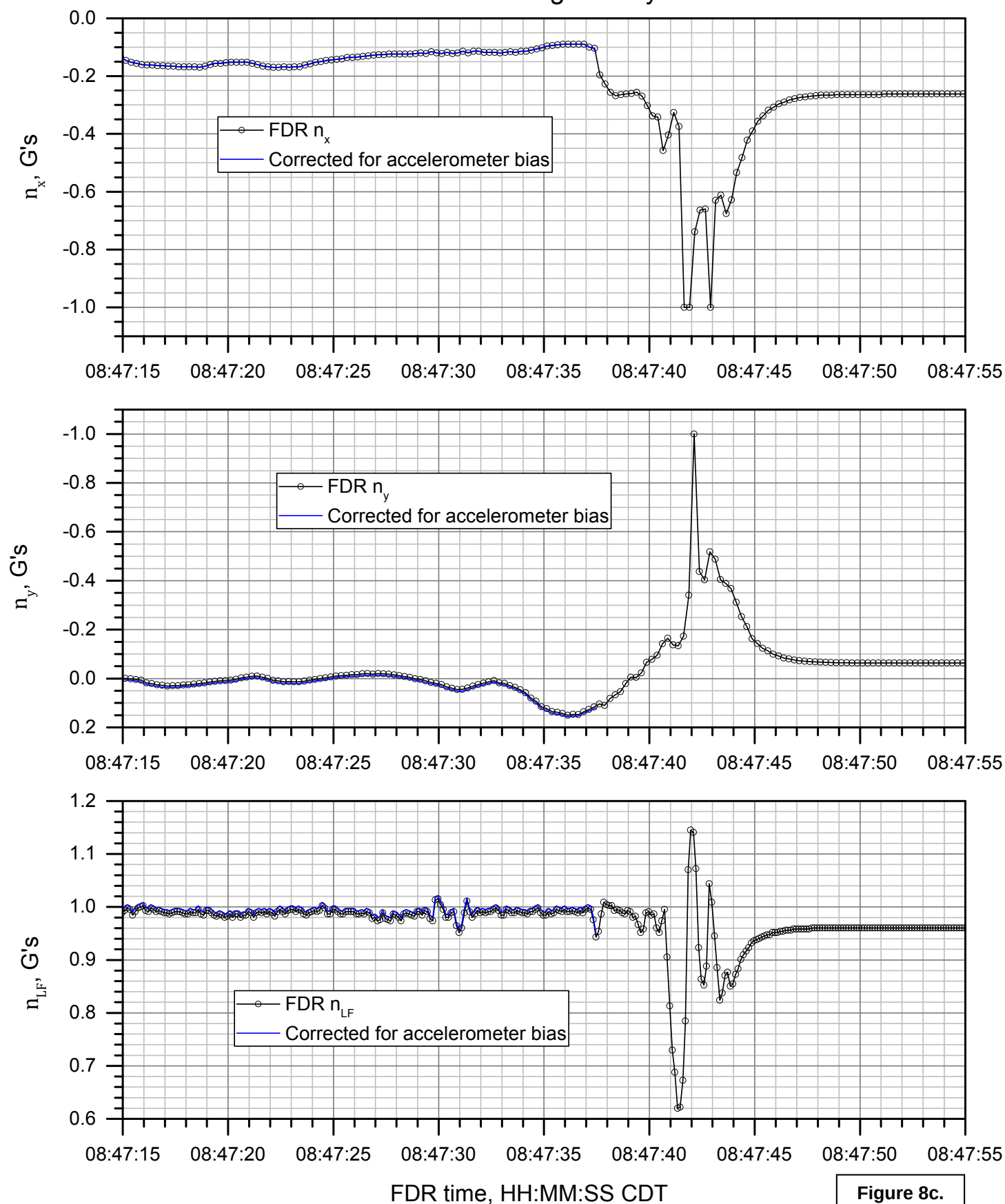


Figure 8b.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Load factors following runway excursion

**Figure 8c.**

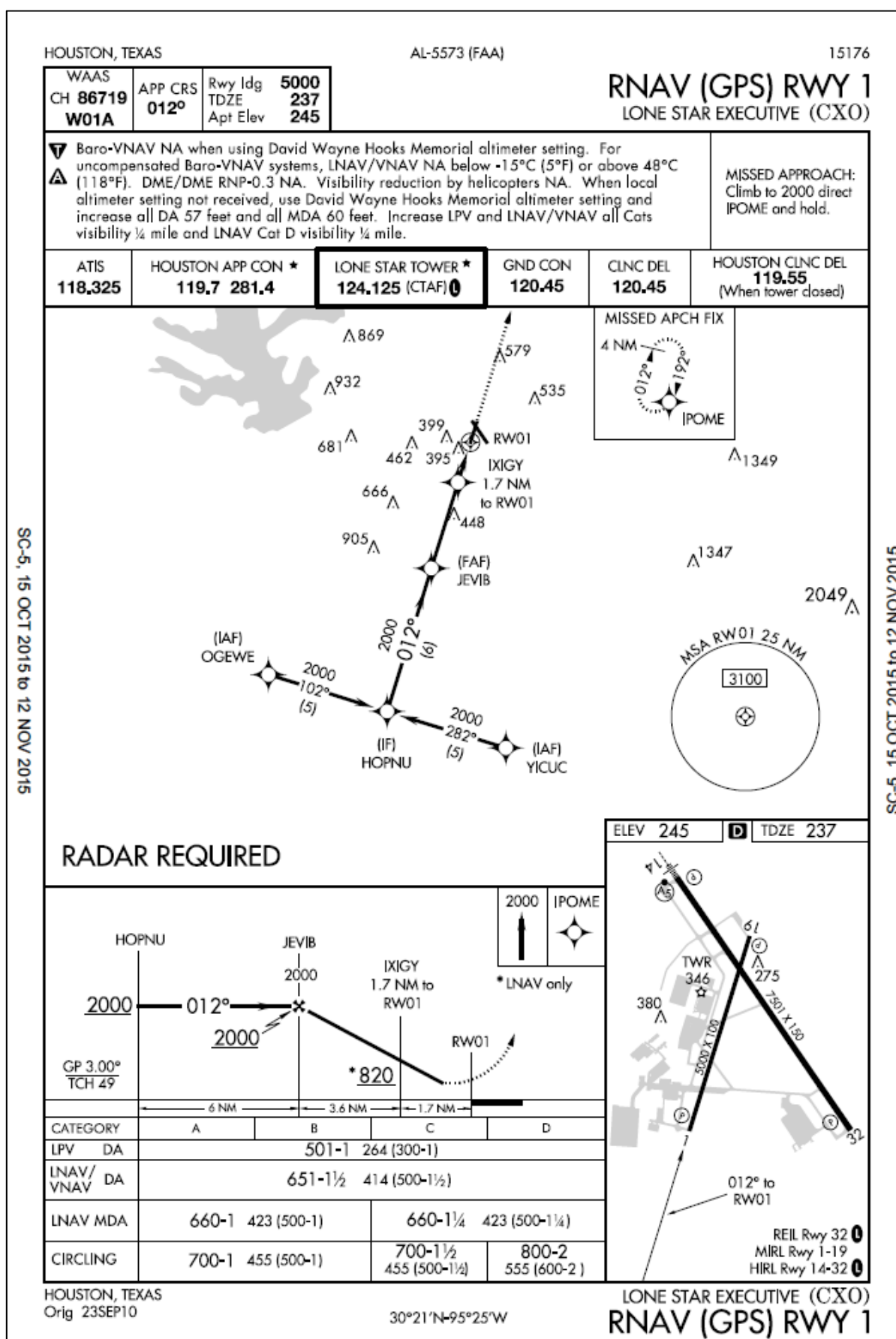


Figure 9.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Euler angles during final approach, landing, & rollout

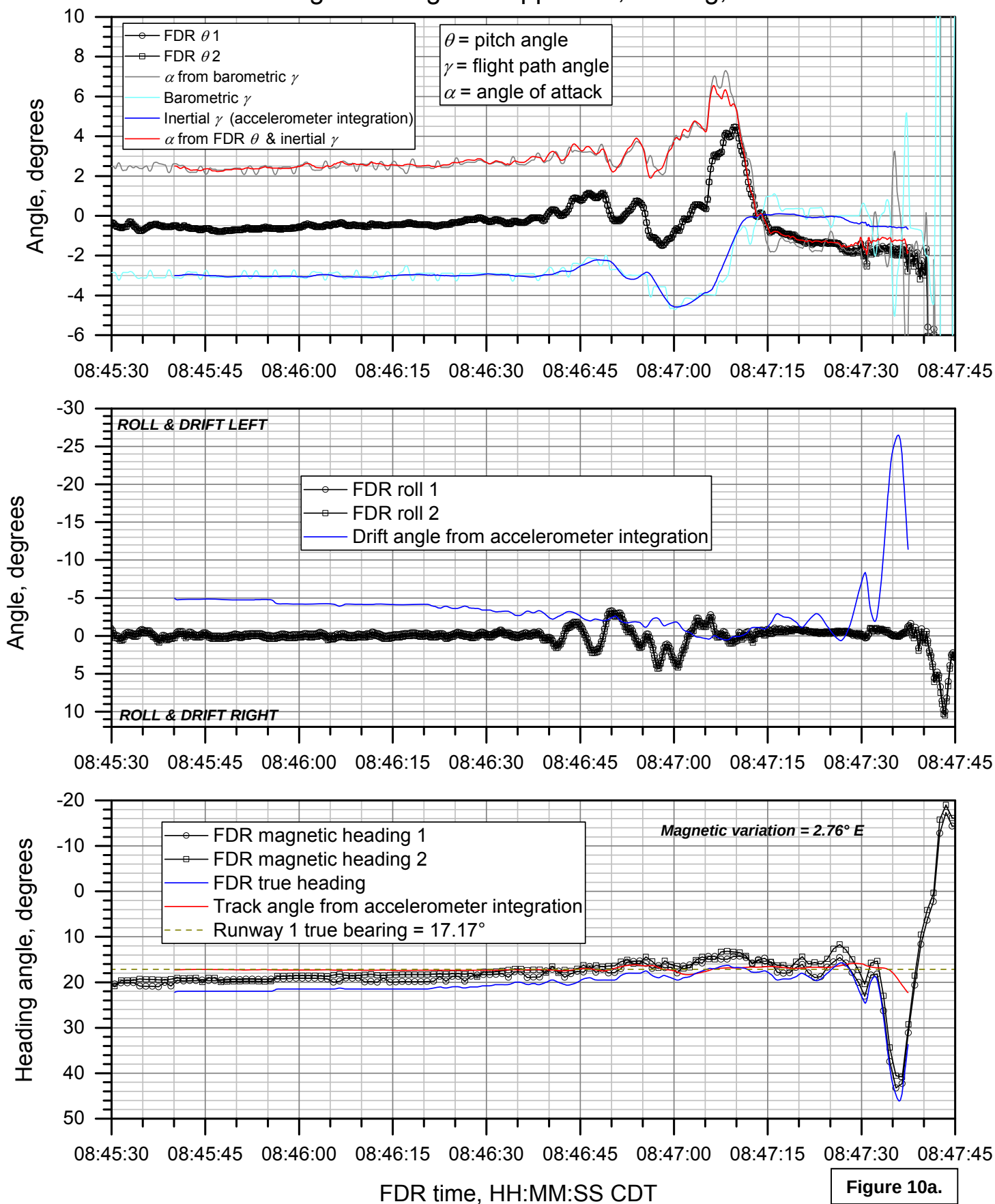


Figure 10a.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Euler angles during final approach, landing, & rollout (detail)

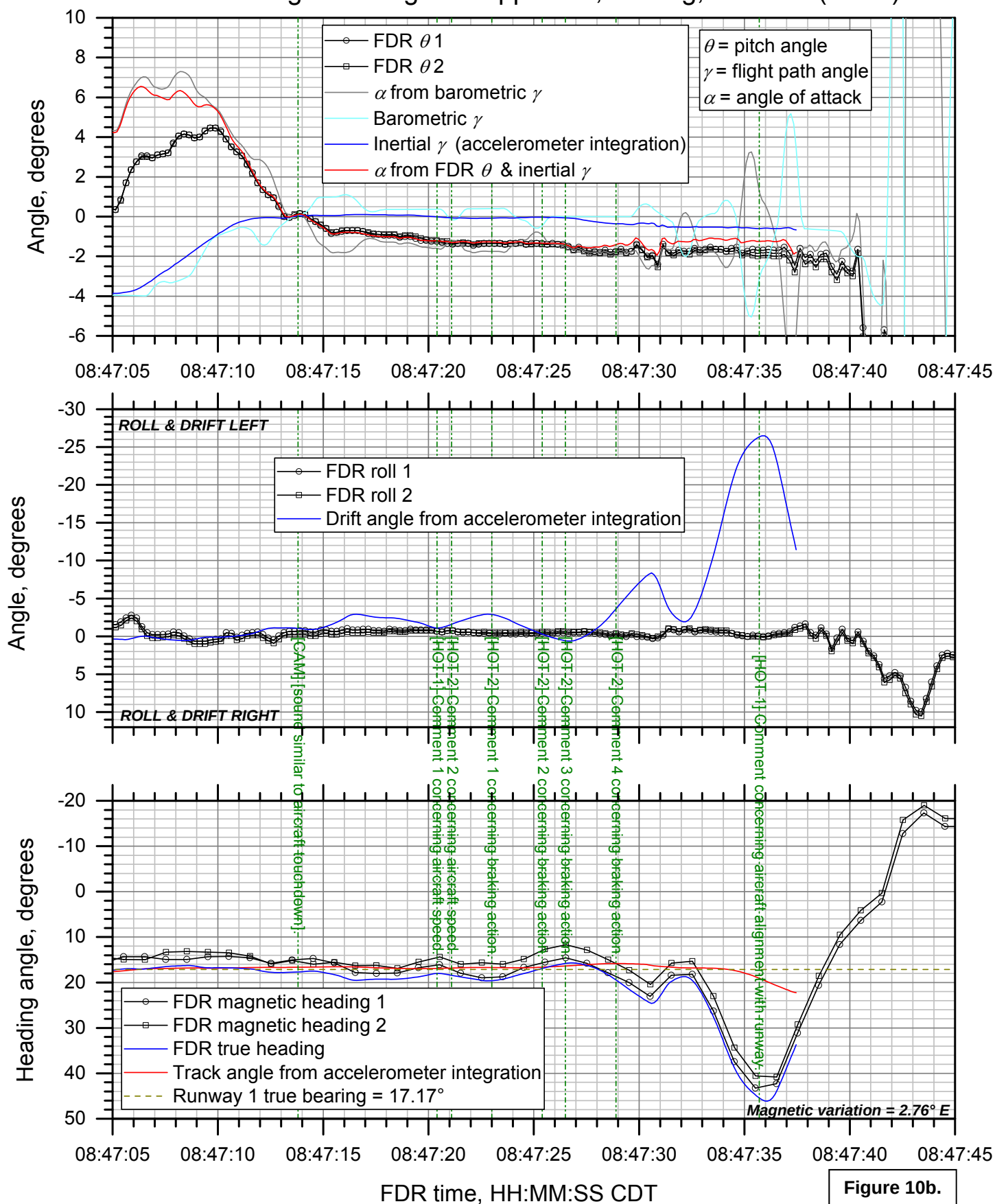


Figure 10b.

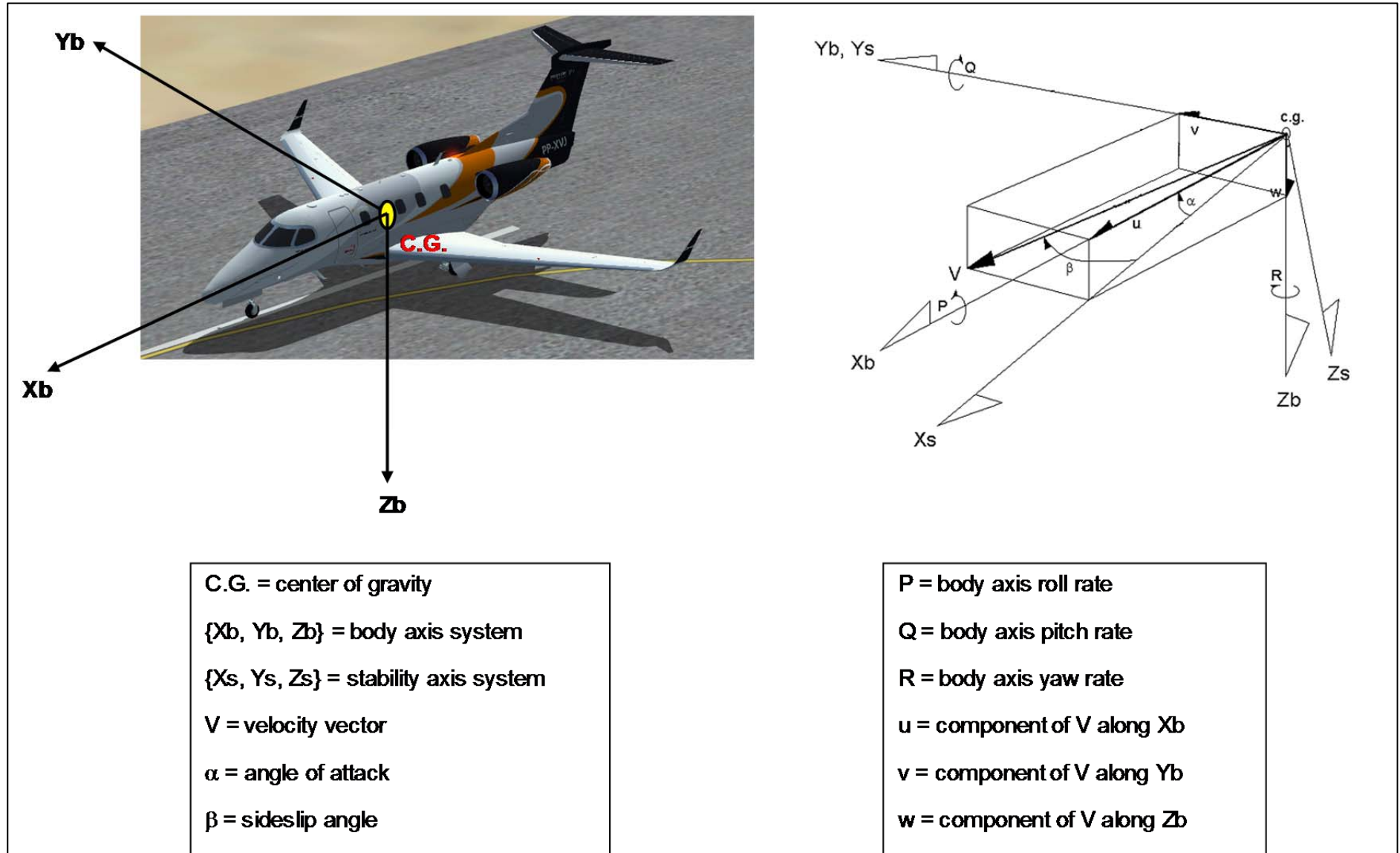
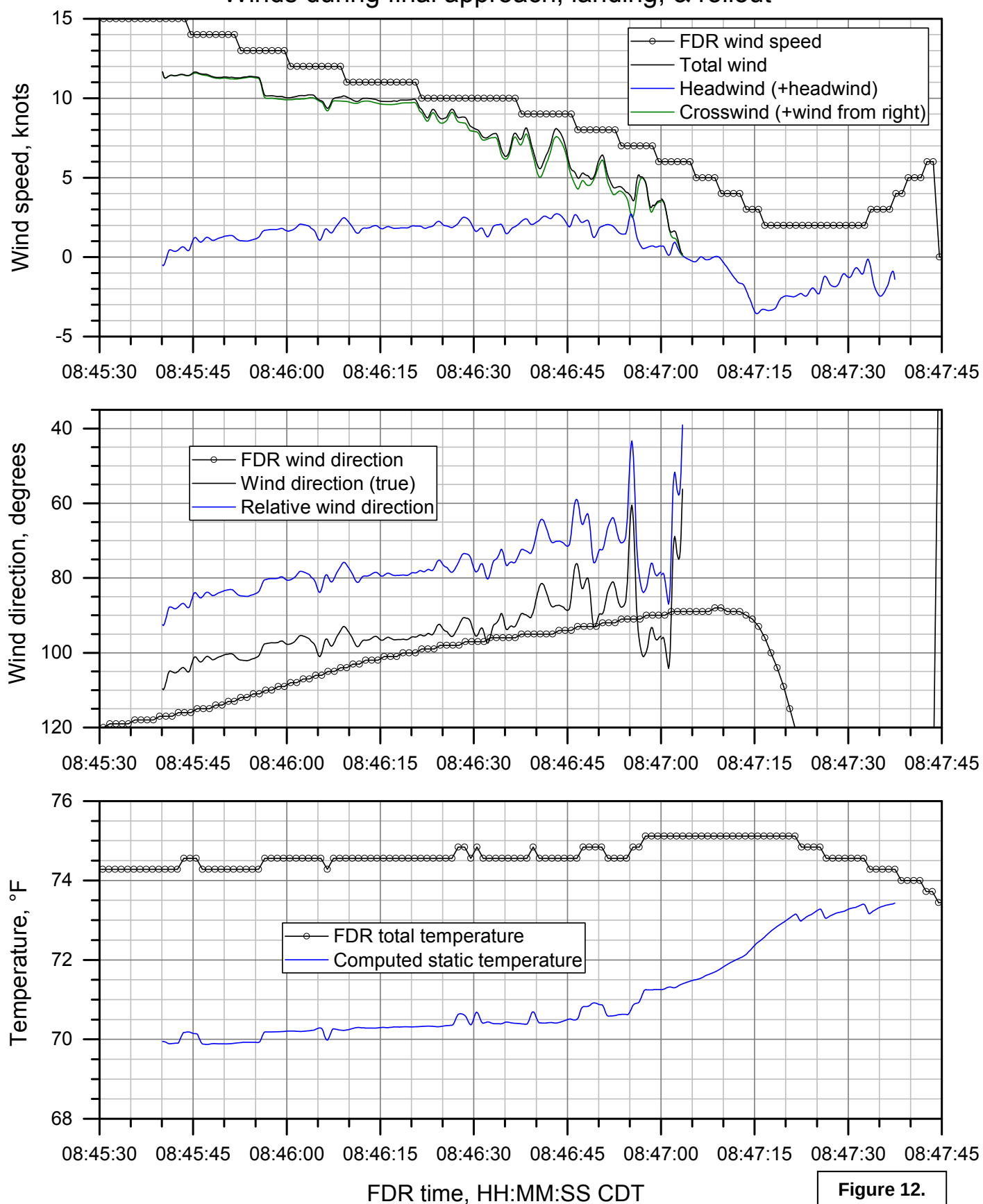


Figure 11.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Winds during final approach, landing, & rollout

**Figure 12.**

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Brake system parameters during rollout

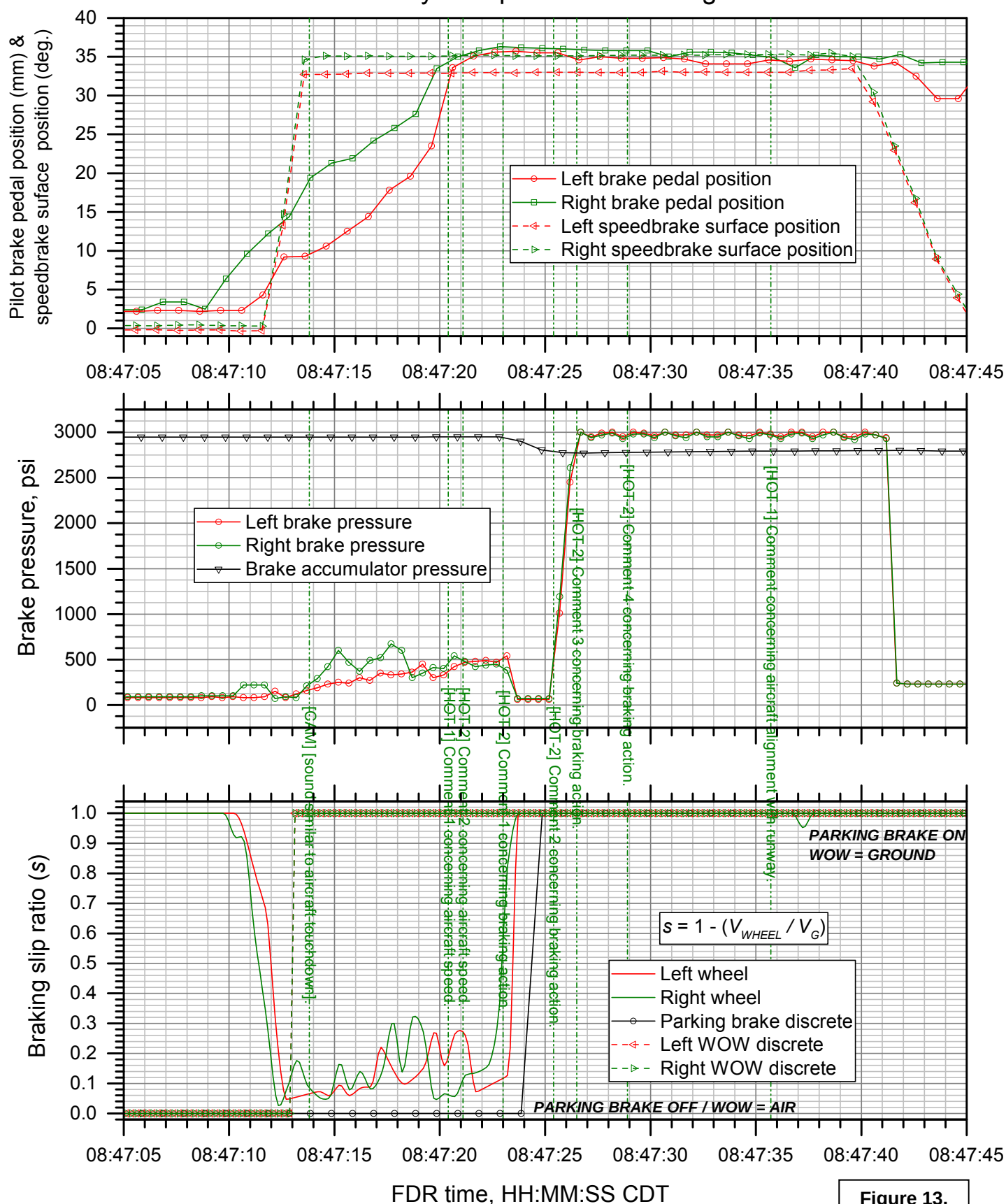


Figure 13.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Braking performance during rollout

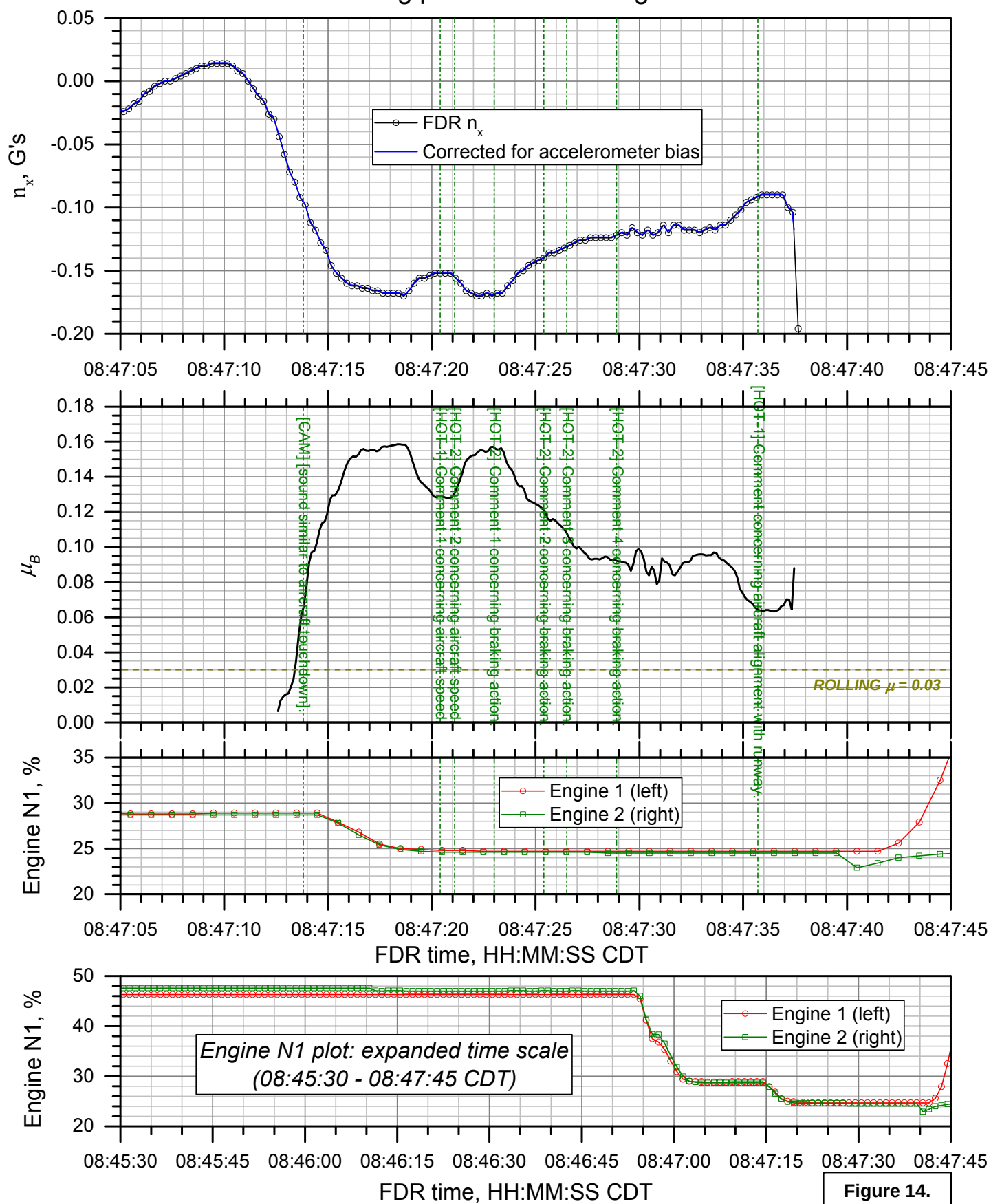


Figure 14.

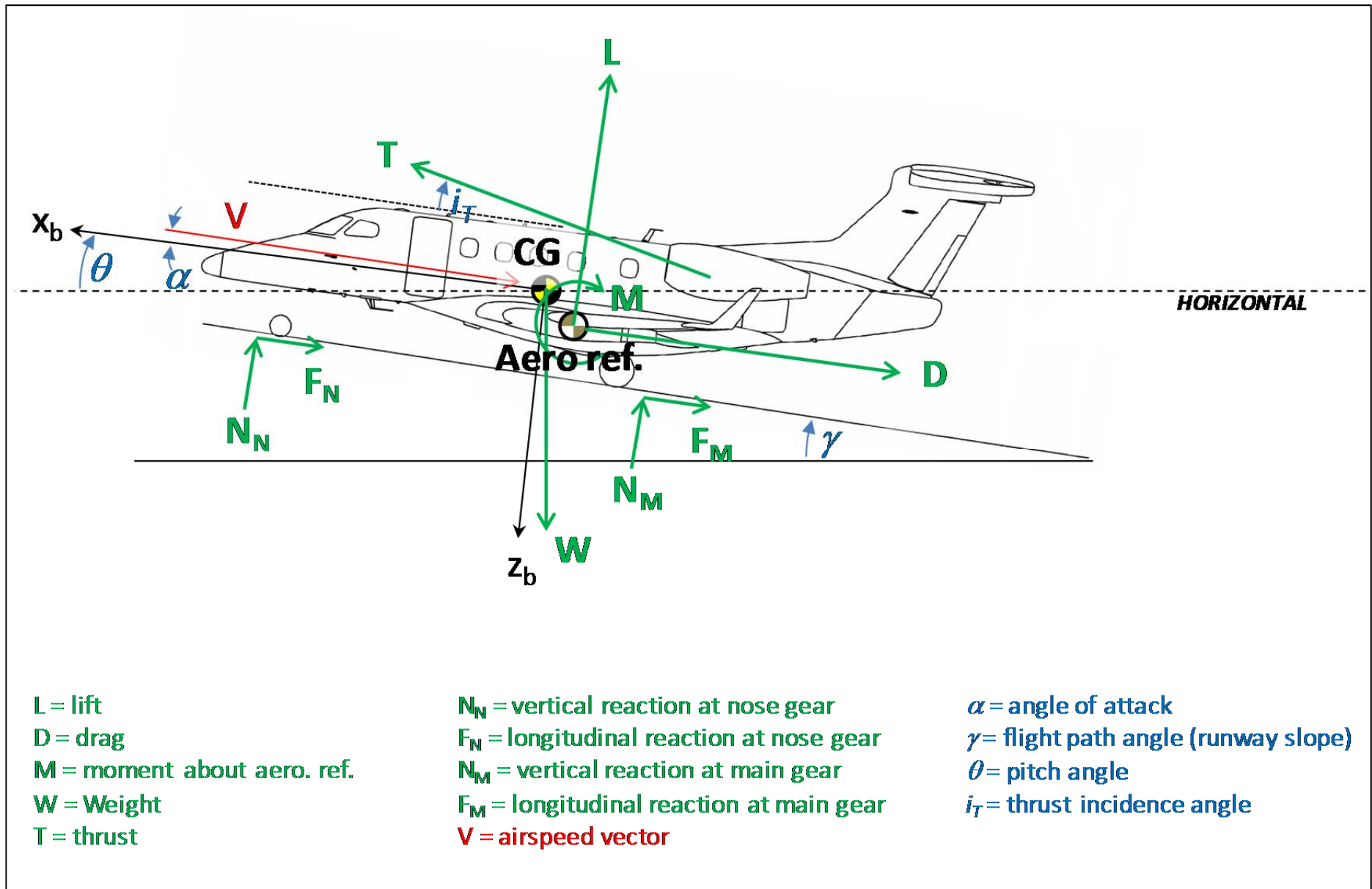


Figure 15. Free body diagram of forces on airplane during ground roll.

LANDING DISTANCE FOR WET RUNWAYS			
MINIMUM REQUIRED RUNWAY LENGTH (ft)			
UNFACTORED LANDING DISTANCE		FACTORED LANDING DISTANCE	
DRY	WET	DRY	WET
1800	2250	3006	3450
2000	2500	3340	3833
2200	2750	3674	4217
2400	3000	4008	4600
2600	3250	4342	4983
2800	3500	4676	5367
3000	3750	5010	5750
3200	4000	5344	6133
3400	4250	5678	6517
3600	4500	6012	6900
3800	4750	6346	7283
4000	5000	6680	7667
4200	5250	7014	8050
4400	5500	7348	8433
4600	5750	7682	8817
4800	6000	8016	9200

Figure 16. EMB-505 landing distance corrections for wet runways, from Reference 4.

CORRECTED LANDING DISTANCE (ft) STANDING WATER COVERED RUNWAY ICE PROTECTION (WINGSTAB+ENG) OFF/ON LANDING FLAP 3			
UNFACTORED LANDING DISTANCE DRY (ft)	STANDING WATER DEPTH (in)		
	0.125	0.250	0.375
1800	3472	3472	3472
2000	3856	3856	3856
2200	4240	4240	4240
2400	4624	4624	4624
2600	5148	5008	5008
2800	5733	5392	5392
3000	6318	5776	5776
3200	6981	6235	6160
3400	7647	6762	6544
3600	8240	7262	6928
3800	8833	7763	7312
4000	9426	8264	7696
4200	10020	8765	8080
4400	10613	9266	8464
4600	11206	9766	8848
4800	11799	10267	9232

Figure 17. EMB-505 landing distance corrections for runways contaminated with standing water, from Reference 4.

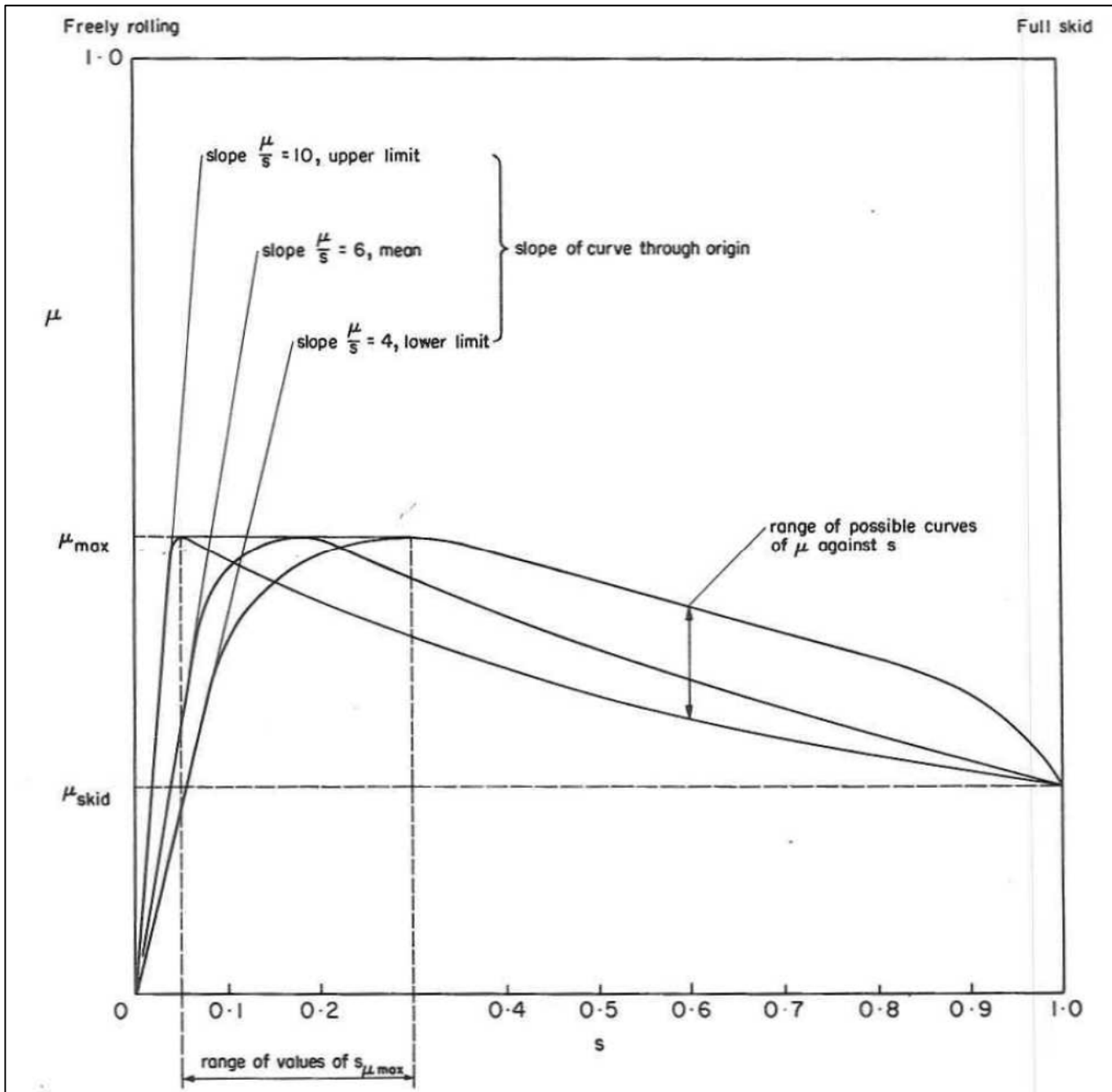


Figure 18. Plot of braking coefficient μ_B vs. wheel slip ratio s , from Reference 19.

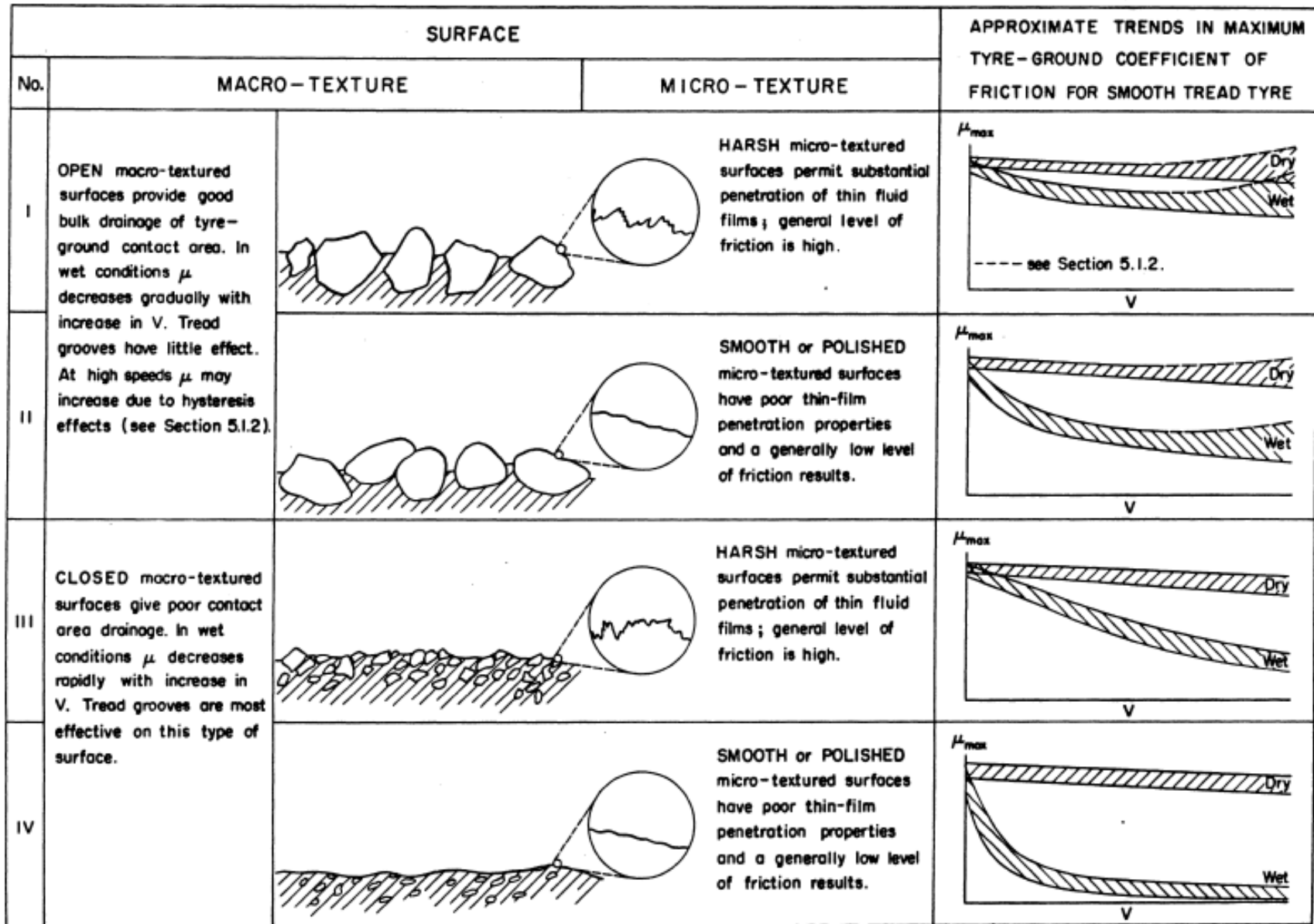


Figure 19. Effect of surface texture on μ_B , from Reference 18.

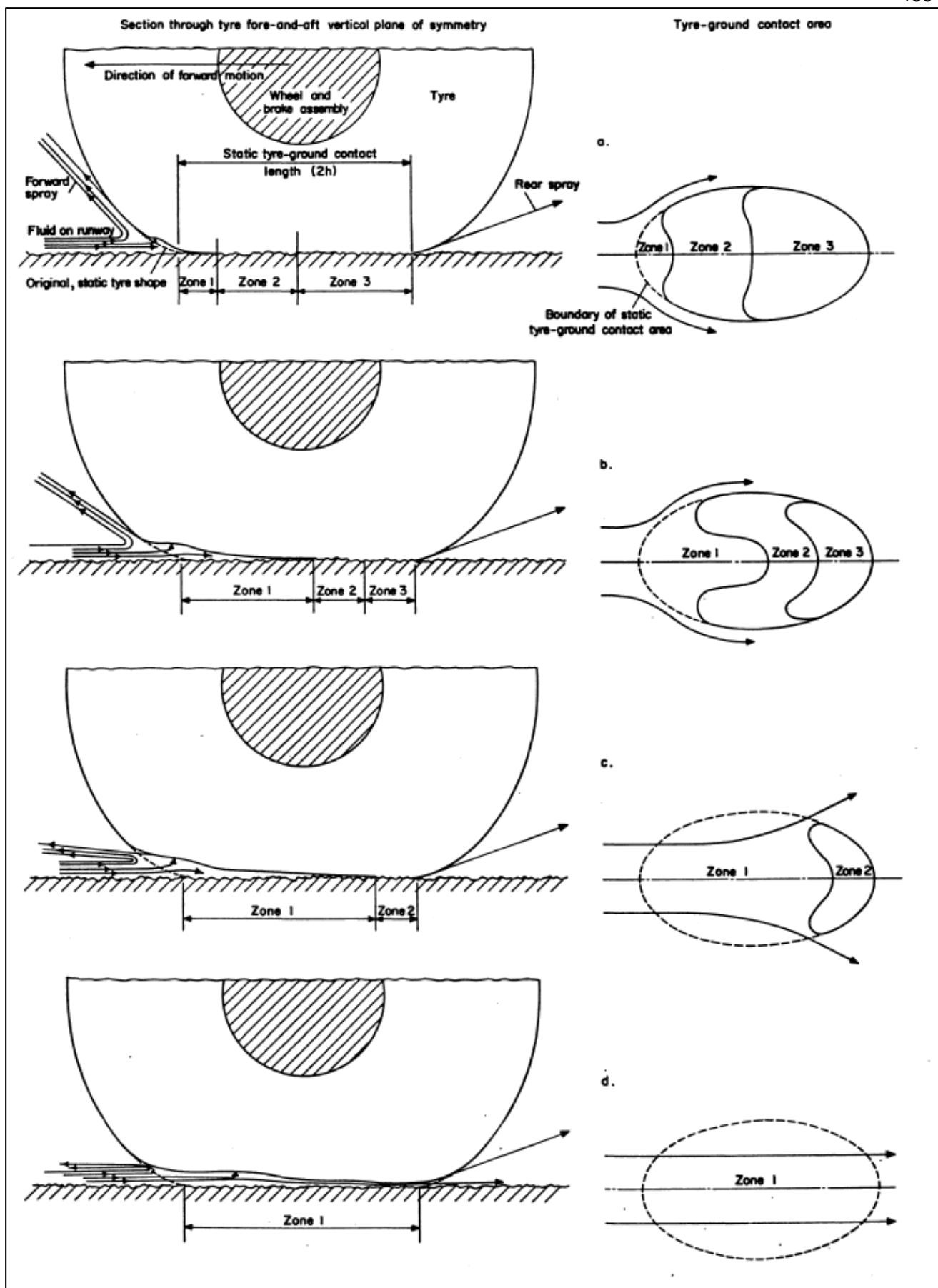


Figure 20. Effect of forward speed on the tyre-ground contact area in wet conditions, from Reference 18.

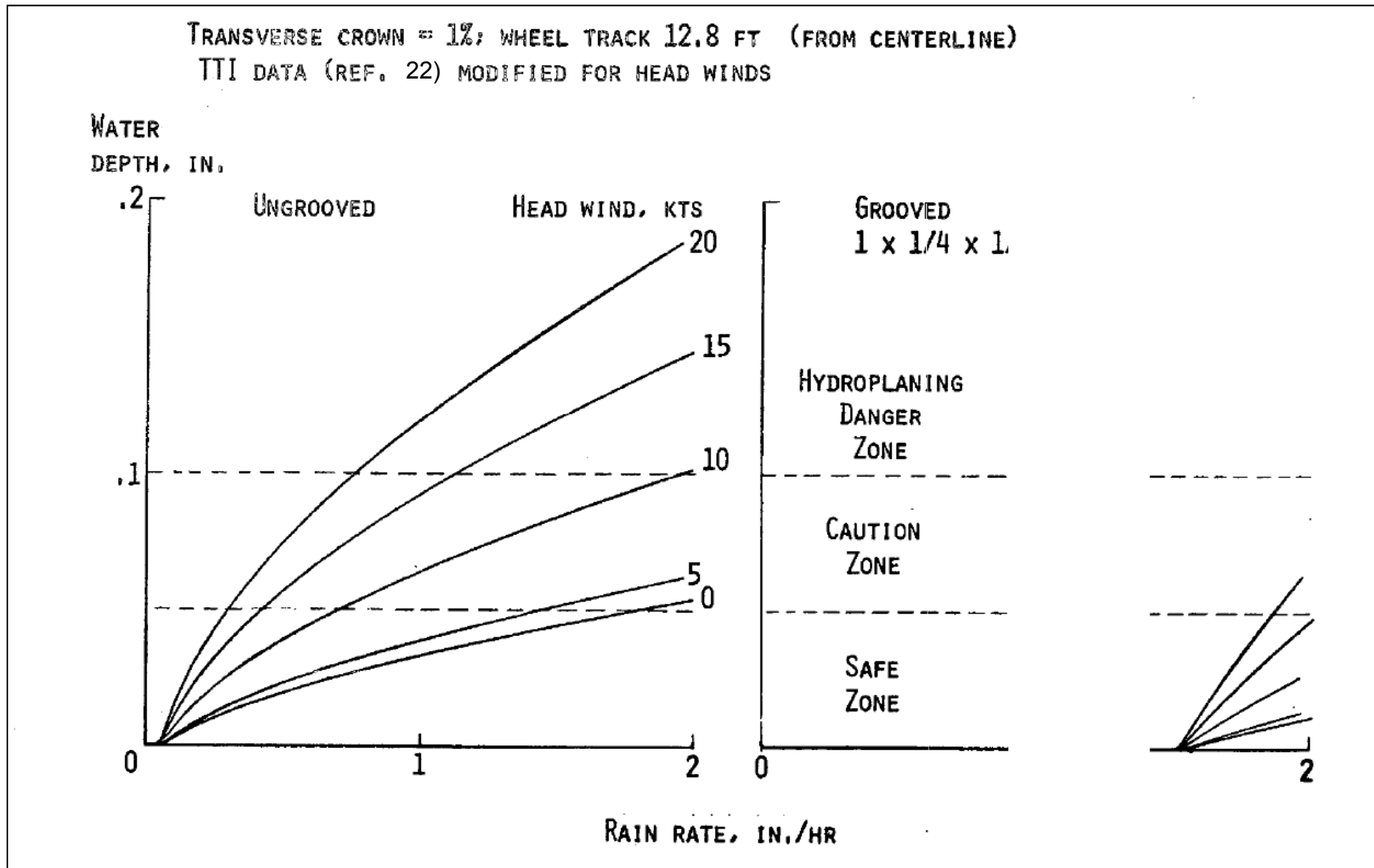


Figure 21. Runway hydroplaning potential during rainstorms, from Reference 21.



(a)

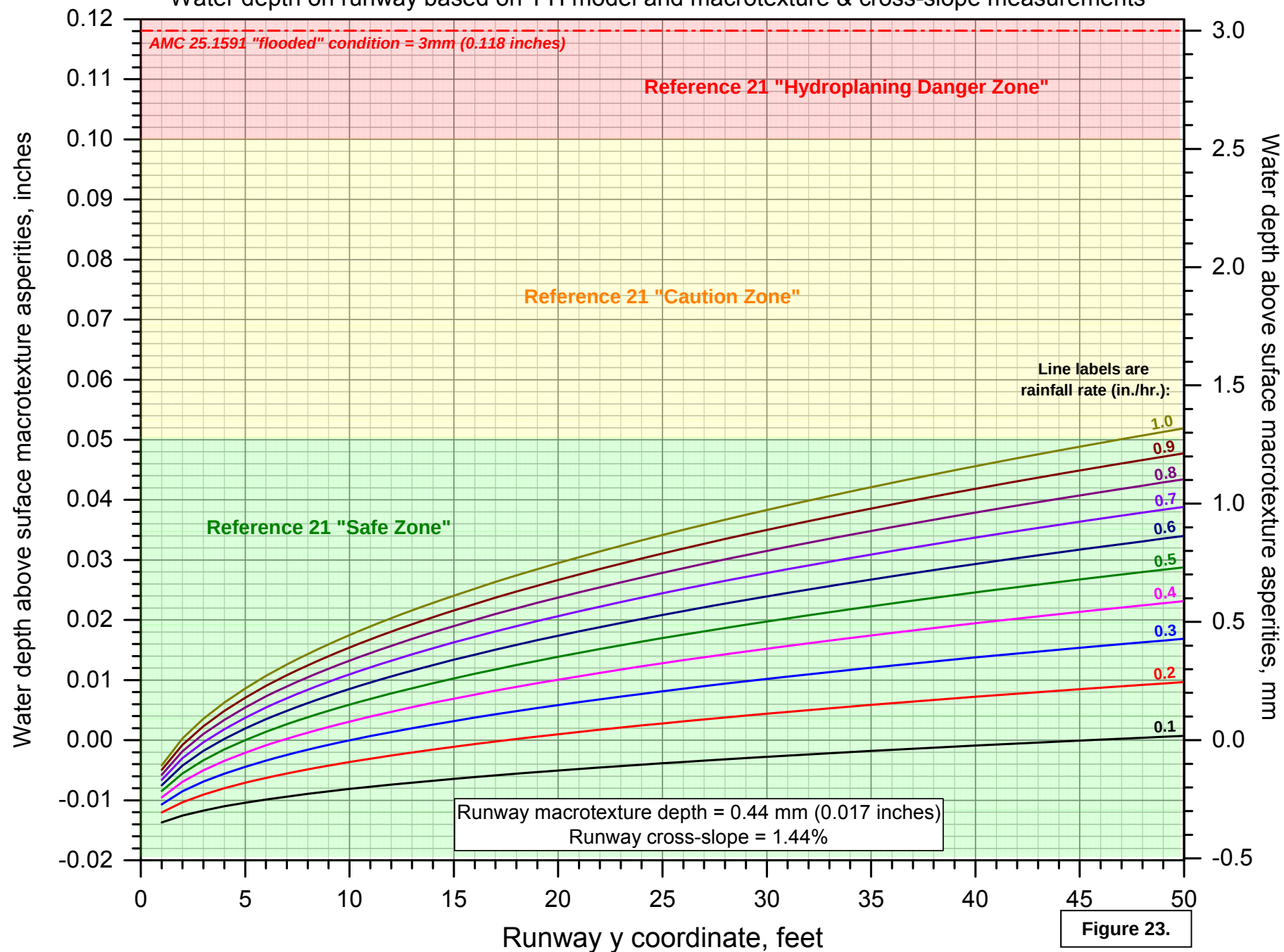


(b)

Figure 22. Post-accident photographs of (a) left main gear tire, and (b) right main gear tire, showing evidence of reverted rubber in the skid patch.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Water depth on runway based on TTI model and macrotexture & cross-slope measurements



CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Distance from threshold and μ_B vs. ground speed: accident scenario

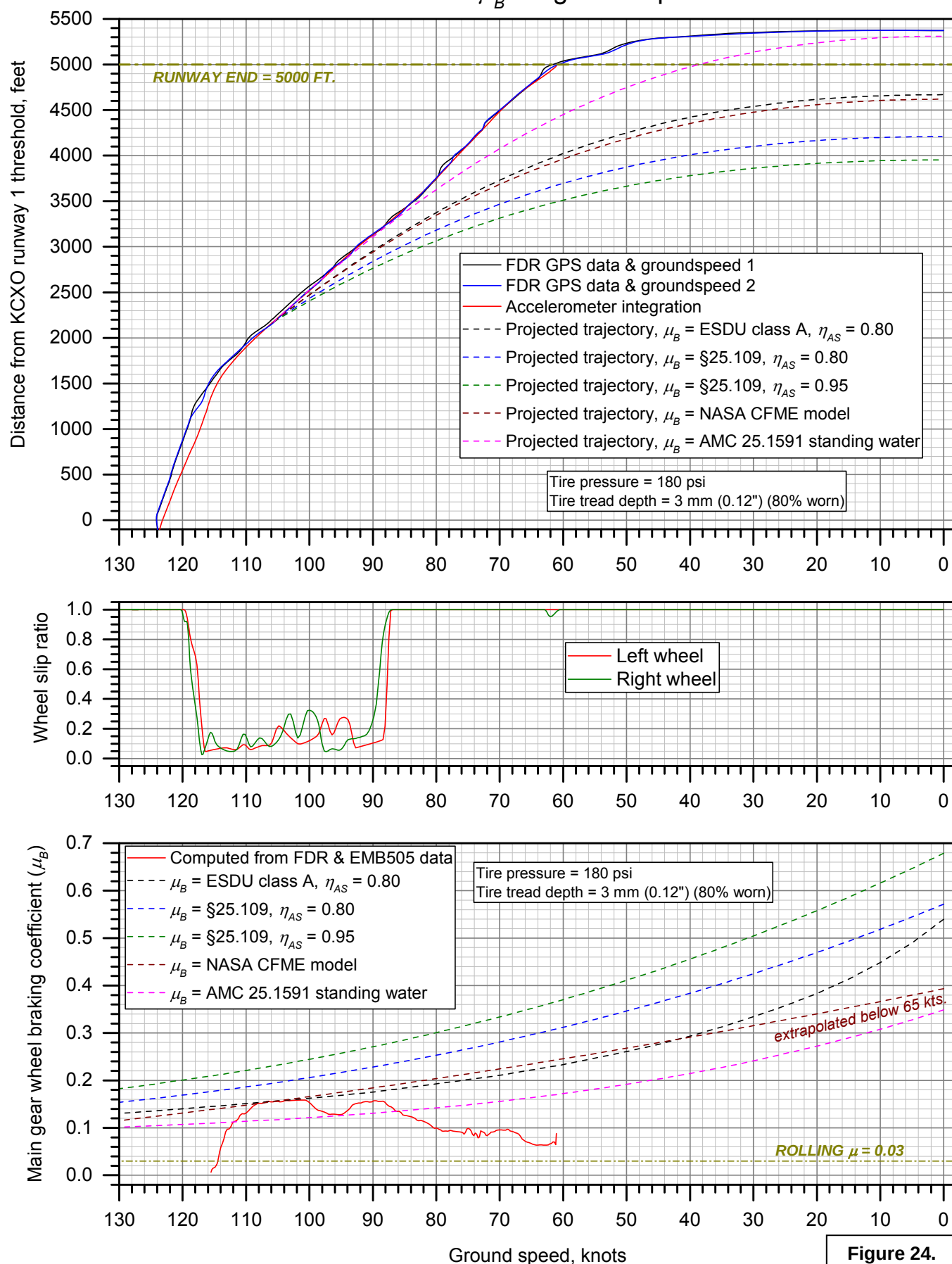
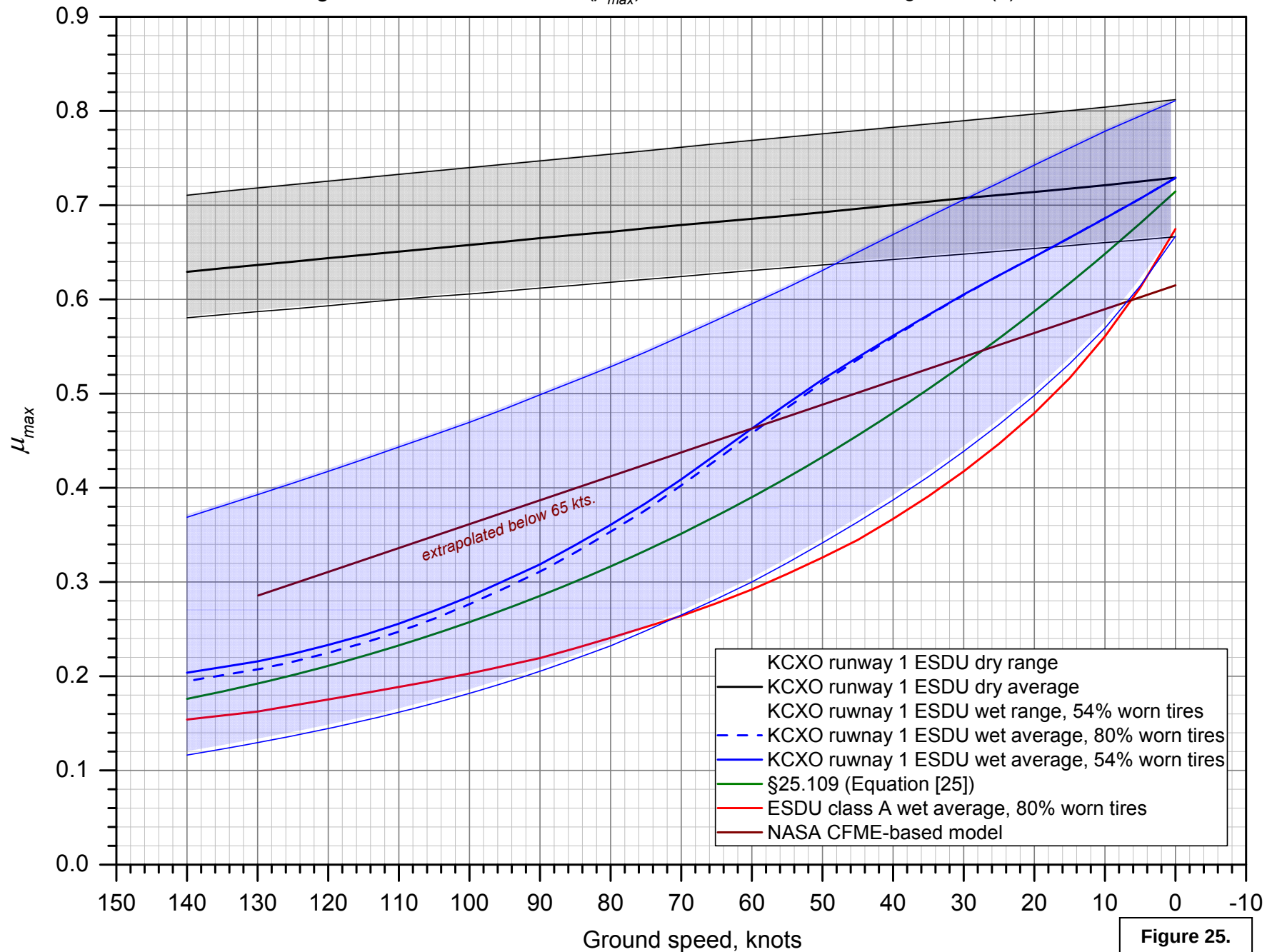


Figure 24.

Maximum tire-to-ground friction coefficient (μ_{max}) based on ESDU 71026, §25.109(c), and NASA models



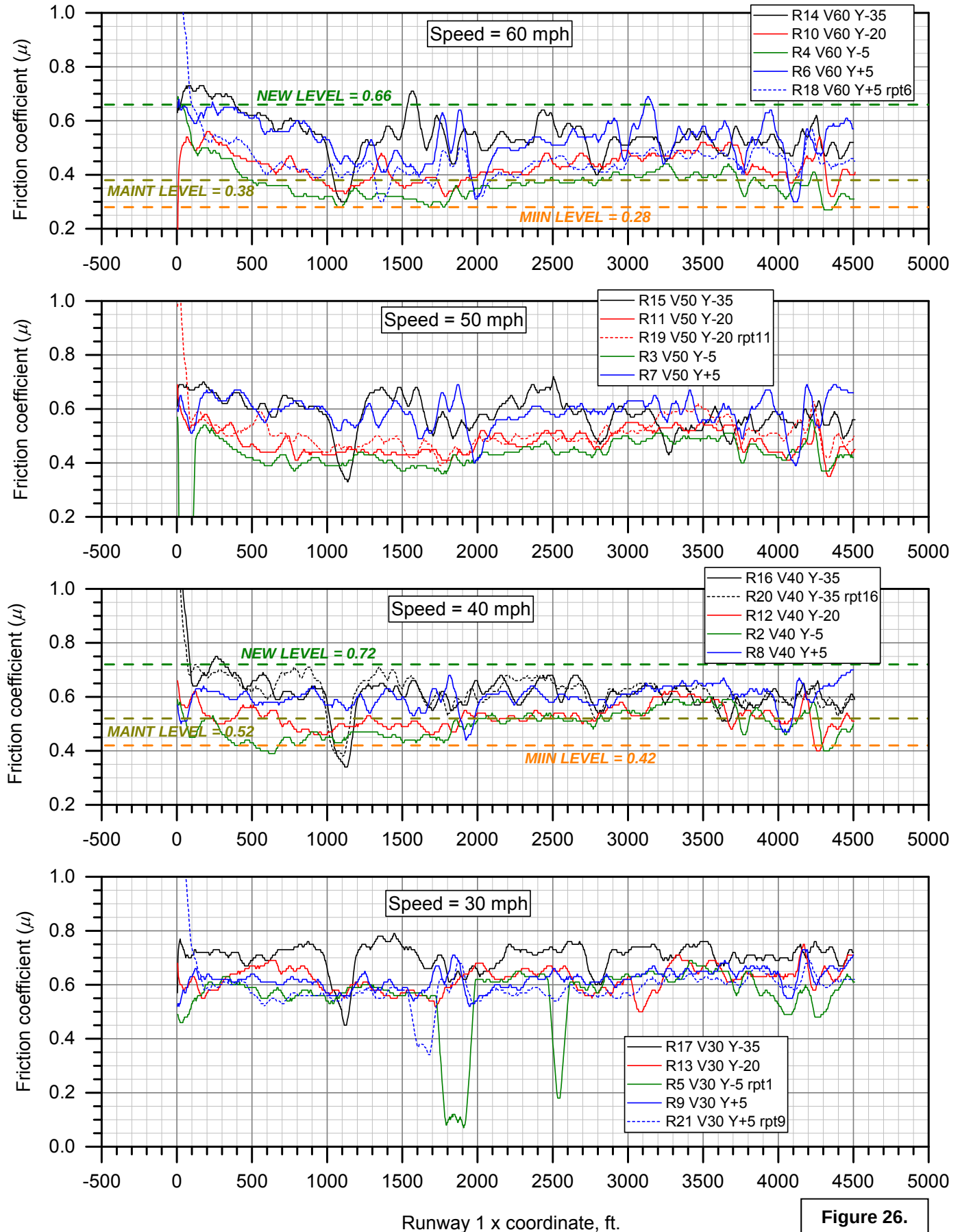
DFT friction coefficient (μ) measurement results: μ vs. x 

Figure 26.

KCXO runway 1 examination, 05/05/2015
DFT friction coefficient (μ) measurement results: μ vs. speed

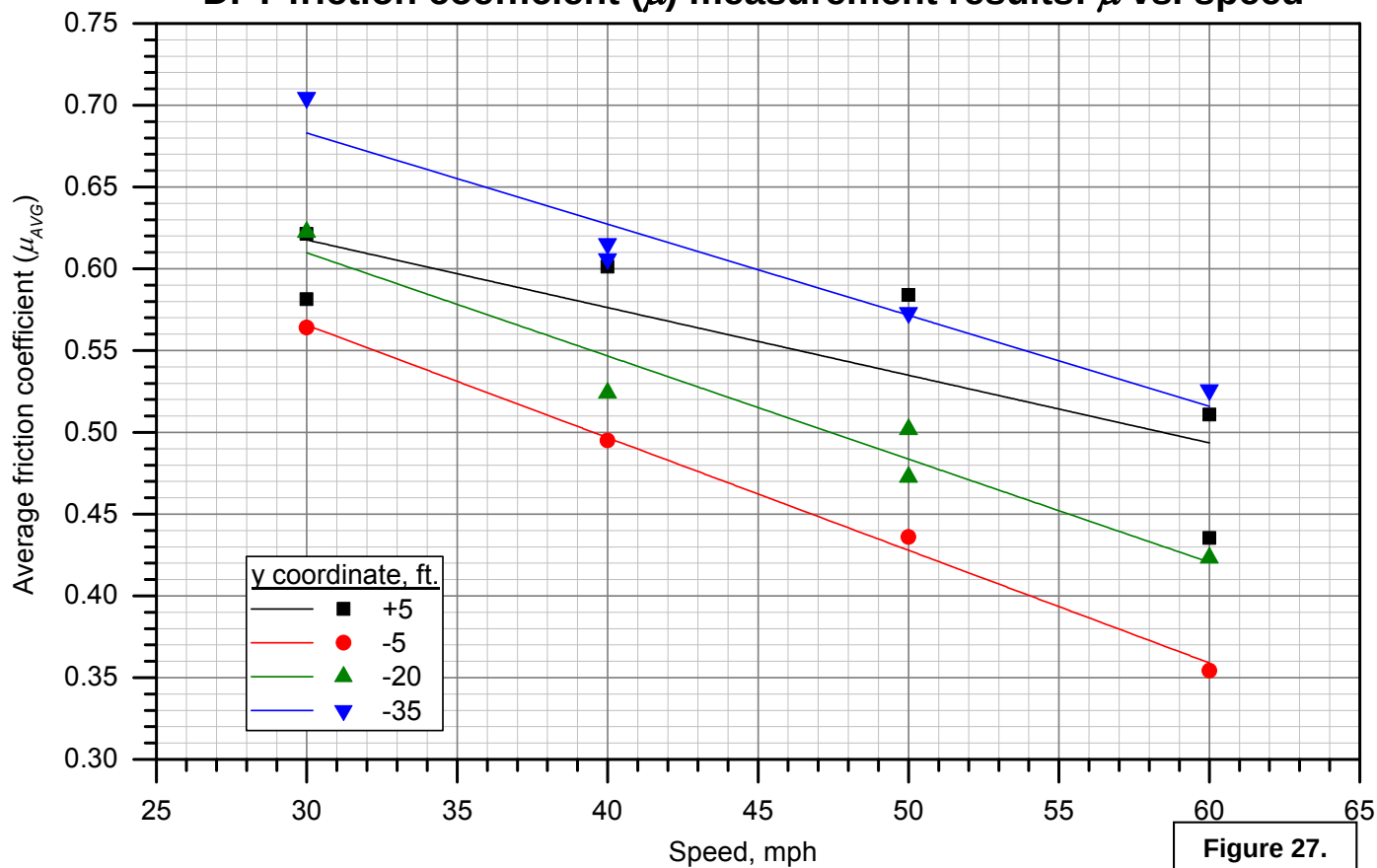


Figure 27.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014
Anti-skid system efficiency based on §25.109 & NASA CFME model

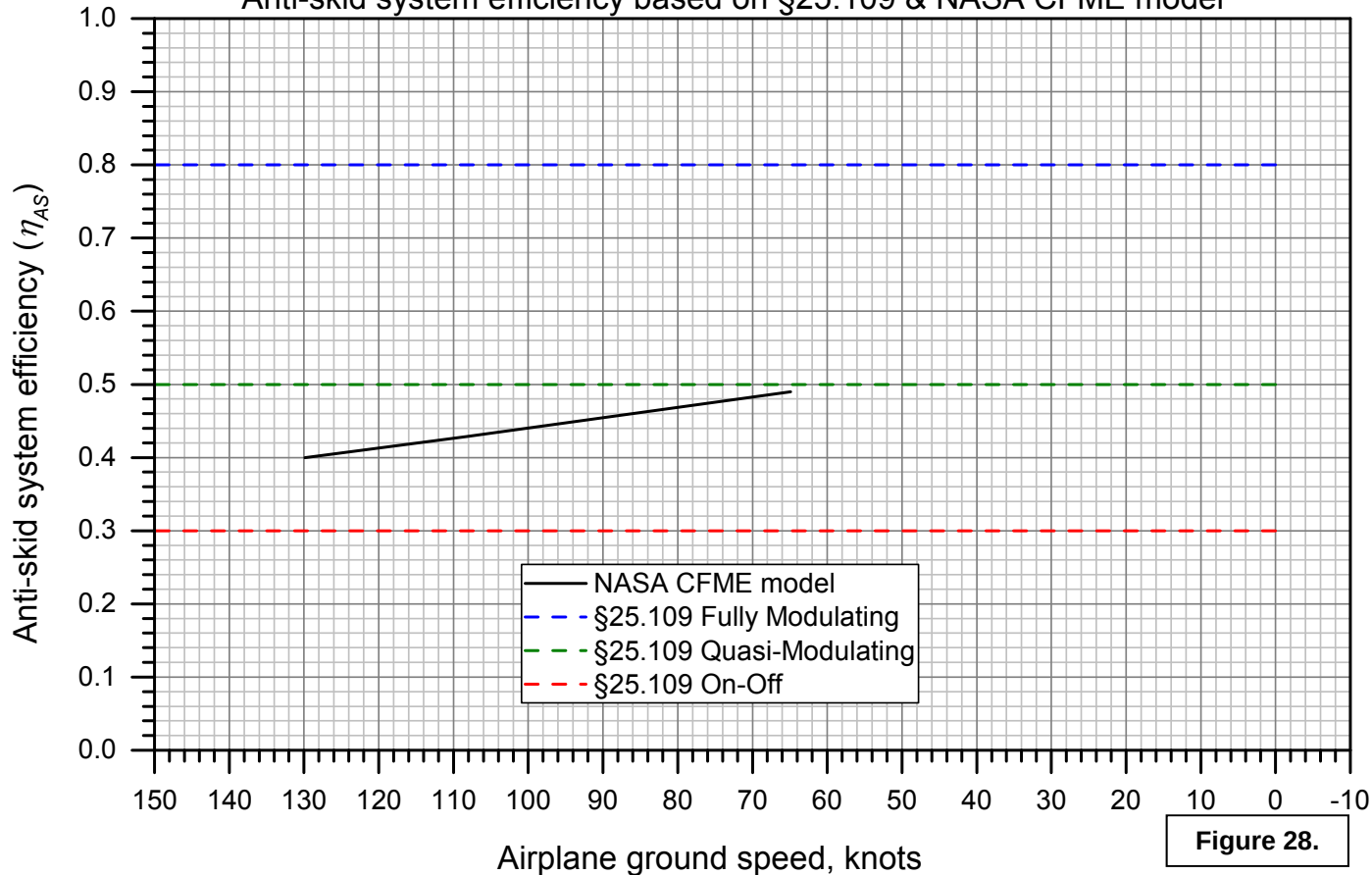


Figure 28.

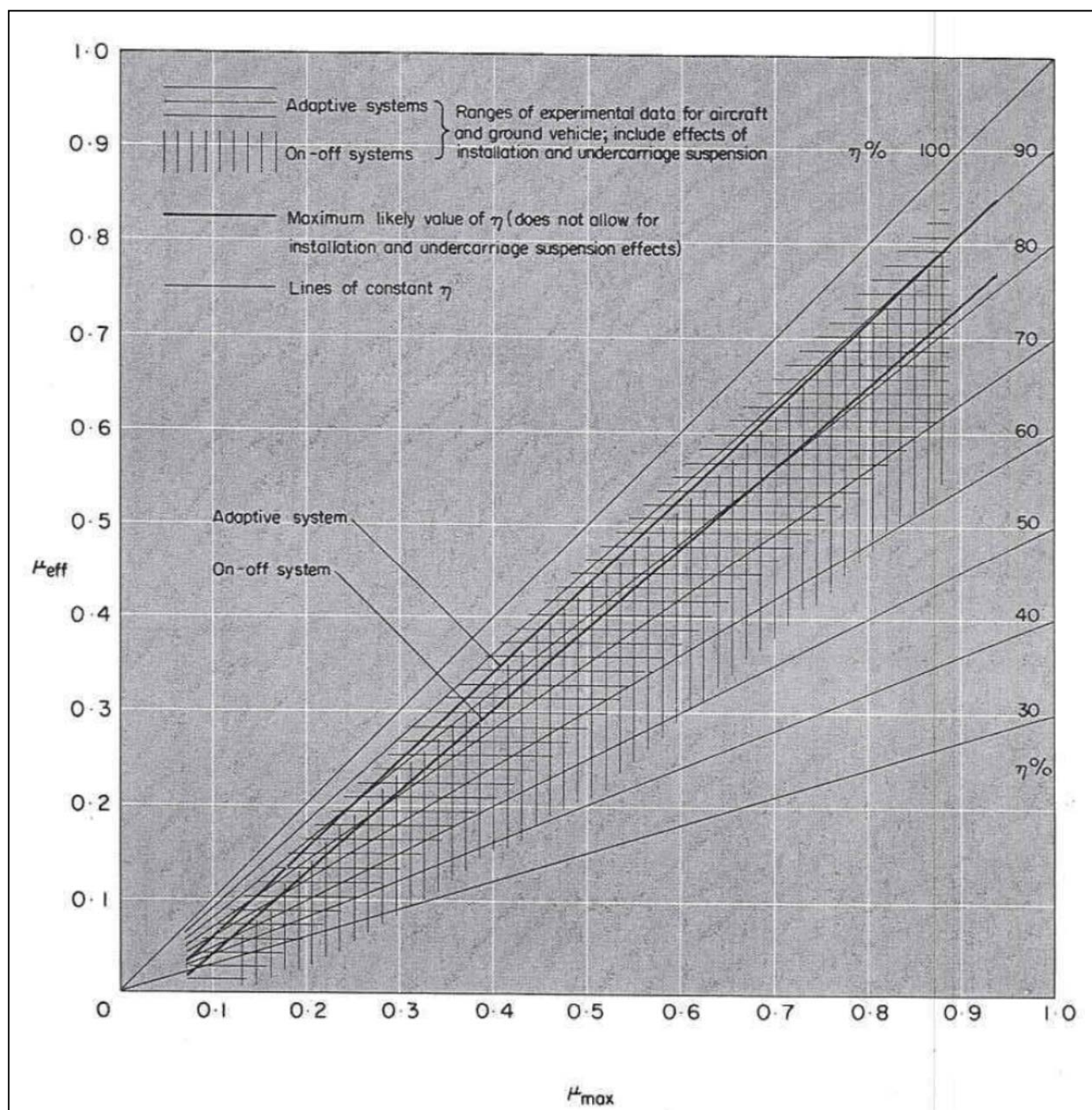
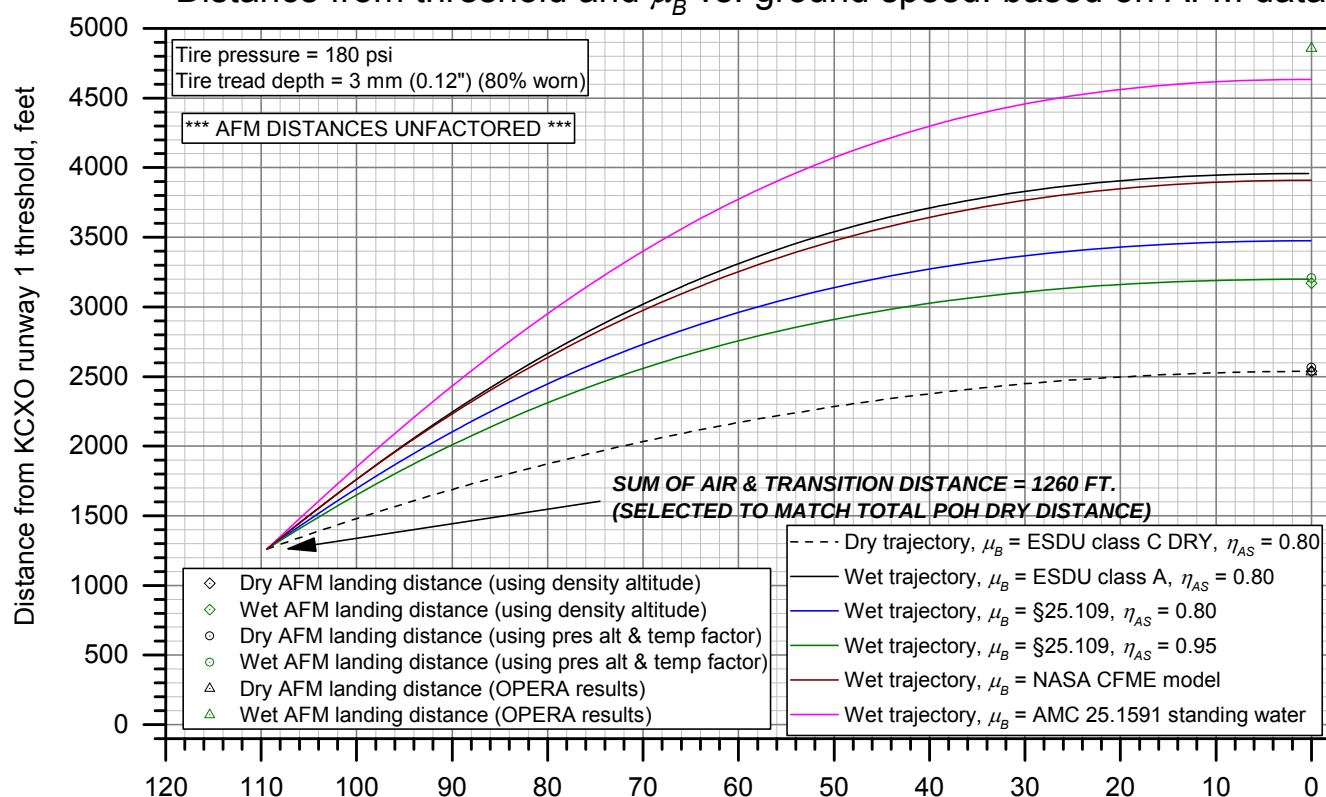


Figure 29. Brake system anti-skid efficiency (η_{AS}), from ESDU 71026 (Reference 19).

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Distance from threshold and μ_B vs. ground speed: based on AFM data



Conditions for AFM unfactored landing distances:

Field elevation = 230 ft. MSL
Altimeter setting = 29.93 "Hg
Static air temperature = 23°C = 73.4° F
Delta temp from ISA = +8.4°C
Density altitude = 1286 ft. MSL
Wind calm
Runway gradient = 0%

Flaps 3
Weight = 15476 lb. (per FDR data at landing)
 V_{REF} = 112 KCAS = 114 KTAS
Touchdown speed = $V_{REF} \cdot 0.96$ = 109.4 KTAS
Pressure altitude = 221 ft. MSL
Temperature factor on landing distance = 1.034

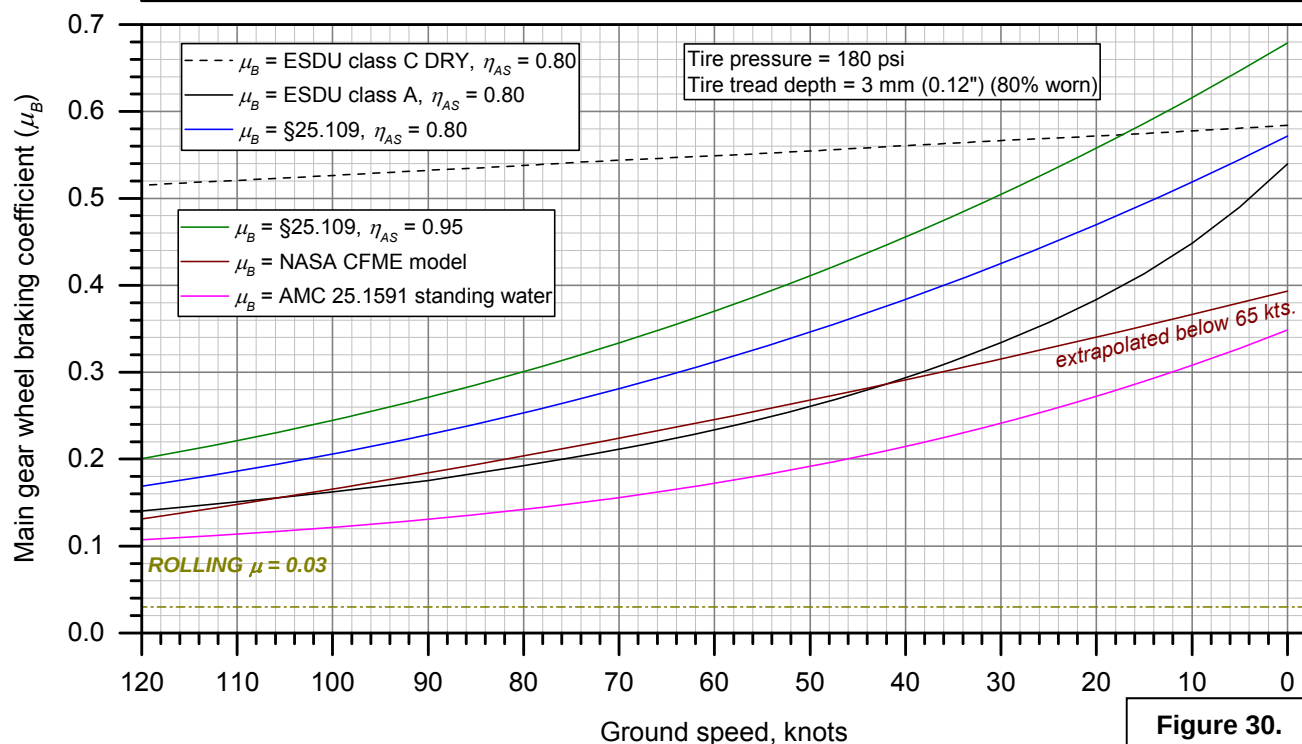


Figure 30.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Deceleration parameters vs. time: accident compared to various μ_B models

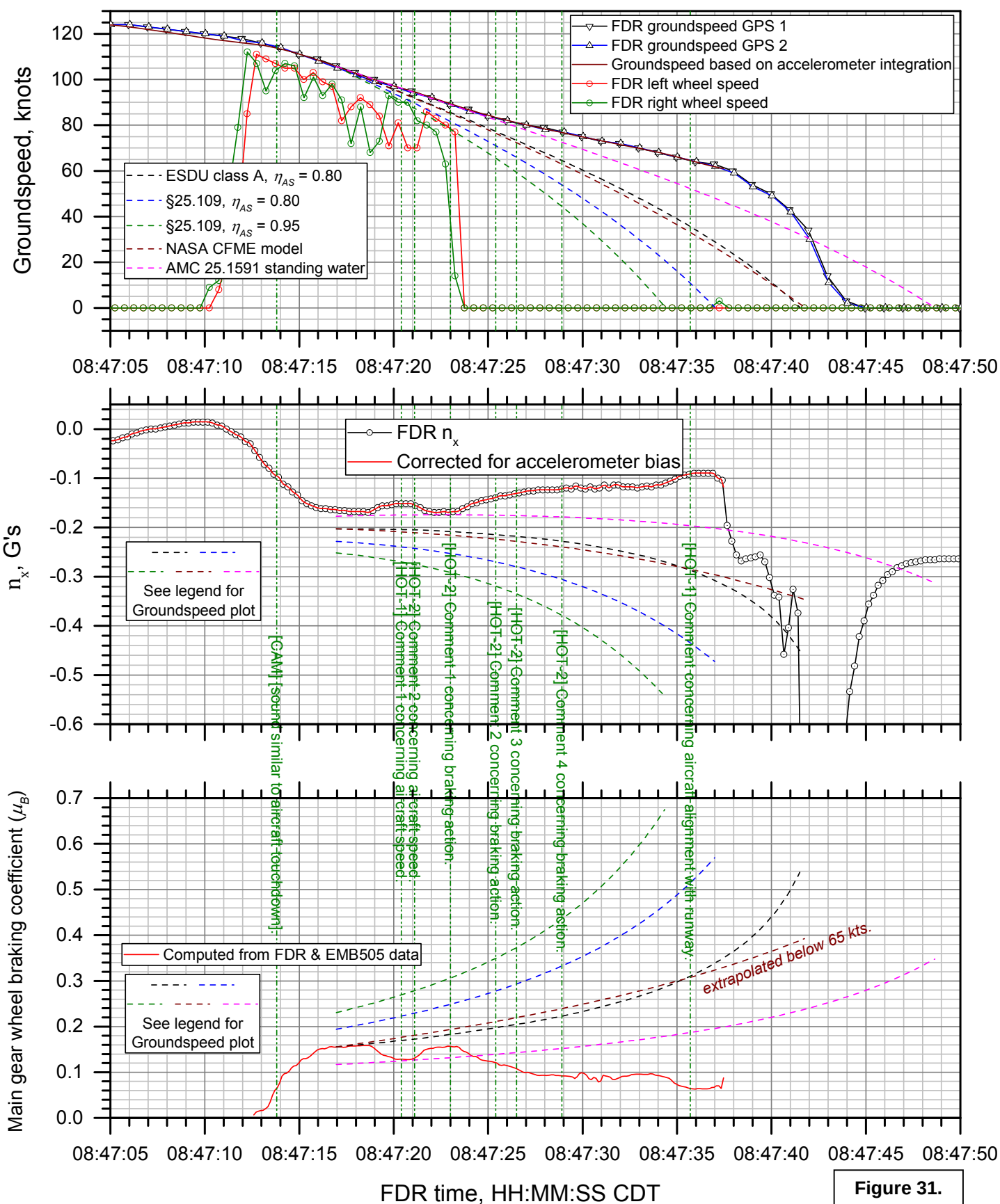


Figure 31.

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

Deceleration parameters vs. distance: accident compared to various μ_B models

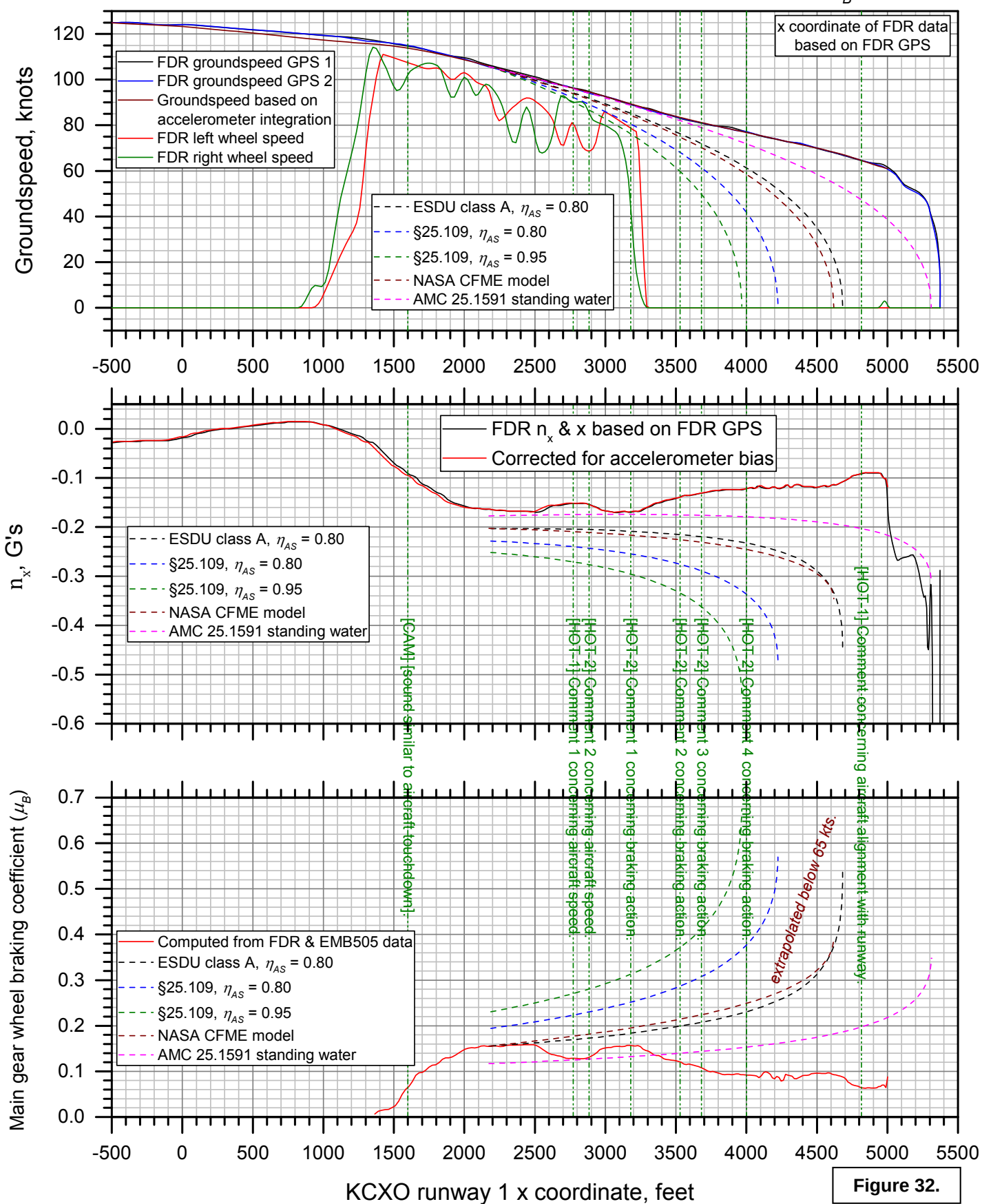


Figure 33: Runway Surface Condition–Pilot Reported Braking Action—Wheel Braking Coefficient Correlation Matrix, from AC 25-32 (Reference 38)

Runway Condition Code	Runway Surface Condition Description	Pilot-Reported Braking Action	Wheel Braking Coefficient
6	Dry	—	90% of certified value used to comply with § 25.125 ¹ .
5	- Frost - Wet (includes damp and 1/8" (3 mm) depth or less of water) 1/8" (3 mm) depth or less of: - Slush - Dry snow - Wet snow	Good	Per method defined in § 25.109(c).
4	-15 °C and colder outside air temperature: Compacted snow	Good to Medium ²	0.20 ³
3	- Wet ("Slippery When Wet" runway) - Dry snow or wet snow (any depth) over compacted snow - Greater than 1/8" (3 mm) depth of: - Dry snow - Wet snow - Warmer than -15 °C outside air temperature: - Compacted snow	Medium ²	0.16 ³
2	Greater than 1/8" (3 mm) depth of: - Water - Slush	Medium ² to Poor	(1) For speeds below 85% of the hydroplaning speed ⁴ : 50% of the wheel braking coefficient determined in accordance with § 25.109(c), but no greater than 0.16 ³ ; and (2) For speeds at 85% of the hydroplaning speed ⁴ and above: 0.05 ³ .
1	Ice	Poor	0.08 ³
0	- Wet ice - Water on top of compacted snow - Dry snow or wet snow over ice	Nil	Not applicable. (No operations in Nil conditions.)

¹ 100% of the wheel braking coefficient used to comply with § 25.125 may be used if the testing from which that braking coefficient was derived was conducted on portions of runways containing operationally representative amounts of rubber contamination and paint stripes.

² The braking action term "FAIR" is in the process of being changed to "MEDIUM" throughout the FAA. Until an official change is published, the term "FAIR" should be used.

³ These wheel braking coefficients assume a fully modulating anti-skid system. For quasi-modulating systems, multiply the listed braking coefficient by 0.625. For on-off systems, multiply the listed braking coefficient by 0.375. (See AC 25-7C to determine the classification of an anti-skid system.) Airplanes without anti-skid systems will need to be addressed separately on a case-by-case basis.

⁴ The hydroplaning speed, V_P , may be estimated by the equation $V_P = 9\sqrt{P}$, where V_P is the ground speed in knots and P is the tire pressure in lb/in².

	40 mph			60 mph		
	Minimum	Maintenance Planning	New Design/ Construction	Minimum	Maintenance Planning	New Design/ Construction
Mu Meter	.42	.52	.72	.26	.38	.66
Dynatest Consulting, Inc. Runway Friction Tester	.50	.60	.82	.41	.54	.72
Airport Equipment Co. Skiddometer	.50	.60	.82	.34	.47	.74
Airport Surface Friction Tester	.50	.60	.82	.34	.47	.74
Airport Technology USA Safegate Friction Tester	.50	.60	.82	.34	.47	.74
Findlay, Irvine, Ltd. Griptester Friction Meter	.43	.53	.74	.24	.36	.64
Tatra Friction Tester	.48	.57	.76	.42	.52	.67
Norsemeter RUNAR (operated at fixed 16% slip)	.45	.52	.69	.32	.42	.63

Figure 34. Friction level classification for runway pavement surfaces (Table 3-2 in Reference 29).

CEN14FA505: EMB-505, N322QS, Conroe, TX, 9/19/2014

150

Runway μ_B classifications based on combined model compared to μ_B computed from CFME measurements for 6 events

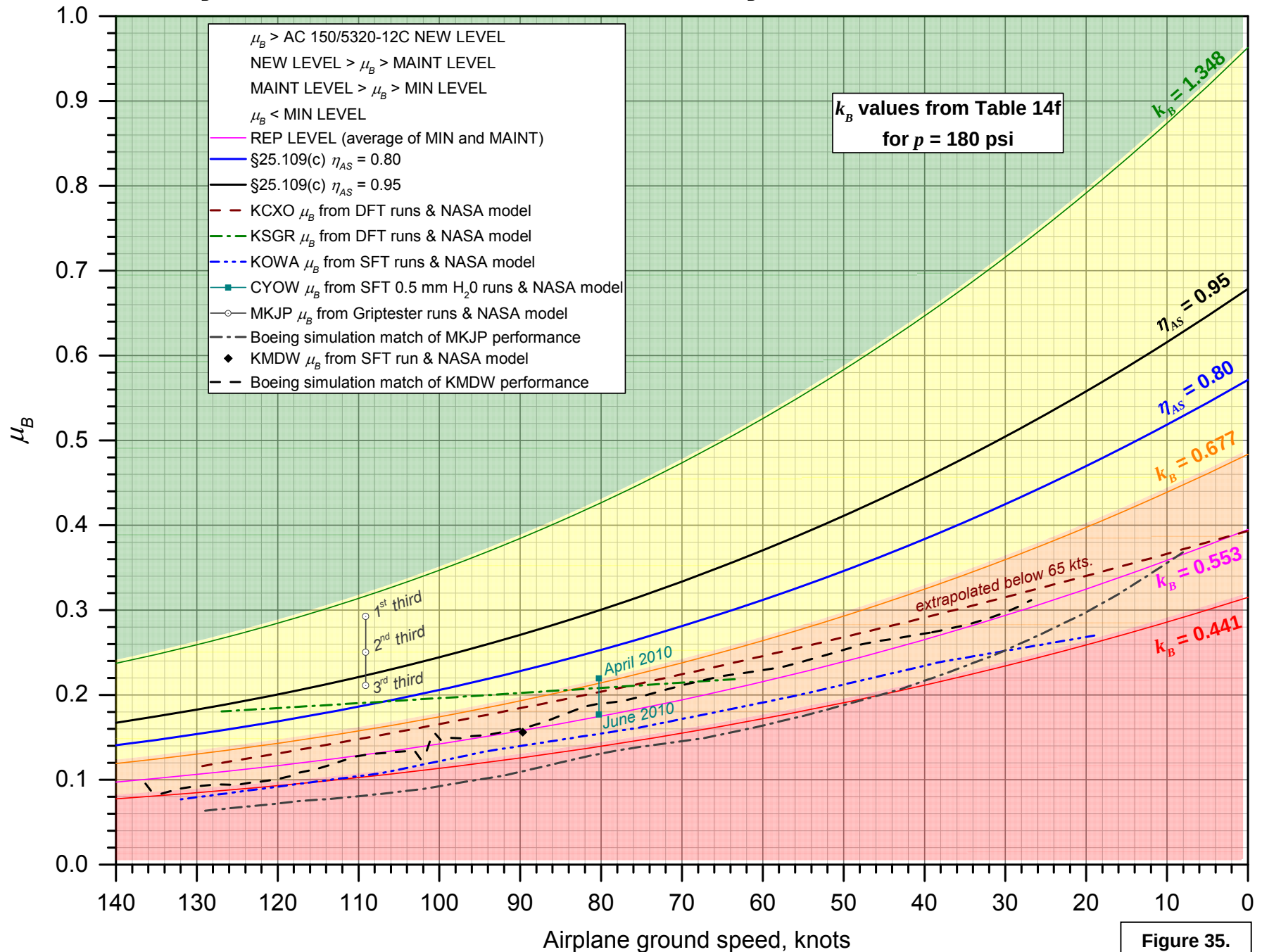


Figure 35.

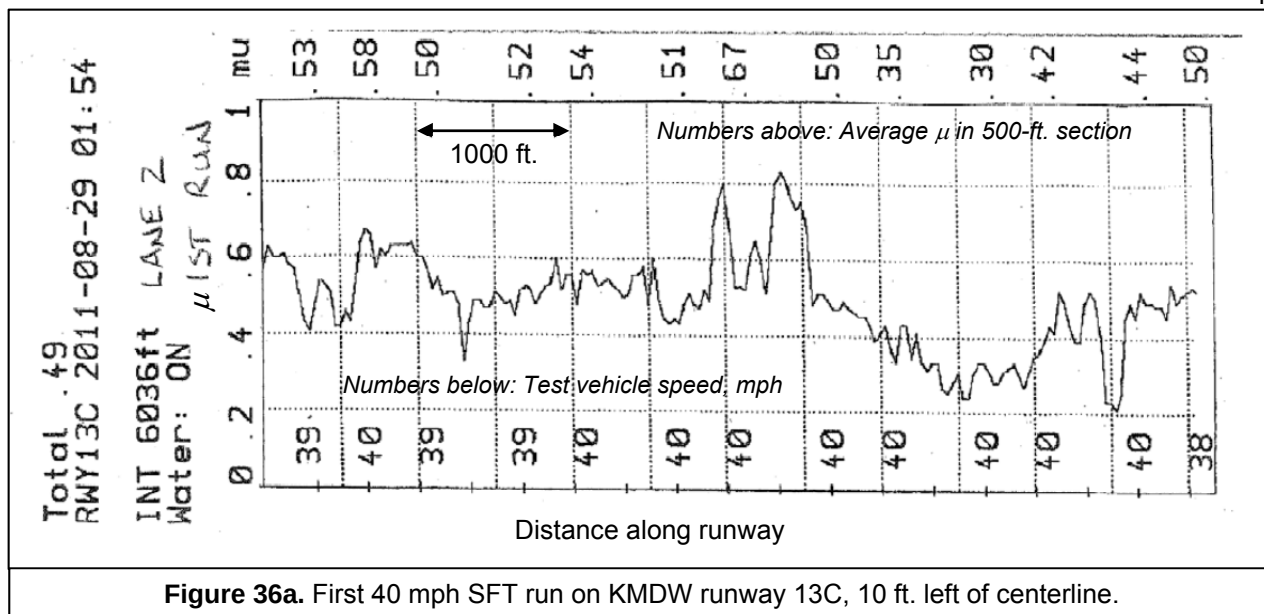


Figure 36a. First 40 mph SFT run on KMDW runway 13C, 10 ft. left of centerline.

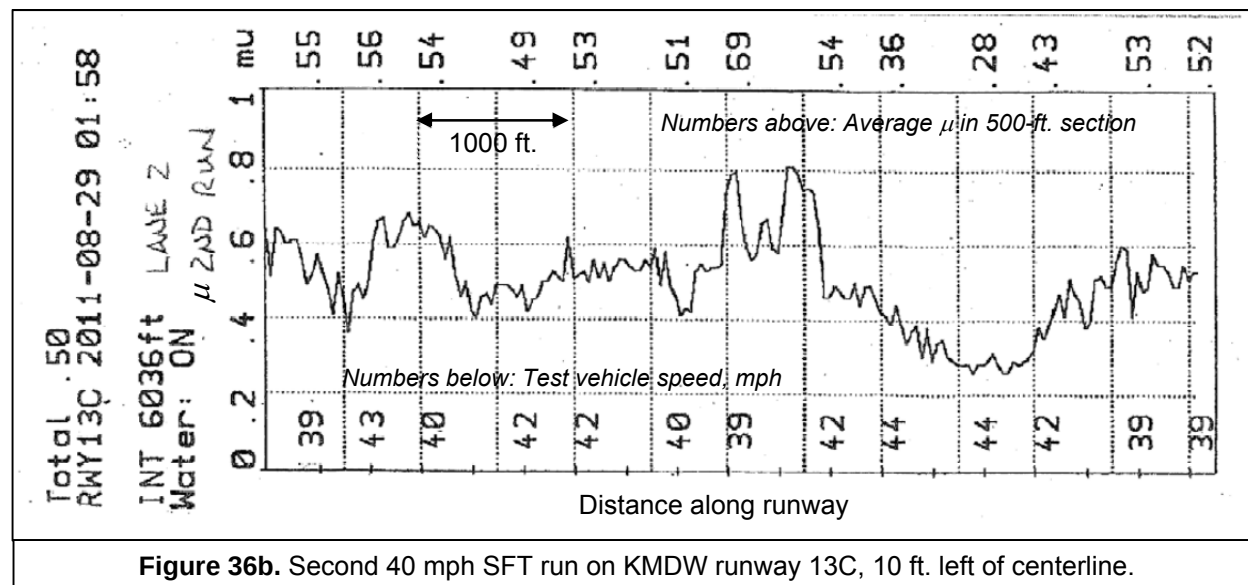


Figure 36b. Second 40 mph SFT run on KMDW runway 13C, 10 ft. left of centerline.

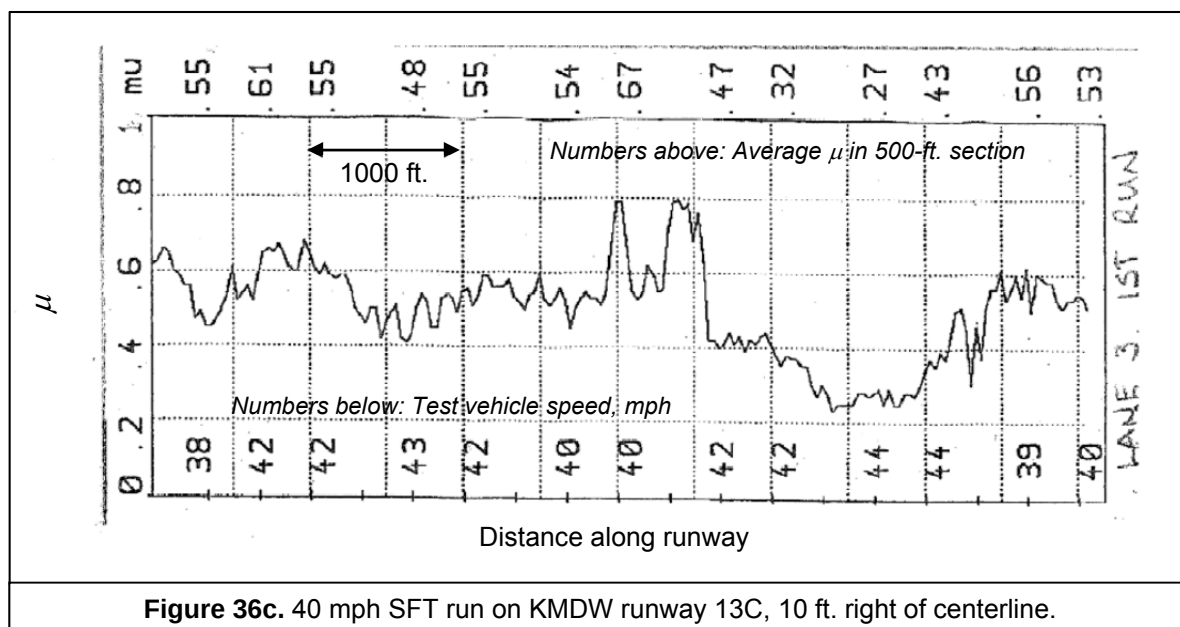
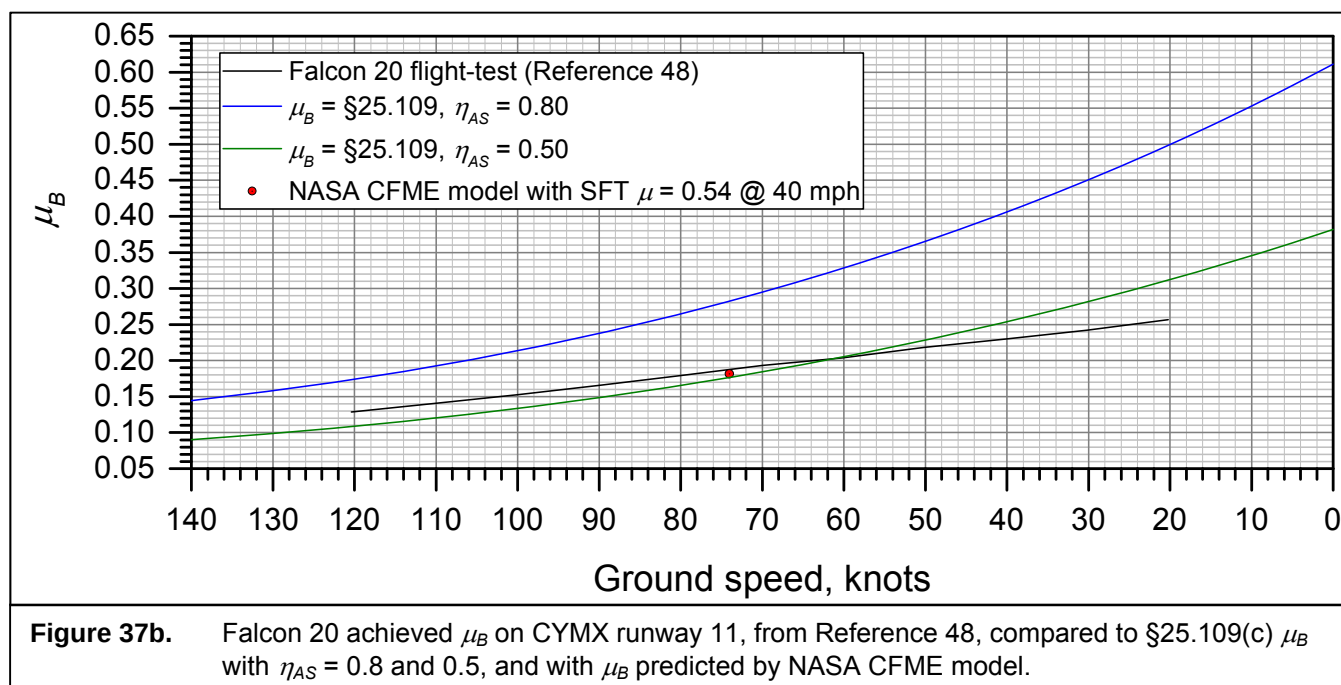
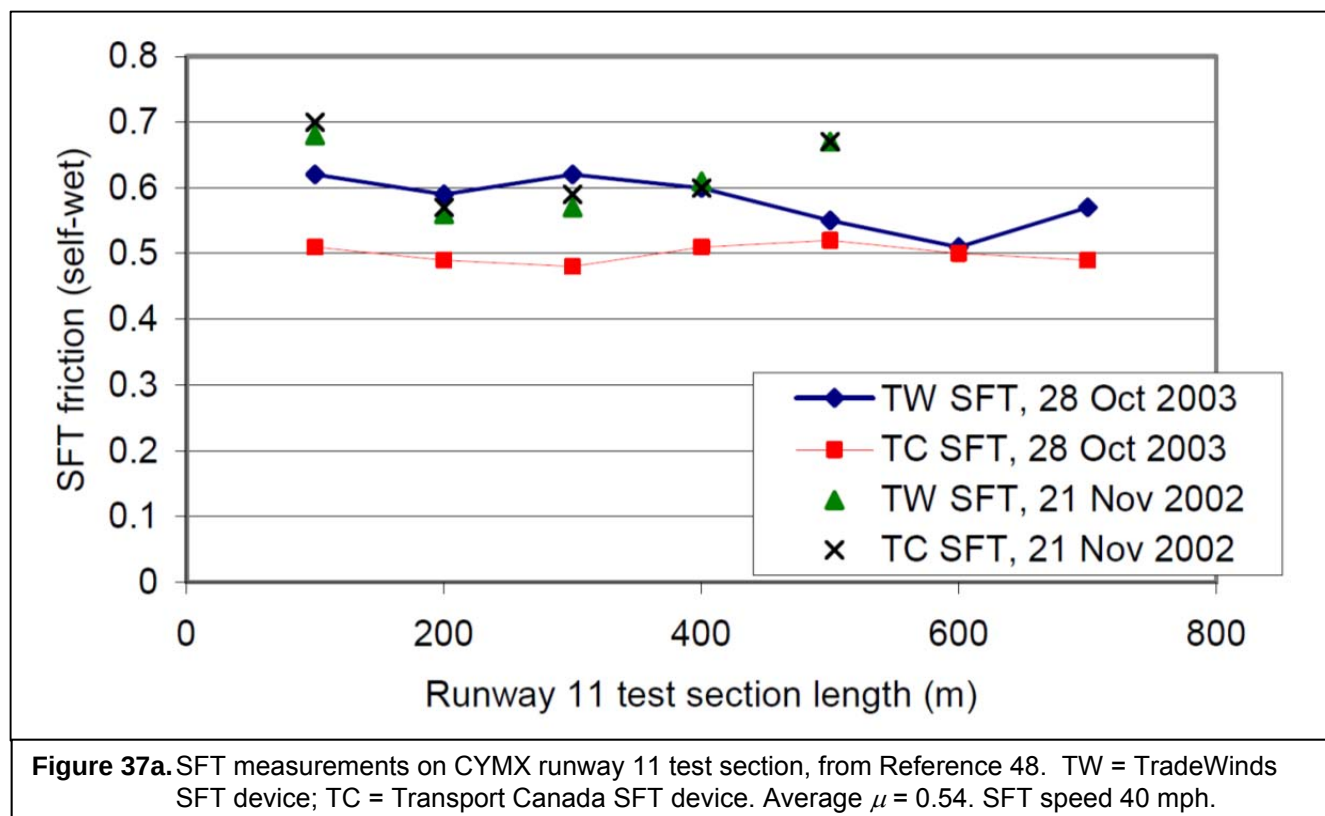
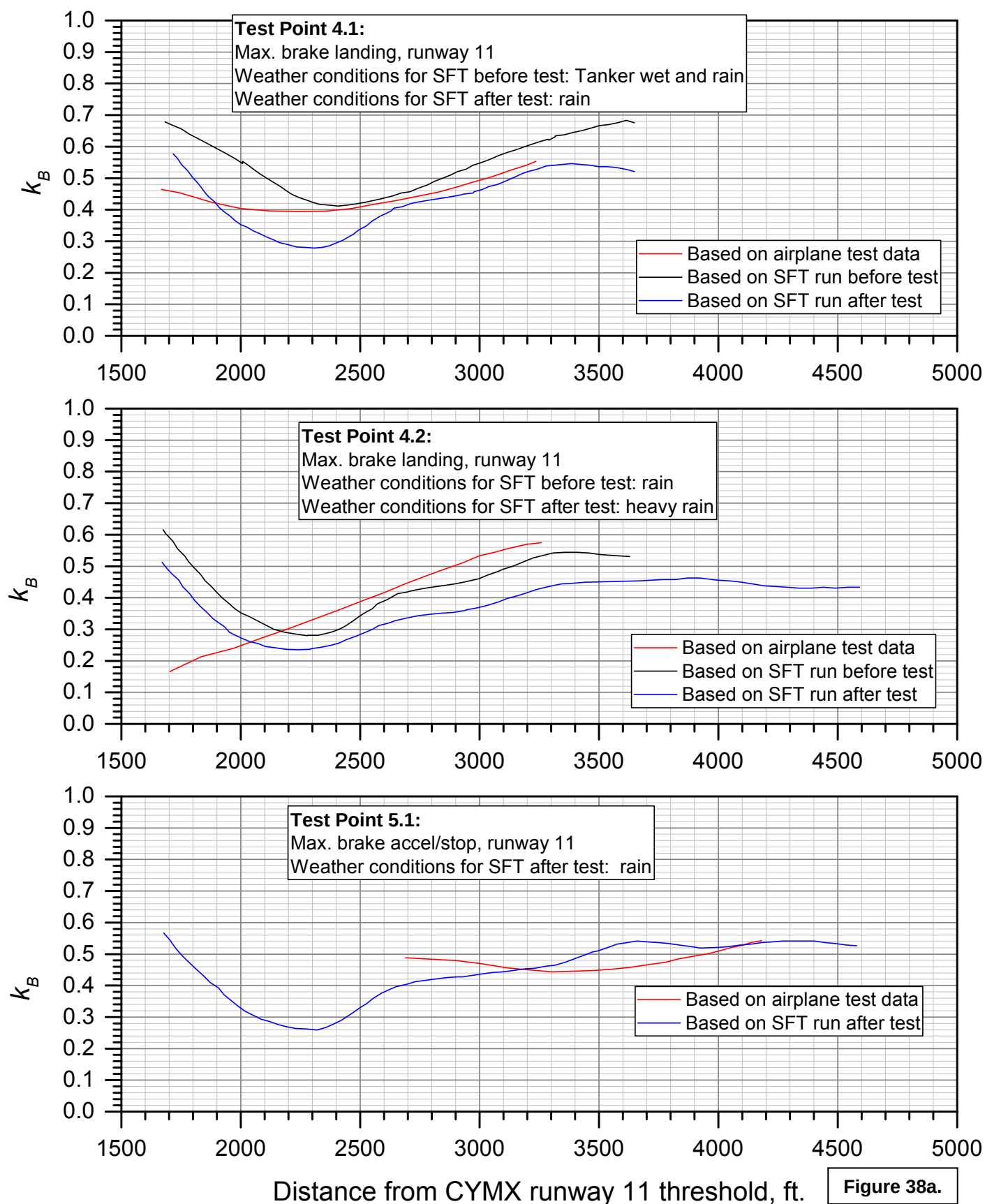


Figure 36c. 40 mph SFT run on KMDW runway 13C, 10 ft. right of centerline.



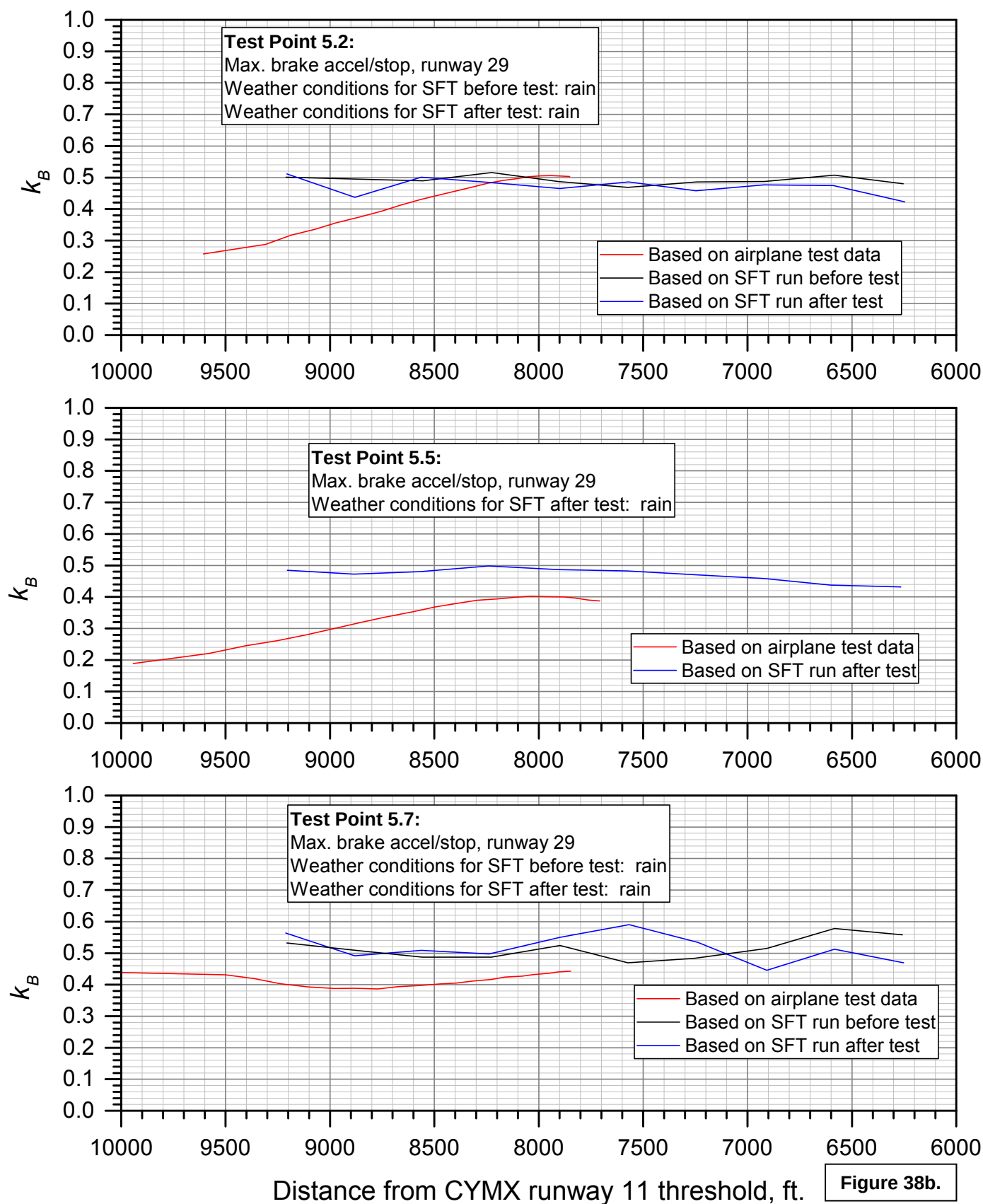
Transport Canada Wet Runway Friction Measurement Program

k_B from SFT CFME and de Havilland Dash 8 Series 400 flight test data (1 of 2)



Transport Canada Wet Runway Friction Measurement Program

k_B from SFT CFME and de Havilland Dash 8 Series 400 flight test data (2 of 2)



DCA11IA047: Boeing 737-7Q8, N799SW, Chicago, IL, 04/26/2011

μ_B from incident data, simulation match, and combined μ_B model

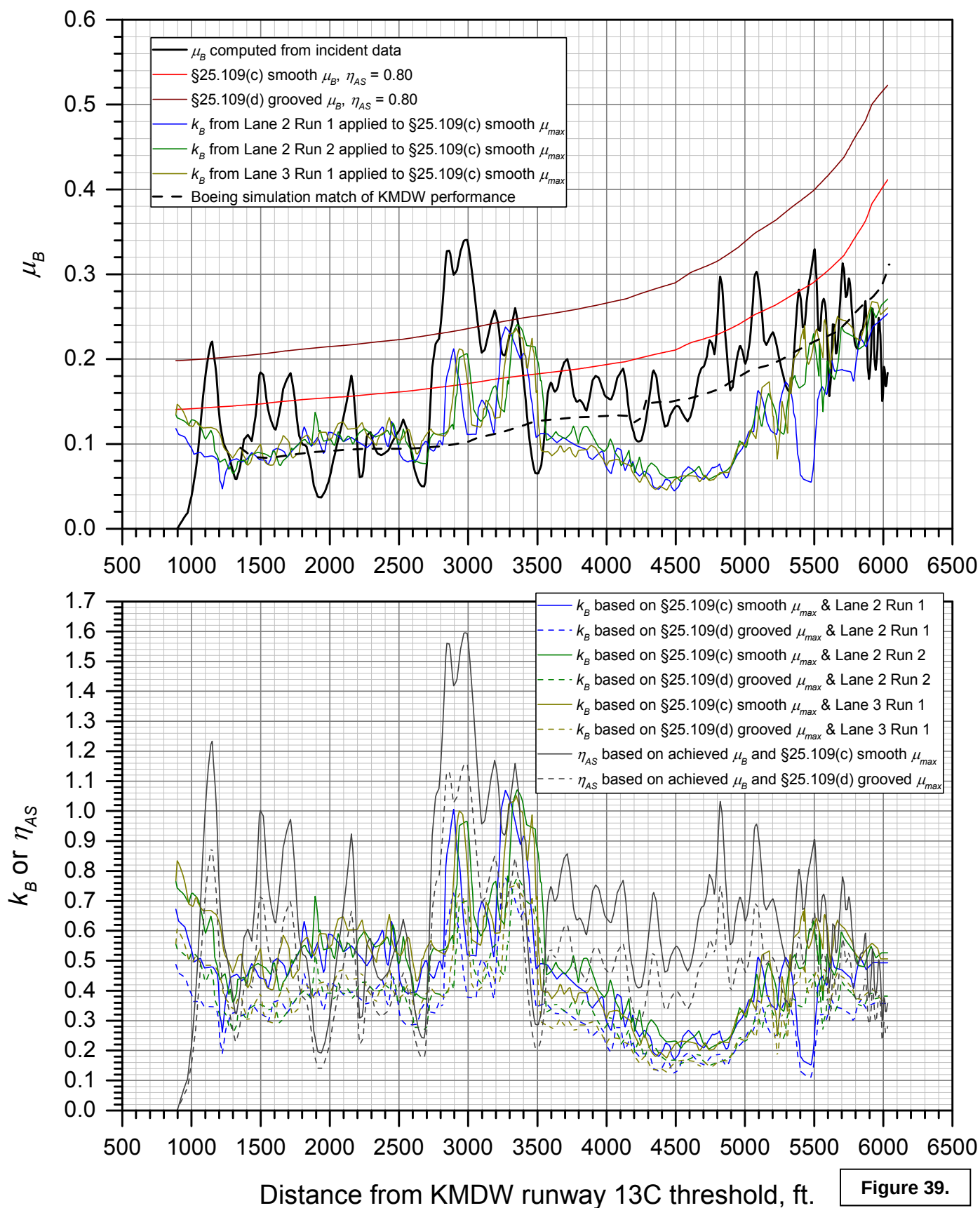


Figure 39.

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APPENDIX A:
KCXO Airport Diagram and Other Information

AIRPORT DIAGRAM

HOUSTON/LONE STAR EXECUTIVE (CXX)
AL-5573 (FAA) HOUSTON, TEXAS

ATIS
118.325
LONE STAR TOWER ★
124.125
GND CON
120.45
CLNC DEL
120.45
119.55 (When Tower Closed)

D

COMPASS
ROSE

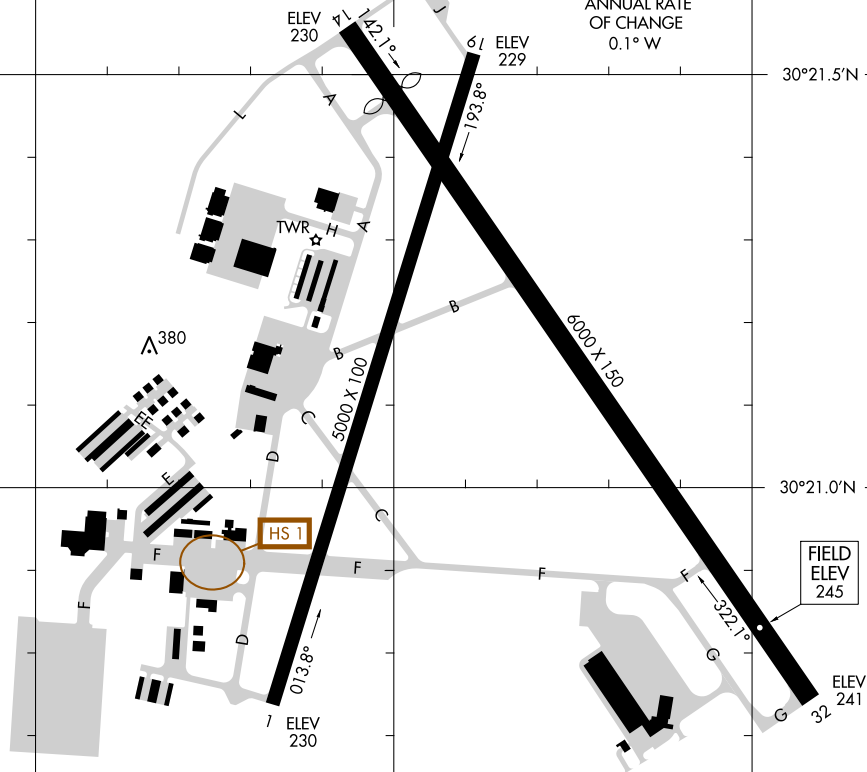
JANUARY 2010
ANNUAL RATE
OF CHANGE
0.1° W

30°21.5'N

30°21.0'N

30°20.5'N

SC-5, 13 NOV 2014 to 11 DEC 2014



RWY 01-19
S-30, D-75, 2S-95
RWY 14-32
S-60, D-100, 2S-127

CAUTION: BE ALERT TO RUNWAY CROSSING CLEARANCES.
READBACK OF ALL RUNWAY HOLDING INSTRUCTIONS IS REQUIRED.

95°25.5'W

95°25.0'W

95°24.5'W

AIRPORT DIAGRAM

Airport Details for KCXO - ACTIVE
Chart Date: 09/23/2010
LONE STAR EXECUTIVE
HOUSTON
AL #: 5573

State:	TEXAS	Magnetic Variation/Year:	E05/2000	Weather Station:	YES
Country:	United States	Site Nbr:	24072.1	Control Tower:	NO
Category:	AERODROME ONLY	Data Source:	405 NGS		
FAR Part 139:	NO	Owner:	NTL	Use:	CIVIL
				Military Type:	
Coordinates		Office		Local Auto Weather	
Latitude:	N 30° 21' 08.5000"	Flight Inspection:	OKC	Weather Source:	ASOS
Longitude:	W 095° 24' 52.3000"	Procedure Development:	120	Type:	3
Field Elevation:	244.9	Region Code:	SW	Frequency:	
Ellipsoid Elevation:	154.5 E	Service Area:	CNTL	Service A:	N
Horizontal Datum:	NAD83	OCC Code:	MID		
Vertical Datum:	NAVD88	International:	NO		

CONTACTS

ALTIMETERS

Type	Primary	Airport ID	Field Alt Source	Latitude	Longitude	Operational Timing
L	YES	KCXO	ASOS	N 30° 21' 08.5000"	W 095° 24' 52.3000"	FULL-TIME
R	NO	KDWH	ASOS	N 30° 03' 42.6000"	W 095° 33' 10.0000"	FULL-TIME

ALTIMETER COMMENTS

RUNWAYS

01 (A) 19 (A) 01 (P) 19 (P) 14 (A) 32 (A) 14 (P) 32 (P)

RUNWAY DETAIL

Landing Strip		Publication Status: A		Pseudo Rwy:	
Chart Date: 02/06/2014		Width: 99		Physical Length: 5000	
Surface: ASPH GOOD					
Rwy Number: 01		Rwy Number: 19		Rwy Number: 01	
Use Category: RUNWAY ONLY		Use Category: RUNWAY ONLY		Use Category: RUNWAY ONLY	
Chart Date: 09/20/2012 Pub. Status: A		Chart Date: 09/20/2012 Pub. Status: A		Chart Date: 09/20/2012 Pub. Status: A	
Data Source: 405 03/03/2009 NGS		Data Source: 405 03/03/2009 NGS		Data Source: 405 03/03/2009 NGS	
Markings: NPI-G		Markings: NPI-G		Markings: NPI-G	
Threshold		Threshold		Threshold	
Latitude: N 30° 20' 44.2700"		Latitude: N 30° 21' 31.5500"		Latitude: N 30° 21' 31.5500"	
Longitude: W 095° 25' 10.1600"		Longitude: W 095° 24' 53.3100"		Longitude: W 095° 24' 53.3100"	
Elevation: 229.6		Elevation: 228.8		Elevation: 228.8	
Ellipsoid Elev: 139.3 S		Ellipsoid Elev: 138.5 E		Ellipsoid Elev: 138.5 E	
Ellipsoid Elev Model: WGS84		Ellipsoid Elev Model: WGS84		Ellipsoid Elev Model: WGS84	
Horz. Datum: NAD83		Horz. Datum: NAD83		Horz. Datum: NAD83	
Vert. Datum: NAVD88		Vert. Datum: NAVD88		Vert. Datum: NAVD88	
Displaced Threshold		Displaced Threshold		Displaced Threshold	
Latitude:		Latitude:		Latitude:	
Longitude:		Longitude:		Longitude:	
Elevation:		Elevation:		Elevation:	
Ellipsoid Elev:		Ellipsoid Elev:		Ellipsoid Elev:	
Ellipsoid Elev Model:		Ellipsoid Elev Model:		Ellipsoid Elev Model:	
Horz. Datum:		Horz. Datum:		Horz. Datum:	
Vert. Datum:		Vert. Datum:		Vert. Datum:	
Landing Length: 5000		Landing Length: 5000		Landing Length: 5000	
FI RWY Length: 5000		FI RWY Length: 5000		FI RWY Length: 5000	
FI RWY Height: 228.8		FI RWY Height: 229.6		FI RWY Height: 229.6	
Tdz Elevation: 236.6		Tdz Elevation: 236.6		Tdz Elevation: 236.6	
True Bearing: 17.17		True Bearing: 197.18		True Bearing: 197.18	
Ft Disp Th:		Ft Disp Th:		Ft Disp Th:	
Gradient: 0.0%		Gradient: 0.0%		Gradient: 0.0%	
RVRTouchdown:		RVRTouchdown:		RVRTouchdown:	
MidPoint:		MidPoint:		MidPoint:	
Rollout:		Rollout:		Rollout:	
Rail: NO		Rail: NO		Rail: NO	
OIS Data Source: ANALPV 03/03/2009 NGS_SURVEY		OIS Data Source: ANALPV 03/03/2009 NGS_SURVEY		OIS Data Source: ANALPV 03/03/2009 NGS_SURVEY	
Assoc. Fac.:		Assoc. Fac.:		Assoc. Fac.:	

RUNWAY LANDING STRIP COMMENTS

RUNWAY DETAIL

Landing Strip		
Chart Date: 03/05/2015	Publication Status: P	Pseudo Rwy:
Surface: ASPH GOOD	Width: 99	Physical Length: 5000

Rwy Number: 01 Use Category: RUNWAY ONLY Chart Date: 03/05/2015 Data Source: THIRD_PARTY 06/26/2011 Markings: NPI-G						Rwy Number: 19 Use Category: RUNWAY ONLY Chart Date: 03/05/2015 Data Source: THIRD_PARTY 06/26/2011 Markings: NPI-G						KCXO19 Use Category: RUNWAY ONLY Chart Date: 03/05/2015 Data Source: THIRD_PARTY 06/26/2011 Markings: NPI-G					
Threshold Latitude: N 30° 20' 44.2266" Longitude: W 095° 25' 10.1247" Elevation: 229.6 Ellipsoid Elev: 139.3 S Ellipsoid Elev Model: NAVD88 Horz. Datum: NAD83 Vert. Datum: NAVD88						Threshold Latitude: N 30° 21' 31.5059" Longitude: W 095° 24' 53.2773" Elevation: 228.7 Ellipsoid Elev: 138.5 S Ellipsoid Elev Model: NAVD88 Horz. Datum: NAD83 Vert. Datum: NAVD88						Threshold Latitude: N 30° 21' 24.2900" Longitude: W 095° 24' 55.8500" Elevation: 237.4 Ellipsoid Elev: 139.3 S Ellipsoid Elev Model: NAVD88 Horz. Datum: NAD83 Vert. Datum: NAVD88					
Displaced Threshold Latitude: Longitude: Elevation: Ellipsoid Elev: Ellipsoid Elev Model: Horz. Datum: UNKNOWN Vert. Datum: UNKNOWN						Displaced Threshold Latitude: Longitude: Elevation: Ellipsoid Elev: Ellipsoid Elev Model: Horz. Datum: UNKNOWN Vert. Datum: UNKNOWN						Displaced Threshold Latitude: Longitude: Elevation: Ellipsoid Elev: Ellipsoid Elev Model: Horz. Datum: UNKNOWN Vert. Datum: UNKNOWN					
VGSI Lights VGSI Lights Type: PAPI-2L Owner: STATE Pilot Cntl Freq: Th Cross Ht: 49.4 High Angle: Com. Date: 03/21/2012 Com. Angle: 3.15 DWB Elev: DWB Thres: Ref Pt Lat: N 30° 20' 51.4400" Ref Pt Long: W 095° 25' 07.5500" Ref Pt Elev: 236.8 Ref Pt Thres: 762 Height Group:						VGSI Lights VGSI Lights Type: PAPI-2L Owner: STATE Pilot Cntl Freq: Th Cross Ht: 48.6 High Angle: Com. Date: 03/21/2012 Com. Angle: 3.00 DWB Elev: DWB Thres: Ref Pt Lat: N 30° 21' 24.2900" Ref Pt Long: W 095° 24' 55.8500" Ref Pt Elev: 237.4 Ref Pt Thres: 763 Height Group:						VGSI Lights VGSI Lights Type: PAPI-2L Owner: STATE Pilot Cntl Freq: Th Cross Ht: 48.6 High Angle: Com. Date: 03/21/2012 Com. Angle: 3.00 DWB Elev: DWB Thres: Ref Pt Lat: N 30° 21' 24.2900" Ref Pt Long: W 095° 24' 55.8500" Ref Pt Elev: 237.4 Ref Pt Thres: 763 Height Group:					
Lights Config Len Owner Mil Type Com Dt Pilot Cntrl MIRL STATE						Lights Config Len Owner Mil Type Com Dt Pilot Cntrl MIRL STATE						Lights Config Len Owner Mil Type Com Dt Pilot Cntrl MIRL STATE					
Landing Length: 5000 FI RWY Length: 5000 FI RWY Height: 228.7 Tdz Elevation: 236.7 True Bearing: 17.16 Ft Disp Th: Gradient: 0.0% RVRTouchdown: MidPoint: Rollout: Rail: NO OIS Data Source: VG 06/26/2011 THIRD_PARTY Assoc. Fac.:						Landing Length: 5000 FI RWY Length: 5000 FI RWY Height: 229.6 Tdz Elevation: 236.7 True Bearing: 197.17 Ft Disp Th: Gradient: 0.0% RVRTouchdown: MidPoint: Rollout: Rail: NO OIS Data Source: VG 06/26/2011 THIRD_PARTY Assoc. Fac.:						Landing Length: 5000 FI RWY Length: 5000 FI RWY Height: 229.6 Tdz Elevation: 236.7 True Bearing: 197.17 Ft Disp Th: Gradient: 0.0% RVRTouchdown: MidPoint: Rollout: Rail: NO OIS Data Source: VG 06/26/2011 THIRD_PARTY Assoc. Fac.:					

RUNWAY DETAIL

Landing Strip		
Chart Date: 02/06/2014	Publication Status: A	Pseudo Rwy:
Surface: CONC GOOD	Width: 150	Physical Length: 7501

Rwy Number: 14		Rwy Number: 32	
Use Category: RUNWAY ONLY	KCXO14	Use Category: RUNWAY ONLY	KCXO32
Chart Date: 07/29/2010	Pub. Status: A	Chart Date: 07/29/2010	Pub. Status: A
Data Source: 405 03/01/1991 NGS		Data Source: 405 03/03/2009 NGS	
Markings: PIR-G		Markings: NPI-G	
Threshold		Threshold	
Latitude: N 30° 21' 33.4734"		Latitude: N 30° 20' 44.5408"	
Longitude: W 095° 25' 03.9041"		Longitude: W 095° 24' 25.1018"	
Elevation: 230.1		Elevation: 241.3	
Ellipsoid Elev: 139.9 S		Ellipsoid Elev: 151.0 S	
Ellipsoid Elev Model: WGS84		Ellipsoid Elev Model: WGS84	
Horz. Datum: NAD83		Horz. Datum: NAD83	
Vert. Datum: NAVD88		Vert. Datum: NAVD88	

		VGSI Lights						
		VGSI Lights Type:		PAPI-2L				
		Owner:		STATE				
		Pilot Cntl Freq:						
		Th Cross Ht:		31.0				
		High Angle:						
		Com. Date:						
		Com. Angle:		3.00				
		DWB Elev:						
		DWB Thres:						
		Ref Pt Lat:						
		Ref Pt Long:						
		Ref Pt Elev:						
		Ref Pt Thres:						
		Height Group:						
		Lights						
		Config	Len	Owner	Mil Type	Com Dt	Pilot Cntrl	
		MALSR		STATE			122.950	
		MIRL		STATE			122.950	

Displaced Threshold	
Latitude:	N 30° 21' 28.6715"
Longitude:	W 095° 25' 00.0957"
Elevation:	230.6
Ellipsoid Elev:	140.4 S
Ellipsoid Elev Model:	WGS84
Horz. Datum:	NAD83
Vert. Datum:	NAVD88

Displaced Threshold	
Latitude:	N 30° 21' 28.6715"
Longitude:	W 095° 25' 00.0957"
Elevation:	230.6
Ellipsoid Elev:	140.4 S
Ellipsoid Elev Model:	WGS84
Horz. Datum:	NAD83
Vert. Datum:	NAVD88

Landing Length: 5411
FI RWY Length: 5411
FI RWY Height: 241.3
Tdz Elevation: 242.8
True Bearing: 145.48
Ft Disp Th: 589
Gradient: 0.2%
RVRTouchdown:
MidPoint:
Rollout:
Rail: YES
OIS Data Source: PIR 03/01/1991 NGS_SURVEY
Assoc. Fac.: CXO ILS (A)

Lights							
Config	Len	Owner	Mil	Type	Com	Dt	Pilot Cntrl
MIRL		STATE					122.950
REIL		STATE					122.950

Displaced Threshold	
Latitude:	
Longitude:	
Elevation:	
Ellipsoid Elev:	
Ellipsoid Elev Model:	
Horz. Datum:	
Vert. Datum:	

Landing Length: 6000
FI RWY Length: 5411
FI RWY Height: 230.6
Tdz Elevation: 244.9
True Bearing: 325.49
Ft Disp Th:
Gradient: -0.2%
RVRTouchdown:
MidPoint:
Rollout:
Rail: NO
OIS Data Source: ANALPV 03/03/2009 NGS_SURVEY
Assoc. Fac.:

RUNWAY LANDING STRIP COMMENTS

RUNWAY 14 COMMENTS

RUNWAY 32 COMMENTS

RUNWAY DETAIL

Landing Strip			
Chart Date: 03/05/2015		Publication Status: P	Pseudo Rwy:
Surface: CONC GOOD		Width: 150	Physical Length: 7501

Rwy Number: 14
Use Category: RUNWAY ONLY
Chart Date: 03/05/2015 Pub. Status: P
Data Source: THIRD_PARTY 06/26/2011
Markings: PIR-G

Threshold	
Latitude:	N 30° 21' 45.7165"
Longitude:	W 095° 25' 13.6157"
Elevation:	234.1
Ellipsoid Elev:	143.8 S
Ellipsoid Elev Model:	NAVD88
Horz. Datum:	NAD83
Vert. Datum:	NAVD88

Displaced Threshold	
Latitude:	
Longitude:	
Elevation:	
Ellipsoid Elev:	
Ellipsoid Elev Model:	NAVD88
Horz. Datum:	NAD83
Vert. Datum:	NAVD88

Landing Length: 7501
FI RWY Length: 7501
FI RWY Height: 241.3
Tdz Elevation: 242.9
True Bearing: 145.48
Ft Disp Th:
Gradient: 0.1%
RVRTouchdown:

Rwy Number: 32
Use Category: RUNWAY ONLY
Chart Date: 03/05/2015 Pub. Status: P
Data Source: THIRD_PARTY 06/26/2011
Markings: NPI-G

Threshold	
Latitude:	N 30° 20' 44.5408"
Longitude:	W 095° 24' 25.1015"
Elevation:	241.3
Ellipsoid Elev:	151.0 S
Ellipsoid Elev Model:	NAVD88
Horz. Datum:	NAD83
Vert. Datum:	NAVD88

Displaced Threshold	
Latitude:	
Longitude:	
Elevation:	
Ellipsoid Elev:	
Ellipsoid Elev Model:	
Horz. Datum:	UNKNOWN
Vert. Datum:	UNKNOWN

Landing Length: 7501
FI RWY Length: 7501
FI RWY Height: 234.1
Tdz Elevation: 245.0
True Bearing: 325.48
Ft Disp Th:
Gradient: -0.1%
RVRTouchdown:

Rwy Number: 32
Use Category: RUNWAY ONLY
Chart Date: 03/05/2015 Pub. Status: P
Data Source: THIRD_PARTY 06/26/2011
Markings: NPI-G

Threshold	
Latitude:	N 30° 20' 44.5408"
Longitude:	W 095° 24' 25.1015"
Elevation:	241.3
Ellipsoid Elev:	151.0 S
Ellipsoid Elev Model:	NAVD88
Horz. Datum:	NAD83
Vert. Datum:	NAVD88

Lights							
Config	Len	Owner	Mil	Type	Com	Dt	Pilot Cntrl
REIL		STATE					122.950
MIRL		STATE					122.950

Landing Length: 7501
FI RWY Length: 7501
FI RWY Height: 234.1
Tdz Elevation: 245.0
True Bearing: 325.48
Ft Disp Th:
Gradient: -0.1%
RVRTouchdown:

Rpt Date:	20:00:36 08/15/2014		
Rpt User:	dso		
MidPoint:		MidPoint:	
Rollout:		Rollout:	
Rail:	YES	Rail:	NO
OIS Data Source:	VG 06/26/2011 THIRD_PARTY	OIS Data Source:	VG 06/26/2011 THIRD_PARTY
Assoc. Fac.:	CXO ILS (P)	Assoc. Fac.:	

RUNWAY LANDING STRIP COMMENTS

RUNWAY 14 COMMENTS

RUNWAY 32 COMMENTS

COMMENTS			
Topic	Priority	Date	Remark
SURVEY	1	11/05/1999	NGS 405 SURVEY DATED 04/18/98
ADDITIONAL_FLIGHT_DATA	1	06/26/2000	ASOS. 936-760-4237
NFDD	3	02/25/2004	PER NFDD #049 DATED 03/12/04, ARPT NAME CHANGED FROM LONE STAR RGNL TO LONE STAR EXECUTIVE, CITY FROM CONROE TO HOUSTON
LIGHTS	5	06/05/2006	RWY 14/32 TO CHANGE RWY 14 VASI TO PAPI PER NFDD #080 DATED 04/26/06
SURVEY	5	06/27/2007	ALTERNATE ALTIMETER SOURCE, KDWH, ADDED PER AVN-120
OWNER	2	10/15/2007	LIGHTS OWNED BY MONTGOMERY COUNTY
GENERAL	7	10/16/2007	RWY 01/19 BEING EXTENDED ON NORTH END. DATA PROVIDED BY LOCAL SURVEY. NFDD #217 DATED 11/08/07
			RWY 19 PAPI DATA PROVIDED BY PROJECT MGR, 11/05/07
			RWY 01 PAPI DATA TO CHANGE ANGLE & MODIFY DATA FORWARDED BY TX ADO FROM PROJECT MGR, 10/15/07
			TDZE USED IN LIEU OF UNKNOWN RRP ELEVATION
NFDD	9	12/09/2008	TCH IS A CALCULATED VALUE PER NFDD # 238 DATED 12/10/08 RWY 32 4 BOX VASI DELETED.

SIAPS

Nav Ident	Nav Type	Description	FAS	Amendment	Type
		RNAV (GPS) RWY 32	329 / TREE / N30°20'43.08" / W095°24'14.66"	1	CIVIL
			409 / TOWER / N30°17'30.60" / W095°21'41.30"		
CXO	ILS	ILS OR LOC RWY 14	379 / TREE / N30°22'36.00" / W095°26'19.00"	2B	CIVIL
		RNAV (GPS) RWY 14	325 / TREE / N30°21'38.48" / W095°25'20.28"	ORG	CIVIL
			553 / TOWER / N30°25'50.00" / W095°26'20.00"		
		RNAV (GPS) RWY 19	374 / TREE / N30°22'12.18" / W095°24'17.43"	ORG	CIVIL
			409 / TREE / N30°23'24.40" / W095°24'42.08"		
		RNAV (GPS) RWY 1	A6 395 / TOWER / N30°20'19.00" / W095°25'43.00"	ORG	CIVIL
CXO	ILS	NDB RWY 14	480 / TANK / N30°23'34.00" / W095°28'30.00"	2B	CIVIL

Rpt Date: 20:00:36 08/15/2014

Rpt User: dso

ASSOCIATED MONITORS

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KCXO Lone Star Executive Airport

Houston, Texas, USA



GOING TO HOUSTON?



FAA INFORMATION EFFECTIVE 18 SEPTEMBER 2014

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[Com](#) | [Nav](#) | [Svcs](#) | [Stats](#) | [Notes](#)

Location

FAA Identifier: CXO

Lat/Long: 30-21-08.5000N / 095-24-52.3000W

30-21.141667N / 095-24.871667W

30.3523611 / -95.4145278

(estimated)

Elevation: 245 ft. / 74.7 m (surveyed)

Variation: 05E (2000)

From city: 37 miles N of HOUSTON, TX

Time zone: UTC -5 (UTC -6 during Standard Time)

Zip code: 77303

Airport Operations

Airport use: Open to the public

Activation date: 05/1944

Sectional chart: [HOUSTON](#)

Control tower: yes

ARTCC: HOUSTON CENTER

FSS: MONTGOMERY COUNTY FLIGHT SERVICE STATION

NOTAMs facility: CXO (NOTAM-D service available)

Attendance: 0700-2100

Wind indicator: lighted

Segmented circle: yes

Lights: DUSK-DAWN. MIRL RY 14/32 PRESET LOW INTST; TO INCR INTST & ACTVT MALSR RY 14 AND REIL RY 32 - CTAF.

Beacon: white-green (lighted land airport)

Operates sunset to sunrise.

Airport Communications

CTAF: 124.125

ATIS: 118.325

WX ASOS: 118.325 (936-760-4237)

LONE STAR GROUND: 120.45 [0700-2200]

LONE STAR TOWER: 124.125 [0700-2200]

HOUSTON APPROACH: 119.7

HOUSTON DEPARTURE: 119.7

CLEARANCE DELIVERY: 119.55 WHEN ATCT CLSD 120.45

BORRN DP: 119.7

DREMR DP: 119.7

INDIE DP: 119.7

KARRR DP: 119.7

LURIC DP: 119.7

MMALT DP: 119.7

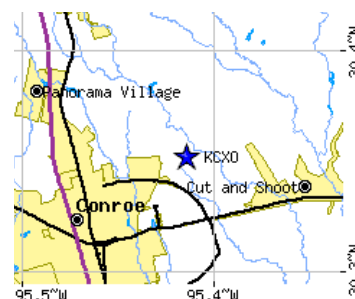
STRYA DP: 119.7

STYCK DP: 119.7

WATFO DP: 119.7

WYLSN DP: 119.7

WX ASOS at DWH (19 nm S): PHONE 281-251-7853

Road maps at: [MapQuest](#) [Bing](#) [Google](#) [Yahoo!](#)

Aerial photo

WARNING: Photo may not be current or correct



Nearby radio navigation aids

VOR radial/distance	VOR name	Freq	Var
IAH r346/24.0	HUMBLE VORTAC	116.60	05E
TNV r075/33.6	NAVASOTA VORTAC	115.90	08E

NDB name	Hdg/Dist	Freq	Var	ID
DAVID HOOKS	025/15.7	521	05E	DWH -
NIXIN	329/23.9	326	05E	BVP -
HUNTSVILLE	153/25.0	308	06E	UTS
WEISER	019/27.7	286	06E	EYQ

Airport Services

Fuel available: 100LL JET-A
 Parking: hangars and tie-downs
 Airframe service: MAJOR
 Powerplant service: MAJOR
 Bottled oxygen: HIGH/LOW
 Bulk oxygen: NONE

Runway Information

Runway 14/32

Dimensions: 6000 x 150 ft. / 1829 x 46 m
 Surface: concrete, in good condition
 Weight bearing capacity: Single wheel: 60.0
 Double wheel: 100.0
 Runway edge lights: medium intensity
RUNWAY 14
 Latitude: 30-21.557890N
 Longitude: 095-25.065068W
 Elevation: 230.1 ft.
 Gradient: 0.3%
 Traffic pattern: left
 Runway heading: 140 magnetic, 145 true
 Displaced threshold: 589 ft.
 Markings: precision, in good condition
 Visual slope indicator: 2-light PAPI on left (3.00 degrees glide path)
 Approach lights: MALSR: 1,400 foot medium intensity approach lighting system with runway alignment indicator lights

Runway end identifier lights: yes
 Touchdown point: yes, no lights
 Instrument approach: ILS/DME
 Obstructions: 10 ft. road, 200 ft. from runway, 40 ft. left of centerline
 10 FT ROAD FM THLD TO 200 FT.

RUNWAY 32
 30-20.742347N
 095-24.418363W
 241.3 ft.
 0.3%
 left
 320 magnetic, 325 true
 no
 nonprecision, in good condition

Runway 1/19

Dimensions: 5000 x 100 ft. / 1524 x 30 m
 Surface: concrete, in good condition
 Weight bearing capacity: Single wheel: 30.0
 Double wheel: 75.0
 Runway edge lights: medium intensity
RUNWAY 1
 Latitude: 30-20.737833N
 Longitude: 095-25.169333W
 Elevation: 229.6 ft.
 Gradient: 0.2%
 Traffic pattern: left
 Runway heading: 012 magnetic, 017 true
 Declared distances: TORA:5000 TODA:5000
 ASDA:5000 LDA:5000
 Markings: nonprecision, in good condition
 Visual slope indicator:

RUNWAY 19
 30-21.525833N
 095-24.888500W
 228.8 ft.
 0.2%
 left
 192 magnetic, 197 true
 TORA:5000 TODA:5000 ASDA:5000
 LDA:5000
 nonprecision, in good condition

Photo by Nigel Milligan / Kevin Williams
 Photo taken 25-Sep-2014
 looking west.

Do you have a better or more recent aerial photo of Lone Star Executive Airport that you would like to share? If so, please [send us your photo](#).

Sectional chart



Airport diagram

CAUTION: Diagram may not be current



Airport distance calculator

Flying to Lone Star Executive Airport? Find the distance to fly.

From to KCXO
[CALCULATE DISTANCE](#)

Sunrise and sunset

	Times for 06-Oct-2014	
	Local (UTC-5)	Zulu (UTC)
Morning civil twilight	06:55	11:55
Sunrise	07:19	12:19
Sunset	19:00	00:00
Evening civil twilight	19:24	00:24

Current date and time

Zulu (UTC)	06-Oct-2014 11:58:15
Local (UTC-5)	06-Oct-2014 06:58:15

METAR

KCXO 061153Z 00000KT 10SM CLR 18/18
 A2988 RMK AO2 SLP113 T01830178
 10189 20167 58001
KDWH 061053Z 00000KT 10SM CLR 20/18
 19nm S A2987 RMK AO2 SLP114 T02000183

TAF

KCXO 060520Z 0606/0706 00000KT P6SM
 FEW025 FM061000 15005KT P6SM
 BKN020 FM061600 17009KT P6SM
 VCSH SCT030 BKN120 FM061900
 17009KT P6SM VCSH SCT040 PROB30
 0619/0623 TSRA BKN040CB BKN250

NOTAMs

[Click for the latest NOTAMs](#)

NOTAMs are issued by the DoD/FAA and will open in a separate window not controlled by AirNav.

2-light PAPI on left (3.15 degrees glide path)	2-light PAPI on left (3.00 degrees glide path)
Touchdown point: yes, no lights	yes, no lights
Obstructions: none	4 ft. tree, 350 ft. from runway, 70 ft. right of centerline, 37:1 slope to clear

Airport Ownership and Management from official FAA records

Ownership: Publicly-owned
 Owner: MONTGOMERY COUNTY
 501 N. THOMPSON ST.
 CONROE, TX 77301
 Phone 936-539-7811
 Manager: SCOTT SMITH
 10260 CARL PICKERING MEMORIAL
 CONROE, TX 77303
 Phone 936-788-8311

Airport Operational Statistics

Aircraft based on the field: 329	Aircraft operations: avg 219/day *
Single engine airplanes: 234	58% local general aviation
Multi engine airplanes: 36	39% transient general aviation
Jet airplanes: 32	2% military
Helicopters: 3	<1% air taxi
Military aircraft: 24	* for 12-month period ending 30 July 2011

Additional Remarks

A23 HELICOPTERS USE RIGHT-HAND TRAFFIC.
 - EXTENSIVE MILITARY HELICOPTER ACTIVITY ON ARPT.
 - AVOID NOISE SENSITIVE AREA 10 MI SW QUADRANT OF ARPT.
 - UNMANNED ACFT MAY BE OPERATING IN THE IMMEDIATE AREA DURING DALGT HRS.

Instrument Procedures

NOTE: All procedures below are presented as PDF files. If you need a reader for these files, you should [download](#) the free Adobe Reader.

NOT FOR NAVIGATION. Please procure official charts for flight.
 FAA instrument procedures published for use between 18 September 2014 at 0901Z and 16 October 2014 at 0900Z.

STARs - Standard Terminal Arrivals

HUDZY TWO	2 pages: [1] [2]
OHIO TWO	download
RIICE SEVEN	2 pages: [1] [2]
WHAEL ONE	download

IAPs - Instrument Approach Procedures

ILS OR LOC RWY 14	download
RNAV (GPS) RWY 01	download
RNAV (GPS) RWY 14	download
RNAV (GPS) RWY 19	download
RNAV (GPS) RWY 32	download
NDB RWY 14	download
NOTE: Special Alternate Minimums apply	download (12KB)

Departure Procedures

ALEXANDRIA SIX	2 pages: [1] [2]
BORRN ONE (RNAV) **CHANGED**	2 pages: [1] [2]
BOWFN FIVE (RNAV)	download
CRIED FIVE	download
DREMR ONE (RNAV) **CHANGED**	2 pages: [1] [2]
EL DORADO FOUR	2 pages: [1] [2]
GIFFA FIVE	2 pages: [1] [2]
INDIE ONE (RNAV) **CHANGED**	2 pages: [1] [2]
INDUSTRY FIVE	2 pages: [1] [2]
JUNCTION SEVEN	download
KARRR TWO (RNAV) **NEW**	2 pages: [1] [2]
LAKE CHARLES TWO	download
LEONA EIGHT	2 pages: [1] [2]
LUFKIN SEVEN	2 pages: [1] [2]

LURIC ONE (RNAV) ****CHANGED**** 2 pages: [\[1\]](#) [\[2\]](#)
 MMALT ONE (RNAV) ****CHANGED**** 2 pages: [\[1\]](#) [\[2\]](#)
 PALACIOS FIVE 2 pages: [\[1\]](#) [\[2\]](#)
 STRYA ONE (RNAV) ****CHANGED**** 2 pages: [\[1\]](#) [\[2\]](#)
 STYCK ONE (RNAV) ****CHANGED**** [download](#)
 WATFO ONE (RNAV) ****CHANGED**** [download](#)
 WYLSN ONE (RNAV) ****CHANGED**** 2 pages: [\[1\]](#) [\[2\]](#)
 NOTE: Special Take-Off Minimums/Departure Procedures apply [download](#) (70KB)

Other nearby airports with instrument procedures:

[KDWH](#) - David Wayne Hooks Memorial Airport (19 nm S)
[6R3](#) - Cleveland Municipal Airport (21 nm E)
[KIAH](#) - George Bush Intercontinental/Houston Airport (22 nm S)
[KUTS](#) - Huntsville Municipal Airport (25 nm N)
[KEYQ](#) - Weiser Air Park (28 nm SW)

FBO, Fuel Providers, and Aircraft Ground Support

Business Name	Contact	Services / Description	Fuel Prices	Comments
 General Aviation Services	123.30 936-760-1717 [web site] [email]	In business since 1982, General Aviation Services will provide you with the best FBO services in the area. We are located center field between taxi ways Bravo and Charlie, the best location on the field for a quick turn around and convenient to all runways, which allows for a smooth and hassle free arrival and departure. We have the best prices in the area. Our experienced, professional, and courteous staff will see to your every request. Make your next stop with us and see why our customers keep coming back for more!" More info and photos of General Aviation Services 	 100LL Jet A FS \$5.65 \$5.10 SS \$5.25 --- GUARANTEED MEMBERS ONLY Discounts Login Join	★★★★★ 14 read write
 Galaxy FBO	ASRI 130.525 936-494-4252 [web site] [email]	Come see what has made Galaxy the best reviewed FBO at the LoneStar Executive Airport! Our friendly and attentive staff is always ready to assist you during your stay at KCXO. Free courtesy cars, volume fuel discounts, maintenance, rental car reservations, oxygen/nitrogen services, hotel reservations, catering, aircraft detailing. More info and photos of Galaxy FBO 	 100LL Jet A FS \$5.49 \$5.19 GUARANTEED MEMBERS ONLY Discounts Login Join	★★★★★ 12 read write
 Wing Jet Center, LLC	936-441-9555 toll-free 1-866-449-9555 [web site] [email]	Aviation fuel, Oxygen service, Aircraft parking (ramp or tiedown), Hangars, Hangar leasing / sales, GPU / Power cart, Passenger terminal and lounge, ...  More info about Wing Jet Center, LLC	 EPIC 100LL Jet A not yet rated FS \$6.69 \$5.25 GUARANTEED FS=Full service SS=Self service UPDATE PRICES	2 read write

Where to Eat: Catering, Restaurants, Food shops

Business Name	Contact	Services / Description	Distance	Comments
Black Walnut Cafe	936-202-2824 [web site]	Restaurant More info about Black Walnut Cafe	on airport	not yet rated 1 read write

Where to Stay: Hotels, Motels, Resorts, B&Bs, Campgrounds

In this space we feature lodging establishments that are convenient to the Lone Star Executive Airport. If your hotel/inn/B&B/resort is near the Lone Star Executive Airport, provides convenient transportation, or is otherwise attractive to pilots, flight crews, and airport users, consider listing it here.

FEATURE A LODGING ESTABLISHMENT

AirNav users who flew into KCXO have stayed at...

[COURTYARD BY MARRIOTT HOUSTON THE WOODLANDS](#)
[SUPER 8 CONROE](#)
[BAYMONT INN AND SUITES](#)
[DAYS INN CONROE](#)

Miles	Price (\$)
12.8	110-111
4.1	48-64
5.4	68-93
4.9	47-60

Hotels in other cities near Lone Star Executive Airport

9 in Conroe	3 in Magnolia
2 in Willis	3 in Cleveland
13 in The Woodlands	2 in New Caney
4 in Montgomery	

Other hotels near Lone Star Executive Airport

[HOLIDAY INN EXPRESS HOTEL & SUITES CONROE INTERSTATE45 NORTH](#)
[HAMPTON INN & SUITES CONROE INTERSTATE 45 NORTH](#)
[COMFORT INN CONROE](#)
[FAIRFIELD INN & SUITES BY MARRIOTT HOUSTON CONROE/WOODLANDS](#)
[LA QUINTA INN & SUITES CONROE](#)
[DAYS INN CONROE](#)
[RAMADA INN- CONROE/THE WOODLANDS](#)

Miles	Price (\$)
3.9	116-117
3.9	125-135
4.0	89-90
4.1	109-119
4.2	95-96
4.2	
5.5	66-70

Distances are approximate, and may vary depending on the actual route traveled and the location of the travel start on the airport.

Would you like to see your business listed on this page?

If your business provides an interesting product or service to pilots, flight crews, aircraft, or users of the Lone Star Executive Airport, you should consider listing it here. To start the listing process, click on the button below

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 [Page from the Texas Airport Directory \(PDF\)](#)

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APPENDIX B:

Data Reduction Procedures for Using Ground Vehicle Friction Measurements to Calculate Aircraft Tire Friction Performance (NASA CFME μ_B Model)

Tom Yager

Distinguished Research Associate
NASA Langley Research Center

Data Reduction Procedures
For
Using Ground Vehicle Friction Measurements
To
Calculate Aircraft Tire Friction Performance
Tom Yager, NASA Langley Research Center

Basic Data Requirements –

1. Accurate and suitable ground vehicle friction measurements must be collected through a speed range (e.g. 10-60 mph) for each wet surface condition evaluated.
2. The test tire(s) operating mode and inflation pressure must be properly maintained and documented
3. The test tire(s) operating mode should be selected to provide one of three friction boundary conditions: locked-wheel skidding, peak braked rolling, or peak yawed (cornering) rolling
4. A characteristic dry friction coefficient, μ_{cd} must be determined experimentally for each ground vehicle test tire operating mode by conducting test runs at very low speed (<3 mph)
5. The aircraft main landing gear tire inflation pressure value must be known

Overall Tire Friction Methodology – See figure 1

Data Reduction Procedures –

STEP 1 - Determine best fit curve for aircraft and ground vehicle friction- speed gradient data. Figure 2 provides an example of the friction data range obtained on a wet slurry seal asphalt surface with the NASA instrumental B-737 aircraft and four different ground test vehicles: a diagonal-braked vehicle, a mu-meter, a Saab friction tester, and a BV-11 skiddometer.

STEP 2 – For each test vehicle, calculate the minimum tire dynamic hydroplaning spin down speed using the following equation (see table I)

$$V_p, \text{Knots} = 9\sqrt{p} \quad (1a)$$

$$V_p, \text{mph} = 10.35\sqrt{p} \quad (1b)$$

where V_p , tire dynamic hydroplaning spindown speed

p , tire inflation pressure, psi

NOTE: Experimental data obtained with the mu-meter trailer indicates a V_p value of 45 mph rather than the 33 mph derived from eq. 1b. Use $V_p = 45 \text{mph}$ for mu-meter calculations.

STEP 3 – Tabulate characteristic dry friction coefficient values obtained experimentally for each ground vehicle test tire (see table I).

STEP 4 – Calculate characteristic dry friction coefficient value for air craft main gear tire using the following equation:

$$\mu_{cd} = 0.93 - 0.0011 p \quad (2)$$

where, μ_{cd} characteristic dry friction coefficient

p , tire inflation pressure, psi

NOTE: Table I gives these values for both the B-737 and B-727 aircraft together with the pertinent ground vehicle tire friction parameters.

STEP 5 – Select and tabulate an appropriate number (minimum 5) of the friction coefficient and ground speed values to properly define the friction-speed gradient data measured by each ground test vehicle. Determine the ground speed/hydroplaning speed ratio associated with each of the selected friction coefficient values (see table II).

STEP 6 – Determine ground vehicle tire hydroplaning parameter values using the following general relationship:

$$\bar{y} = \frac{\mu_{wet}}{\mu_{cd}} \quad (3)$$

where $\bar{y}$, tire hydroplaning parameter

μ_{wet} , Experimental or predicted wet pavement friction coefficient value

μ_{cd} , characteristic dry friction coefficient value

In determining the tire hydroplaning parameter, distinction is made between two types of tire operating modes-non rotating and rotating. For locked-wheel, sliding (non rotating) tire friction data (e.g. DBV), the tire hydroplaning parameter is labeled $\bar{y}_L$. For braked or yawed rolling (rotating) tire friction data (e.g. BV-11, SFT and Mu-meter), the tire hydroplaning parameter is labeled $\bar{y}_R$. The relationship between $\bar{y}_L$ and $\bar{y}_R$, which was empirically derived from NASA track aircraft tire test data, is given in table III. Hence, knowing one tire hydroplaning parameter allows determination of the other (see table III).

STEP 7 – Calculate aircraft tire maximum braking friction coefficient, μ_{max} , values by simply multiplying the $\bar{y}_R$ values determined in STEP 6 by the aircraft tire characteristic dry friction coefficient value determined for eq. 2 in STEP 4 (see table II).

STEP 8 – Determine estimated aircraft tire effective braking coefficient, μ_{eff} , values by use of the following equations:

$$\text{For } \mu_{max} < 0.7; \mu_{eff} = 0.2 \mu_{max} + 0.7143 \mu_{max}^2 \quad (4a)$$

$$\text{For } \mu_{max} \geq 0.7; \mu_{eff} = 0.7 \mu_{max} \quad (4b)$$

These relationships between aircraft tire maximum braking and effective braking friction coefficient are based on the assumption that the total aircraft braking system (tires, brakes, hydraulics, gear, and antiskid) efficiency can be generalized by a single curve defined by equations 4 a and b. Values derived for B-737 aircraft are listed in table II.

STEP 9 – Calculate an equivalent aircraft ground speed associated with each μ_{eff} value by multiplying the appropriate ground vehicle speed ratio obtained in STEP 5 by the aircraft tire hydroplaning speed determined in STEP 2 (see table II).

STEP 10 – Compare estimated aircraft tire friction performance to actual measured performance (see figure 3).

Supplemental Data Analysis –

1. Statistical methods should be used to identify data set tolerances and degree of confidence in data correlation.
2. Parameter sensitivity studies should be performed to define effects on data correlation agreement.

Table I.- Compilation of test aircraft and ground vehicle tire friction parameters

TEST PARAMETER	TEST AIRCRAFT		GROUND TEST VEHICLES			
	B-737	B-727	DIAGONAL BRAKED	MU- METER	FRICTION TESTER	BV-11 SKIDDOMETER
Tire: Size Infl. Press. kPa (psi) Tread design	Main gear 40 x 14 1069 (155) 4-Groove	Main gear 49 x 17 931 (135) 6-Groove	ASTM E524 G78 x 15 165 (24) Smooth	RL-2 4.00 - 8 69 (10) Smooth	RL-2 4.00 - 8 207 (30) Smooth	RL-2 4.00 - 8 207 (30) Smooth
Braking method	Maximum Antiskid	Maximum Antiskid	Locked Wheel	None (7.5° yaw)	Constant 10% Slip	Constant 17% Slip
Friction reading	μ_{EFF}	μ_{EFF}	μ_{SKID}	μ_{SIDE}	μ_{DRAG}	μ_{DRAG}
Spin-down hydroplaning Speed, V_p , knots (mph)	112* (129)	105* (121)	44.1* (50.8)	39.1 (45)	49.3* (56.7)	49.3* (56.7)
Low speed characteristic dry friction, μ_{cd}	0.76*	0.78*	1.20	0.90	1.10	1.10

* Calculated values using:

$$(V_p) \text{ spin-down} = 3.43 \sqrt{p}$$

for SI Units

$$\mu_{\text{cd}} = 0.93 - 1.6 \times 10^{-4} p$$

$$(V_p) \text{ spin-down} = 9 \sqrt{p}$$

for U.S. Customary Units

$$\mu_{\text{cd}} = 0.93 - 1.1 \times 10^{-3} p$$

where p, tire inflation pressure, kPa (psi)

Table II - Compilation of parameter values used to estimate aircraft braking performance from ground vehicle data
(a) Slurry seal asphalt surface; Truck wetted; Water depth 0.5mm (0.02 in.)

GROUND TEST VEHICLE	FAIRED μ	SPEED, V_G		V_G/V_P	TIRE HYDROPLANING PARAMETERS		ESTIMATED B-737 AIRCRAFT BRAKING			ACTUAL B-737 A/C μ_{EFF}
		KNOTS	MPH		$\bar{Y}_L$	$\bar{Y}_R$	μ_{MAX}	μ_{EFF}	V_G , KNOTS	
Diagonal	0.77	10	12	0.227	0.642	0.895	0.680	0.466	25.4	
Braked	.59	20	23	.454	.492	.742	.564	.340	50.8	0.365
Vehicle	.47	30	34	.680	.392	.642	.488	.268	76.2	.290
(DBV)	.38	40	46	.907	.317	.564	.429	.217	101.6	—
	.31	50	58	1.134	.258	.495	.376	.176	126.6	—
↓	.24	60	69	1.361	.200	.412	.313	.133	152.4	—
Saab	—	10	12	.203	—	—	—	—	22.7	—
Friction	.93	20	23	.406	.581	.845	.642	.423	45.5	.380
Tester	.78	30	34	.609	.460	.709	.539	.315	68.2	.315
(SFT)	.66	40	46	.811	.350	.600	.456	.240	90.8	.250
	.54	50	58	1.014	.255	.491	.373	.174	113.6	—
↓	.43	60	69	1.217	.188	.391	.297	.122	136.3	—
BV-11	—	10	12	.203	—	—	—	—	22.7	—
SKiddometer	.93	20	23	.406	.581	.845	.642	.423	45.5	.380
	.80	30	34	.609	.478	.727	.553	.329	68.2	.315
	.67	40	46	.811	.359	.609	.463	.246	90.8	.250
	.55	50	58	1.014	.262	.500	.380	.179	113.6	—
↓	.44	60	69	1.217	.193	.400	.304	.127	136.3	—
Mu-meter	.88	10	12	.256	.873	.978	.743	.520	28.7	.430
	.83	20	23	.512	.689	.922	.701	.491	57.3	.345
	.78	30	34	.767	.604	.867	.659	.442	85.9	.260
	.72	40	46	1.023	.544	.800	.608	.386	114.6	—
	.67	50	58	1.279	.494	.744	.565	.341	143.2	—
↓	.62	60	69	1.535	.441	.689	.524	.301	171.9	—

Table III. - Relationship between rotating ($\bar{Y}_R$) and nonrotating ($\bar{Y}_L$) tire hydroplaning parameters.

$\bar{Y}_R$	$\bar{Y}_L$	$\bar{Y}_R$	$\bar{Y}_L$	$\bar{Y}_R$	$\bar{Y}_L$	$\bar{Y}_R$	$\bar{Y}_L$	$\bar{Y}_R$	$\bar{Y}_L$
0.000	0.000	.200	.095	.400	.193	.600	.350	.800	.544
.005	.002	.205	.097	.405	.196	.605	.355	.805	.548
.010	.005	.210	.099	.410	.199	.610	.360	.810	.551
.015	.007	.215	.101	.415	.202	.615	.365	.815	.555
.020	.010	.220	.104	.420	.205	.620	.370	.820	.560
.025	.012	.225	.106	.425	.208	.625	.375	.825	.564
.030	.015	.230	.108	.430	.211	.630	.380	.830	.568
.035	.017	.235	.111	.435	.215	.635	.385	.835	.572
.040	.019	.240	.113	.440	.218	.640	.390	.840	.576
.045	.021	.245	.116	.445	.221	.645	.395	.845	.581
.050	.024	.250	.118	.450	.225	.650	.400	.850	.586
.055	.026	.255	.120	.455	.228	.655	.405	.855	.591
.060	.028	.260	.122	.460	.232	.660	.410	.860	.597
.065	.030	.265	.125	.465	.235	.665	.415	.865	.602
.070	.033	.270	.127	.470	.239	.670	.421	.870	.608
.075	.035	.275	.130	.475	.243	.675	.426	.875	.614
.080	.038	.280	.132	.480	.247	.680	.431	.880	.620
.085	.040	.285	.134	.485	.250	.685	.437	.885	.626
.090	.043	.290	.137	.490	.254	.690	.442	.890	.634
.095	.045	.295	.139	.495	.258	.695	.447	.895	.642
.100	.047	.300	.141	.500	.262	.700	.451	.900	.650
.105	.050	.305	.144	.505	.266	.705	.456	.905	.659
.110	.052	.310	.146	.510	.270	.710	.461	.910	.667
.115	.054	.315	.148	.515	.274	.715	.466	.915	.677
.120	.057	.320	.151	.520	.279	.720	.471	.920	.687
.125	.059	.325	.154	.525	.283	.725	.476	.925	.698
.130	.062	.330	.156	.530	.287	.730	.481	.930	.709
.135	.064	.335	.158	.535	.292	.735	.485	.935	.720
.140	.066	.340	.161	.540	.296	.740	.490	.940	.734
.145	.068	.345	.163	.545	.300	.745	.495	.945	.748
.150	.071	.350	.166	.550	.305	.750	.500	.950	.762
.155	.073	.355	.168	.555	.309	.755	.504	.955	.779
.160	.075	.360	.170	.560	.314	.760	.509	.960	.795
.165	.078	.365	.173	.565	.318	.765	.514	.965	.815
.170	.080	.370	.175	.570	.322	.770	.518	.970	.835
.175	.083	.375	.178	.575	.327	.775	.523	.975	.859
.180	.085	.380	.181	.580	.332	.780	.527	.980	.882
.185	.087	.385	.184	.585	.336	.785	.531	.985	.910
.190	.090	.390	.187	.590	.340	.790	.535	.990	.940
.195	.092	.395	.190	.595	.345	.795	.540	.995	.975
								1.000	1.000

Figure 1.- Methodology used to estimate aircraft tire friction performance.

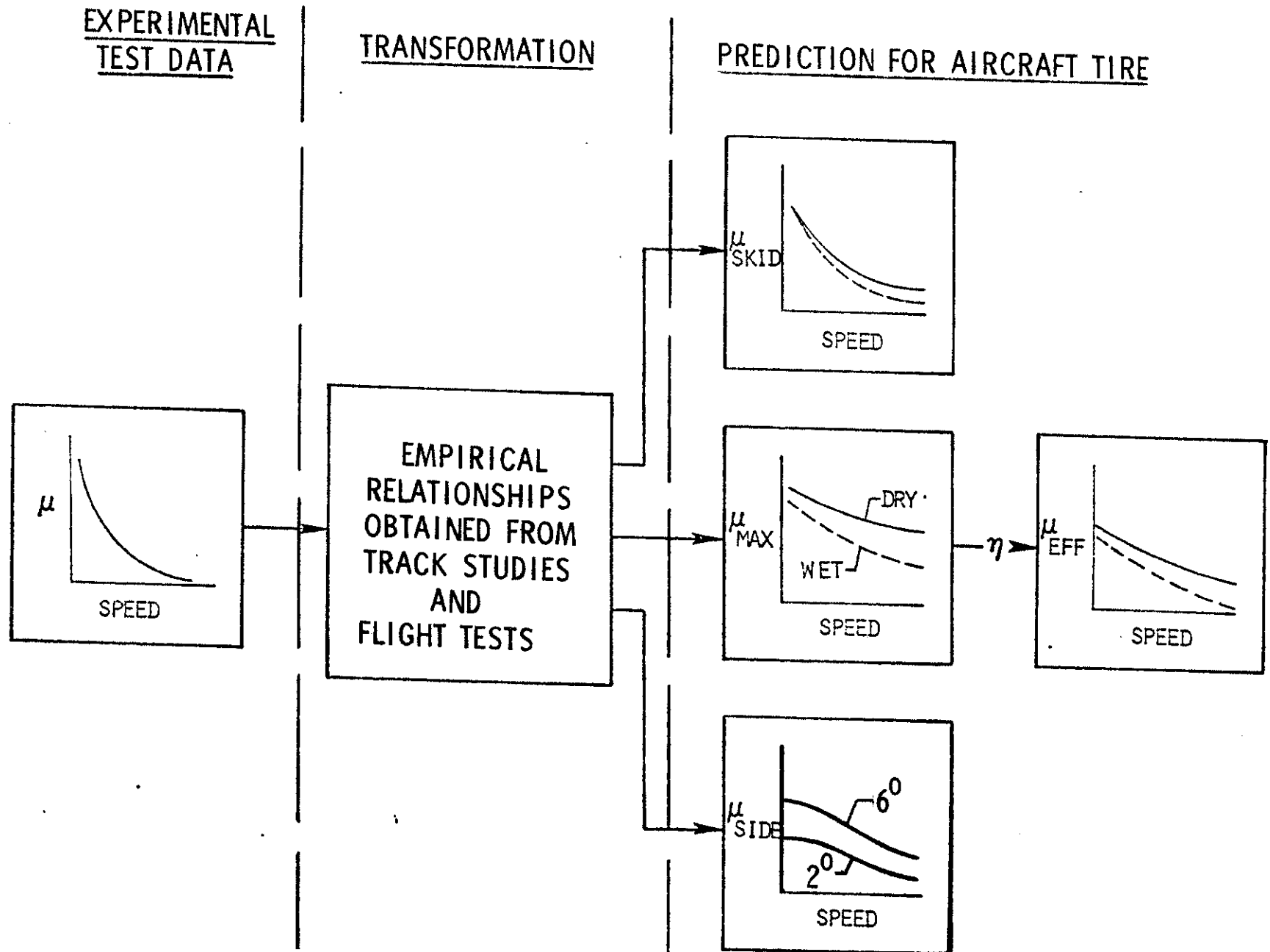


Figure 2 - RANGE OF AIRCRAFT AND GROUND VEHICLE PROTECTIVE MEASUREMENTS

SLURRY SEAL ASPHALT SURFACE
THICK WETTED WATER DEPTH 0.5 INCH (0.02 M)

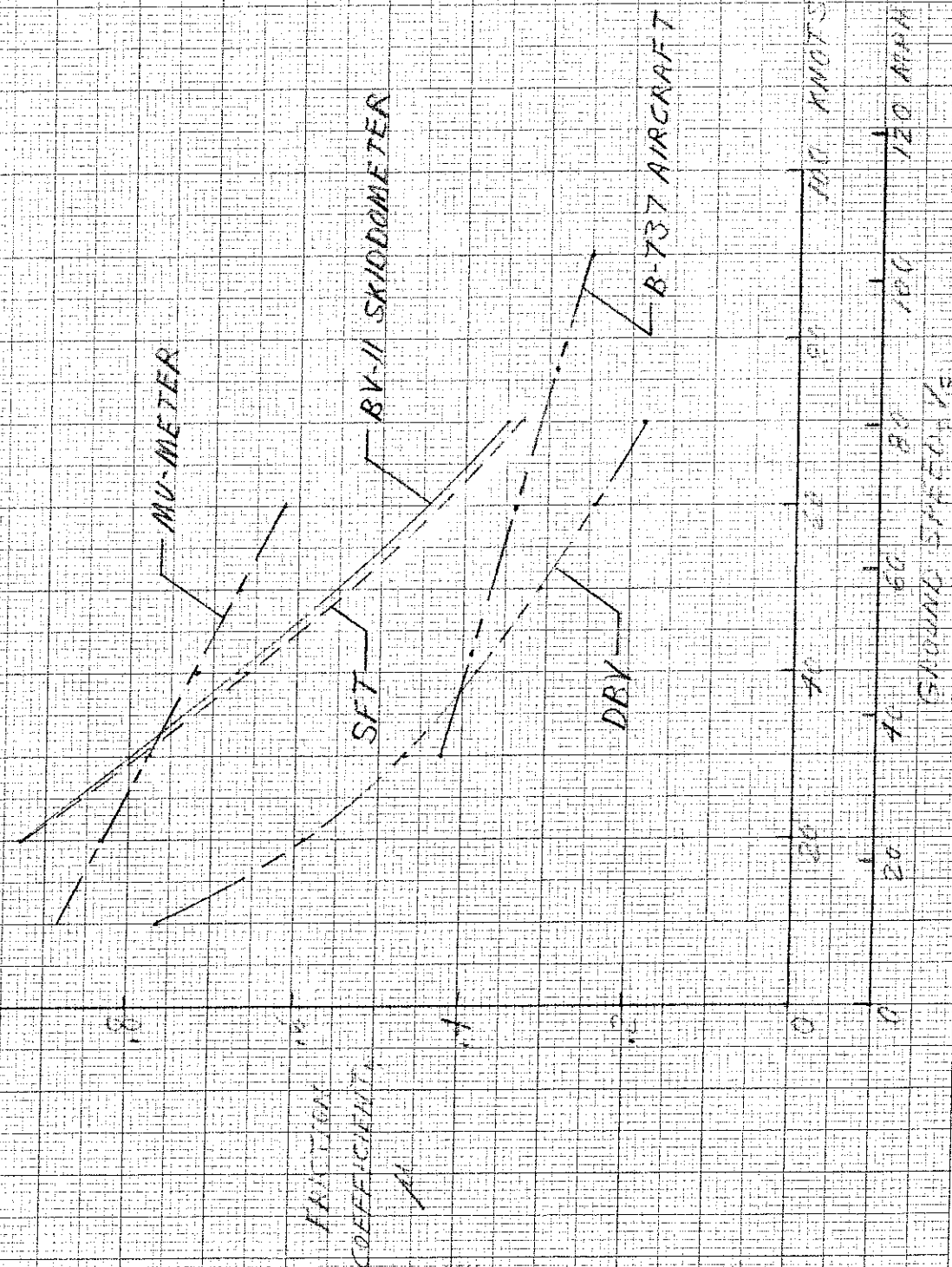
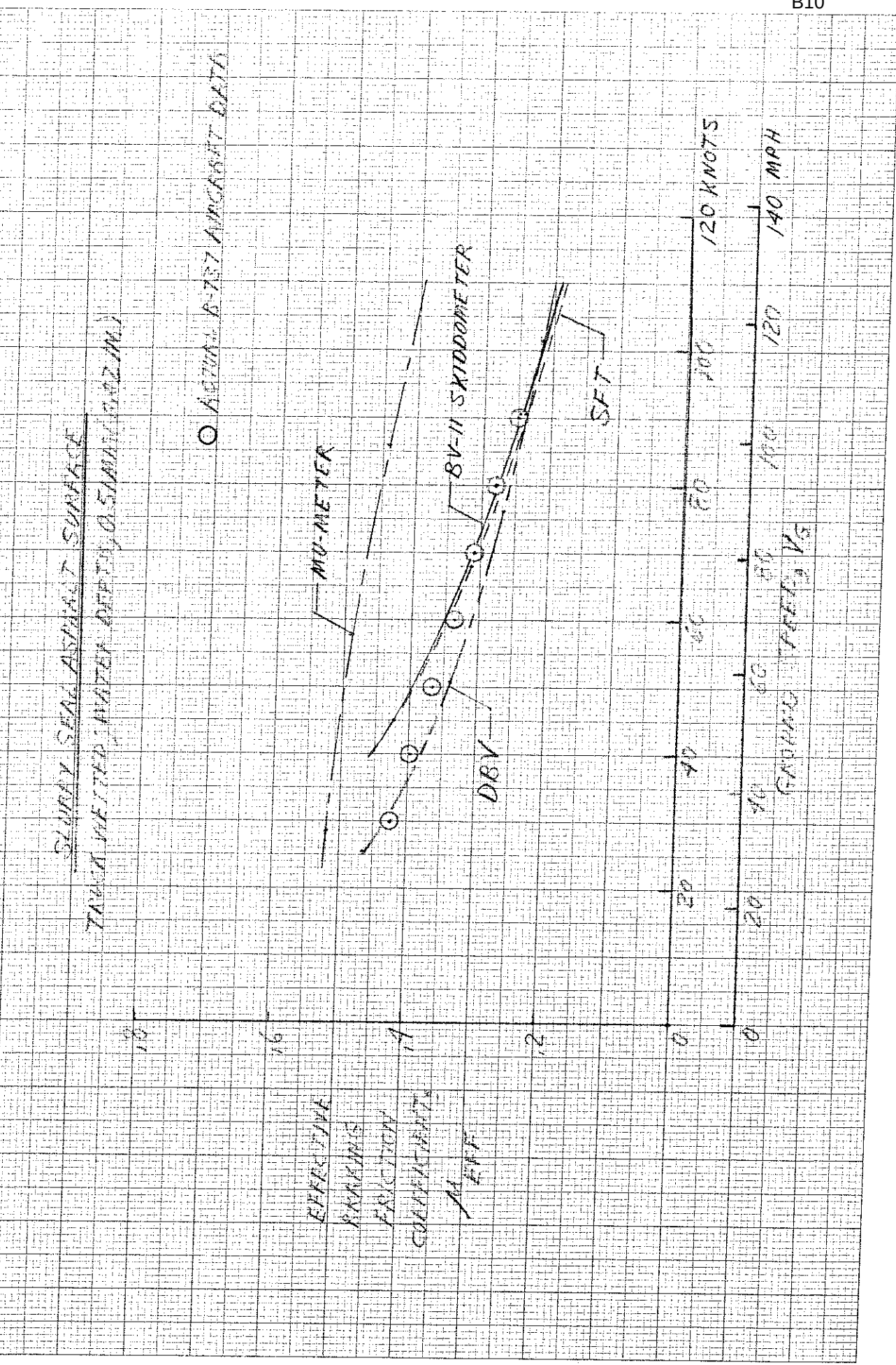


Figure 3. - ESTIMATED AIRCRAFT BRAKING PERFORMANCE FROM SPEED WHEEL FRICTION DATA

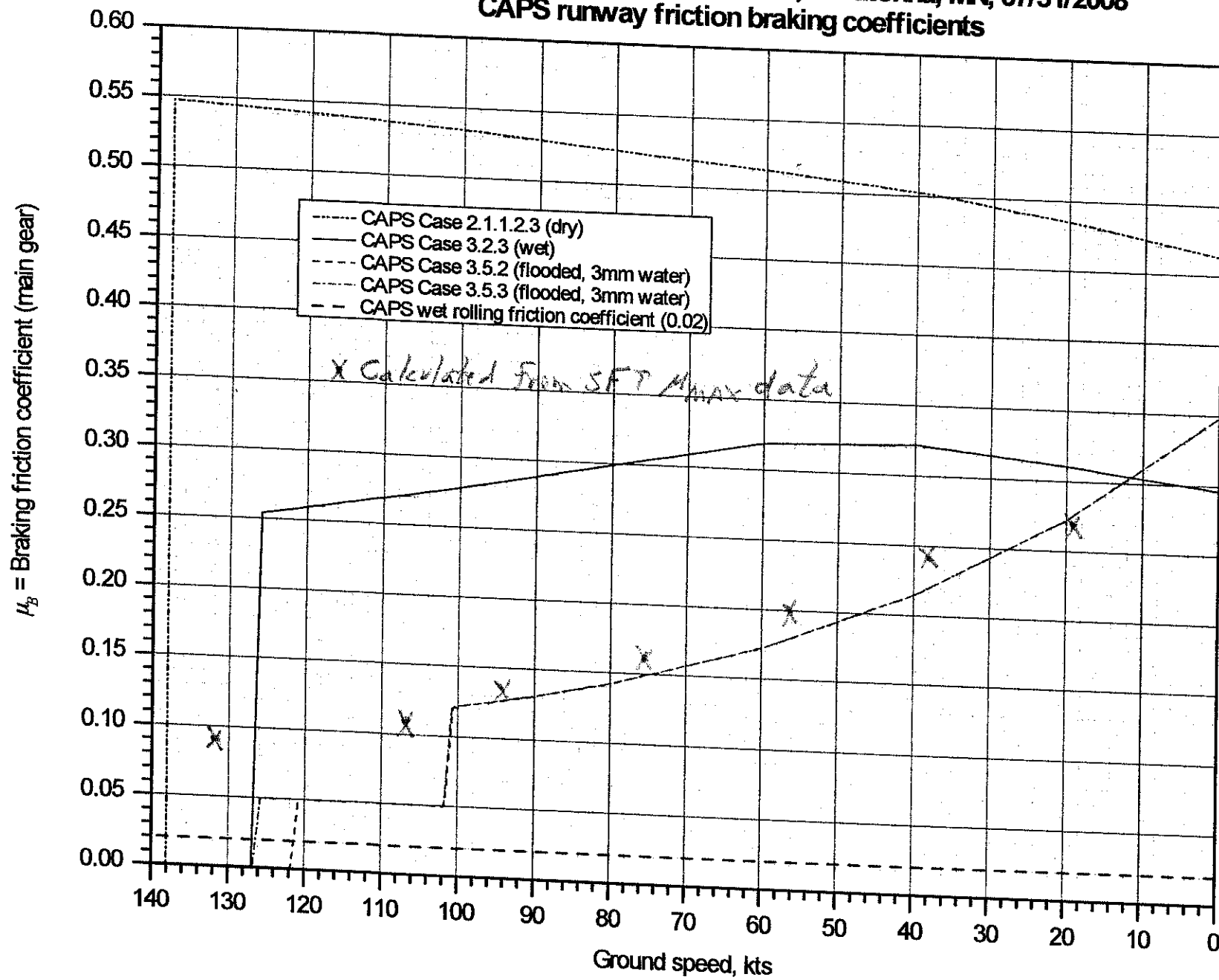


SET $M_{GRY} = 1.10$; $V_p = 50.9$ mph

SECRET

[illegible]

DCA08MA085: BAe125-800A, N818MV, Owatonna, MN, 07/31/2008
CAPS runway friction braking coefficients



APPENDIX C:

FAA Safety Alert For Operators (SAFO) 15009



SAFO

Safety Alert for Operators

U.S. Department
of Transportation
**Federal Aviation
Administration**

SAFO 15009
DATE: 8/11/15

Flight Standards Service
Washington, DC

http://www.faa.gov/other_visit/aviation_industry/airline_operators/airline_safety/safo

A SAFO contains important safety information and may include recommended action. SAFO content should be especially valuable to air carriers in meeting their statutory duty to provide service with the highest possible degree of safety in the public interest. Besides the specific action recommended in a SAFO, an alternative action may be as effective in addressing the safety issue named in the SAFO.

Subject: Turbojet Braking Performance on Wet Runways

Purpose: This SAFO warns airplane operators and pilots that the advisory data for wet runway landings may not provide a safe stopping margin under all conditions.

Background: Landing overruns which occur on wet runways typically involve multiple contributing factors such as long touchdown, improper use of deceleration devices, tailwind and less available friction than expected. Several recent runway landing incidents/accidents have raised concerns with wet runway stopping performance assumptions. Analysis of the stopping data from these incidents/accidents indicates the braking coefficient of friction in each case was significantly lower than expected for a wet runway as defined by the Federal Aviation Administration (FAA) in Federal Air Regulation (FAR) 25.109 and Advisory Circular (AC) 25-7C methods. These incidents/accidents occurred on both grooved and un-grooved or non-Porous Friction Course overlay (PFC) runways. The data indicates that applying a 15% safety margin to wet runway time-of-arrival advisory data as, recommended by SAFO 06012, may be inadequate in certain wet runway conditions.

Discussion: The root cause of the wet runway stopping performance shortfall is not fully understood at this time; however issues that appear to be contributors are runway conditions such as texture (polished or rubber contaminated surfaces), drainage, puddling in wheel tracks and active precipitation. Analysis of this data indicates that 30 to 40 percent of additional stopping distance may be required in certain cases where the runway is very wet, but not flooded.

For non-grooved or non-PFC runways, experience has shown that wheel braking may be degraded when the runway is very wet. If active moderate or heavy precipitation exists, the operator should consider additional conservatism in their time-of-arrival assessment.

For grooved or PFC runways, experience has shown that wheel braking is degraded when the runway is very wet. If active heavy precipitation exists; the operator should consider additional conservatism in their time-of-arrival assessment.

Possible methods of applying additional conservatism when operating on a runway which experience has shown is degraded when very wet are assuming a braking action of medium or fair when computing time-of-arrival landing performance or increasing the factor applied to the wet runway time-of-arrival landing performance data.

In some cases manufacturers have provided improved performance landing data for grooved/PFC runways. This improved performance grooved/PFC runway landing data should only be used when following any other Airplane Flight Manual (AFM) requirements and/or requirements of section 7 of AC 121-195(d)-1a, "FAR PART 121 OPERATIONAL APPROVALS OF AIRCRAFT WITH OPERATIONAL LANDING PERFORMANCE ON WET RUNWAYS" or equivalent operation specification.

Some of the wet runway braking shortfalls have occurred at US airports where Title 14 of the Code of Federal Regulations (14 CFR) 139 runway design and maintenance standards apply. Operators should be aware that the aforementioned runway design and maintenance standards may not be met in other countries. Many country's standards for design, construction and maintenance of runways are based on International Civil Aviation Organization (ICAO) Annex 14 runway design and maintenance standards, however they may lack oversight in implementation of these standards. Also, outside of the United States there is often less usage of grooving or PFC overlay which, when present, will normally aid in drainage and mitigate the risk of hydroplaning during active precipitation, thus impacting braking action.

Operators should be aware of the runway maintenance program and wet runway friction capability at the airports to which they operate. Mitigation should be considered at airports where aircraft operators have reason to suspect the runway's capability of creating good friction while very wet during active precipitation.

As stated initially the other common contributing factors for wet runway excursions are long touchdown, improper application of deceleration devices and tailwind landings. Aircraft operators should review their flight training programs to ensure flight crews are familiar with the assumptions used in creating the data used for the time-of-arrival assessment such as the assumed distance from threshold to touchdown, recommended uses of deceleration devices; aircraft operators should also ensure flight crews are aware of the wind assumed in the original dispatch calculations for the flight. Advisory Circular 91-79A has been recently updated to address these issues and operators should review the guidance contained therein.

In 2015 a committee of manufacturers and regulators will further investigate the issues with wet runway braking performance shortfalls. Airport and aircraft operators will be included in this investigation.

Recommended Action: Directors of safety and directors of operations (Part 121); directors of operations (part 135, and 125), program managers, (Part 91K), and Pilots (Part 91) should take appropriate action within their operation to address the safety concerns with landing performance on wet runways discussed in this SAFO.

Contact: Questions or comments regarding this SAFO should be directed to the Air Transportation, New Program Implementation Branch, AFS-240 at (202) 267-8166.