

NATIONAL TRANSPORTATION SAFETY BOARD

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

October 29, 2020

Aircraft Performance Study

by John O'Callaghan

Operator: Southwest Airlines flight 278

Location: Bob Hope Airport (KBUR), Burbank, California

Date: December 6, 2018

Time: 09:05 Pacific Standard Time (PST)
(17:05 Coordinated Universal Time (UTC))

Aircraft: Boeing 737-7H4, registration N752SW

NTSB#: DCA19IA036

TABLE OF CONTENTS

A.	INCIDENT.....	3
B.	GROUP	3
C.	HISTORY OF FLIGHT.....	3
	<i>Objective and scope of the Aircraft Performance Study.....</i>	<i>4</i>
	<i>Summary of results.....</i>	<i>5</i>
	<i>Summary of airborne performance during the approach and landing</i>	<i>7</i>
	<i>Summary of directional control and deceleration performance on the runway</i>	<i>8</i>
D.	DETAILS OF THE INVESTIGATION	10
I.	The Boeing 737-7H4 Airplane	10
II.	Ground Scars and Markings	11
III.	Surveillance data	11
IV.	Recorded flight data	12
	<i>FDR and CVR data description.....</i>	<i>12</i>
	<i>Correlation of FDR, CVR, and ADS-B Times.....</i>	<i>12</i>
V.	Performance Calculations based on FDR Data	13
	<i>Overview.....</i>	<i>13</i>
	<i>True airspeed calculation.....</i>	<i>14</i>
	<i>Pressure-based true altitude and density altitude calculations</i>	<i>16</i>
	<i>True altitude based on radio altimeter and terrain elevation data</i>	<i>17</i>
	<i>Accelerometer data corrections and integration.....</i>	<i>18</i>
	<i>Accelerometer integration results and consequent ILS deviations.....</i>	<i>20</i>
	<i>Flight path angle (γ), angle of attack (α), and sideslip angle (β) calculations</i>	<i>22</i>
	<i>Static pressure error correction.....</i>	<i>24</i>
	<i>Wind calculations.....</i>	<i>25</i>
	<i>Braking friction calculations</i>	<i>26</i>
VI.	Regulations and guidance concerning operations on wet runways	29
	<i>Overview.....</i>	<i>29</i>
	<i>Required AFM landing distance data for Part 25 transport category airplanes</i>	<i>31</i>
	<i>Operational regulations concerning dispatch and arrival landing distance assessments.....</i>	<i>33</i>
	<i>En-route landing distance assessments: CAT.OP.MPA.300 & FAA SAFOs 06012 & 19001</i>	<i>34</i>
	<i>Southwest Airlines Flight Operations Manual Requirements</i>	<i>36</i>

	<i>Guidance concerning braking performance on wet runways: SAFOs 15009 and 19003</i>	<i>37</i>
	<i>Flight Test Harmonization Working Group wet runway regulatory recommendations.....</i>	<i>39</i>
VII.	Comparison of wet-runway μ_B models and resulting landing distances	41
	<i>Overview.....</i>	<i>41</i>
	<i>Definition of 14 CFR §25.109 wet runway braking friction coefficients</i>	<i>42</i>
	<i>Comparison of achieved and modeled μ_B, and corresponding landing distances</i>	<i>45</i>
	<i>NASA μ_B model based on Continuous Friction Measurement Equipment (CFME) data</i>	<i>46</i>
	<i>CFME μ values defined in AC 150/5320-12C</i>	<i>49</i>
	<i>Expected μ_B for incident landing based on combined NASA CFME and §25.109 models.....</i>	<i>50</i>
	<i>μ_B “requested” via brake application</i>	<i>51</i>
	<i>The TALPA RCAM and AC 25-32.....</i>	<i>53</i>
	<i>Boeing 737-700 FCOM & SWA PWB landing distances for the incident conditions.....</i>	<i>55</i>
	<i>Comparison of incident flare and touchdown with previous flaps 40 landings.....</i>	<i>59</i>
	<i>Boeing RAAS and RSAT Flight Deck Enhancements.....</i>	<i>60</i>
E.	CONCLUSIONS	62
	<i>Execution of the approach and landing.....</i>	<i>62</i>
	<i>Reported vs. actual wind conditions</i>	<i>62</i>
	<i>Anticipated and achieved runway friction.....</i>	<i>62</i>
	<i>Flight deck enhancements for increasing situational awareness near runways.....</i>	<i>63</i>
F.	REFERENCES	64
G.	GLOSSARY	66
	<i>Acronyms.....</i>	<i>66</i>
	<i>English symbols.....</i>	<i>67</i>
	<i>Greek symbols.....</i>	<i>68</i>
	FIGURES	69
	APPENDIX A:	A1
	APPENDIX B:	B1

NATIONAL TRANSPORTATION SAFETY BOARD

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

October 29, 2020

Aircraft Performance Study

by John O'Callaghan

A. INCIDENT

Operator: Southwest Airlines flight 278
Location: Bob Hope Airport (KBUR), Burbank, California
Date: December 6, 2018
Time: 09:05 Pacific Standard Time (PST)
(17:05 Coordinated Universal Time (UTC))¹
Aircraft: Boeing 737-7H4, registration N752SW
NTSB#: DCA19IA036

B. GROUP

Chairman: John O'Callaghan
National Resource Specialist - Aircraft Performance
National Transportation Safety Board (NTSB)
490 L'Enfant Plaza E, SW
Washington, DC 20594

Members: N/A

C. HISTORY OF FLIGHT

On December 6, 2018, about 09:03 Pacific Standard Time, Southwest Airlines flight 278, a Boeing 737-7H4, N752SW, overran runway 08 during the landing roll at Bob Hope Airport (KBUR), Burbank, California, and came to rest in the engineered materials arresting system (EMAS) at the departure end of the runway. The 2 certificated airline transport pilots, 3 cabin crewmembers, and 112 passengers were not injured and evacuated the airplane via airstairs. The airplane sustained minor damage. The regularly scheduled domestic passenger flight was operating under the provisions of 14 Code of Federal Regulations Part 121. Instrument flight rules conditions prevailed at the airport at the time of the incident, and an instrument flight rules flight plan was filed for the flight, which originated at Metropolitan Oakland International Airport (KOAK), Oakland, California, about 0810 Pacific standard time.

¹ Local time at KBUR on the day of the accident was Pacific Standard Time (PST). PST = UTC - 8 hours. Times in this *Study* use PST unless otherwise noted.

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:

- Airplane resting location.
- Ground scars / markings.
- Air Traffic Control (ATC) surveillance (ADS-B) data.
- Flight Data Recorder (FDR) data.
- Cockpit Voice Recorder (CVR) information.
- Surveillance video information.²
- Runway 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.

This *Study* describes the results of using the data listed above in defining, as far as possible, the position of N752SW relative to the KBUR runway 8 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* compares the wheel braking friction coefficient (μ_B) achieved by N752SW during the incident landing with the μ_B underlying the wet-runway landing distances published in the Flight Crew Operating Manual (FCOM) (Reference 1) and computed by the Southwest Airlines (SWA) Performance Weight and Balance (PWB) system, and the μ_B predicted by a NASA model based on runway friction measurements that successfully predicts the μ_B achieved in other accident landings investigated by the NTSB (see Reference 9). While the achieved μ_B lies *between* the μ_B levels specified in transport category airplane certification standards for ungrooved (smooth) and grooved wet runways (KBUR runway 8 is grooved asphalt), it generally matches the μ_B predicted by the NASA model and assumed in the FCOM/PWB. Consequently, in this incident the achieved μ_B is consistent with operational expectations and hence does not raise the same concern as the lower-than-expected μ_B achieved in the accidents described in Reference 9. Nonetheless, the achieved μ_B is lower than the μ_B for grooved runways modeled in the certification standards, and indicates that these standards overestimate the μ_B achievable

² Video frames from 4 of 12 cameras that recorded portions of the incident landing are presented in *Addendum 1* to this *Study*.

on some wet grooved runways, just as Reference 9 indicates that the standards overestimate the μ_B achievable on some wet smooth runways.

The landing distances specified by the FCOM and PWB System are predicated not only on a μ_B model of the runway for a given runway surface condition,³ but also on the conduct of the approach and landing according to specified procedures and performance criteria. These include assumptions concerning approach speed, winds, the touchdown point, and the use of deceleration devices such as speedbrakes (spoilers), reverse thrust, and wheel brakes. The *Study* compares the conduct of the incident approach against these criteria, and quantifies how deviations from the assumed criteria affect the required landing distance.

Summary of results

Southwest Airlines (SWA) uses a “Performance Weight and Balance” software system⁴ to compute required landing distances based on airplane weight, flap setting, winds, and runway pavement conditions or braking action reports. The landing distance, approach reference speed (V_{REF}) and approach target speed (V_{TARGET})⁵ are provided by the PWB system in a “Landing Data Report.” For the incident landing, the Landing Data Report specified that, including a 15% safety factor, the airplane could stop on the 5,802 ft. runway with 245 ft. remaining, assuming the following conditions:

- Airplane weight = 120,800 lb.
- Flaps 40
- Autobrakes set to MAXIMUM
- Winds from 278° @ 5 kt.
- Temperature = 9° C
- Altimeter setting = 29.85” Hg
- V_{REF} = 126 kt.
- V_{TARGET} = 131 kt.
- Detent 2 reverse thrust on both engines
- Safety margin = 15% (i.e., the landing distance used to compute the runway length remaining after the stop is the distance required to stop multiplied by 1.15).

³ The runway surface condition in the FCOM is characterized by a “reported braking action,” as discussed in Section D-VII.

⁴ As stated in the SWA B737NG Aircraft Operating Manual (Reference 2), “The PWB System is a real-time, performance and weight and balance data computation system used to produce data required to operate an aircraft within the limitations specified in the Airplane Flight Manual (AFM) and CFRs.” Additional information about the PWB system can be found in References 2 and 3. For brevity, “the PWB system” is referred to in this *Study* simply as “the PWB.”

⁵ V_{REF} is the approach reference speed based on weight and flap setting specified in the Airplane Flight Manual. V_{TARGET} is the actual airspeed to be flown during the approach, and is equal to V_{REF} plus additives for winds and gusts, as specified in the Aircraft Operating Manual; the minimum V_{TARGET} is $V_{REF} + 5$ knots, and was used in this case.

In addition, the SWA B737NG Airplane Operating Manual (AOM) (Reference 2), in Section 12.1.1 “Normal Landing,” instructs the pilot flying to “touch down between 1,000 and 1,500 ft from the landing threshold on centerline”⁶ and notes that

PWB stopping margin information is based on the assumption that aircraft touchdown occurs not later than 1,500 ft from the usable end of the runway. If the aircraft lands beyond the 1,500-ft mark, the PWB System-computed stopping margin will be invalid, and in some cases, the runway length will be insufficient to stop the aircraft. ...

If touchdown occurs beyond 1,500 ft, the ability to stop on the remaining runway may be compromised. Also, if the current conditions are significantly different than the anticipated conditions at the time of PWB programming (e.g., wet runway vs. dry runway, tailwind vs. calm wind), the PWB System-computed stopping margin may be invalid.

If a landing is made in either of these situations, higher than planned braking may be needed to account for the reduced or insufficient stopping margin. The situation becomes more critical on shorter runways; therefore, a go-around is the better option. A go-around is possible until the thrust reverser levers are raised.

Section 11.8.1 of the AOM, titled “Go-Around/Missed Approach Requirements,” states that

The Pilot Flying must execute a go-around/missed approach if any of the following occur:

...

- The Pilot determines that a landing in the touchdown zone cannot be safely accomplished because of one or both of the following:
 - The required descent or maneuvering will exceed the stabilized approach criteria.
 - The aircraft touches down beyond 1,500 ft with an insufficient PWB System-computed stopping margin.

The results of this *Study* indicate that the airspeed over the runway threshold was 137 KIAS, or $V_{REF} + 11$ knots instead of the nominal $V_{REF} + 5$ knots; a tailwind of 13 to 18 knots was present over the runway, instead of the 5 kt. tailwind assumed in the PWB computation; and touchdown occurred about 2,500 ft. past the displaced threshold, or 1,000 ft. beyond the nominal 1,500 ft. touchdown point assumed in the PWB. All these factors act to increase the required landing distance beyond the distance computed by the PWB (and published in the FCOM), and per the criteria outlined in the AOM, make the PWB calculations “invalid.” At 5,802 ft., KBUR runway 8 is a relatively short runway (and is specifically identified as such in SWA training material⁷). Consequently, per the AOM, the higher tailwind and touchdown beyond 1,500 ft. would have made the incident landing “more critical” and “a go-around ... the better option.”

As noted above, the PWB incorporates a 15% safety margin into its landing distance calculations. Accounting for this margin and the touchdown point 1,500 ft. from the threshold assumed in the PWB calculations, the actual ground roll distance computed by

⁶ The AOM also instructs pilots to “use a normal aim point approximately 1,000 ft down the runway.”

⁷ Southwest Airlines “Distance Learning” module 2016 DL3 1.0, “General Review: Safety.”

the PWB is 3,145 ft.⁸ Since KBUR runway 8 is 5,802 ft. long, the touchdown point that results in the airplane stopping with zero runway remaining is 2,657 ft. from the threshold, per the PWB calculations. The airplane touched down 2,504 ft. from the threshold, but the higher airspeed and greater tailwind than assumed in the PWB calculations prevented it from stopping in the 3,145 ft. of ground roll computed by the PWB.

In this *Study*, the touchdown points that result in zero runway remaining for the *actual* airspeed and tailwind present during the incident are calculated, for different μ_B models, including those underlying the FCOM “good” braking action landing distances, the μ_B underlying both smooth and grooved wet runways in airplane certification standards, and the actual μ_B achieved during the incident landing. In all cases, except for the grooved wet runway μ_B model, the airplane would have had to touch down before the actual 2,504 ft. mark in order to stop before the end of the runway. With the grooved wet runway μ_B model, the airplane could have touched down as far as 2,853 ft. from the threshold and still have stopped on the runway. However, neither the FCOM nor the PWB take credit for the higher μ_B modeled for grooved wet runways in the certification standards (these standards are described in Section D-VI).

As noted above, a tailwind of 13 to 18 knots was present over the runway, based on the true airspeed and ground speed computed from the FDR data. This tailwind is consistent with winds recorded by the Automated Surface Observation System (ASOS) on the field; however, the tailwind reported to the flight crew by the Burbank Air Traffic Control (ATC) tower and through the Automatic Terminal Information Service (ATIS) was only about 5 to 11 kt.⁹ The maximum tailwind allowed by the SWA AOM is 10 kt.

Summary of airborne performance during the approach and landing

This *Study* examines the performance of N752SW from the time it descended through about 2,000 ft. above mean sea level (MSL) on final approach, to its resting point about 71 ft. into the EMAS, about 144 ft. past the end of runway 8. The summary descriptions of N752SW's performance during the approach, landing, and rollout provided in this and the following subsection are developed in greater detail, and with supporting plots and figures, in subsequent sections of the *Study*.

At 09:01:00, N752SW was configured for a flaps 40 landing with the landing gear extended as it descended through 1,980 ft. MSL (1,253 ft. above the touchdown zone elevation (TDZE) of 727 ft.) at an indicated airspeed of 138 knots (KIAS) and rate of descent of 1,039 ft./min. The airplane was on glide slope and centerline for the runway 8 ILS

⁸ To compute this number, the landing distance available assumed by the PWB must be known; this distance is cited in the Landing Data Report as 5,587 ft., which is shorter than the physical 5,802 ft. length of the runway. The PWB computes the available distance as the distance from the glideslope antenna to the end of the runway, plus 1,000 ft. The PWB places the glideslope antenna 1,215 ft. from the threshold, so the available distance is 5,802 ft. – 1,215 ft. + 1,000 ft. = 5,587 ft. The PWB landing distance required for the incident landing, which includes a 15% safety margin, is therefore 5,587 ft. – 245 ft. runway remaining = 5,342 ft. Removing the 15% safety margin, the actual distance required is 5,342 ft. / 1.15 = 4,645 ft. The PWB assumes a 1,500 ft. air distance, so the actual landing roll required is 4,645 ft. – 1,500 ft. = 3,145 ft.

⁹ See Table 5.

approach, with the autopilot and autothrottle engaged. Per Reference 3, the Captain was the pilot flying (PF). The flaps 40 landing reference speed (V_{REF}) at the landing weight of 120,600 lb. was 126 kt.; the target approach speed of $V_{REF} + 5$ kt. was 131 kt.¹⁰ The true airspeed at 09:01:00 was 147 kt., and due to a 5 kt. tailwind, the ground speed was 152 kt.

N752SW remained on-glideslope and on-centerline, with the airspeed varying between 130 and 138 KIAS, until the autopilot and autothrottle were disconnected at 09:02:01.8. Following the autopilot and autothrottle disconnect, the airplane started to drift to the right of the centerline. The maximum lateral drift was about 60 ft. to the right of the centerline at 09:02:14, about 2,890 ft. (0.48 nm) from the runway threshold, after which the airplane returned to the centerline at 09:02:27, about 480 ft. from the runway threshold.

The Instrument Landing System (ILS) glide slope Course Deviation Indicator (CDI) parameter recorded on the FDR indicated that N752SW started to drift above the glide slope at 09:02:10, about 3,986 ft. (0.66 nm) from the threshold, with the glide slope CDI deviation increasing steadily past this point.

N752SW crossed the runway threshold at 09:02:25, at a radio altitude of 54 ft.¹¹ and at an indicated airspeed of 137 kt. (140 kt. after correcting for static port pressure errors), a true airspeed of 140 kt., and a ground speed of 156 kt., corresponding to a 16 kt. tailwind. The throttles were reduced from 52° (corresponding to about 60% N1) to idle (36°) at 09:02:32, 7 seconds and 1,700 ft. past the threshold. The airplane touched down at 09:02:34.8, 9.8 seconds after crossing the threshold, 2,504 ft. from the threshold, at an indicated airspeed of 126 kt. (132 kt. after correcting for static port pressure errors), a true airspeed of 133.5 kt., and a ground speed of 151 kt., corresponding to a 17.5 kt. tailwind.

Summary of directional control and deceleration performance on the runway

At 09:02:35, immediately after touchdown, the speedbrake handle moved aft to 46° and the speedbrakes deployed. The speedbrake handle movement was most likely an automatic deployment as the result of main gear tire spin-up and gear compression; the position of the handle recorded on the FDR prior to touchdown indicates it was in the “armed” position, as it would have had to have been for the deployment to have been automatic following main gear wheel spin-up and gear compression.¹²

¹⁰ The flap setting, gear position, and airplane weight were recorded by the FDR. The V_{REF} speeds are published in the FCOM. The SWA B737NG AOM (Reference 2) states that to compute the approach speed, “add wind factor of ½ headwind component + peak gust (min 5 kt, max 15 kt)” to V_{REF} . Airspeed corrections due to static port pressure errors, and the wind speed and direction present during the approach and landing, are presented in Section D-V of this *Study*. The approach speed of 131 kt. is also listed in the PWB Landing Data Report, and cited in Reference 3; however, the Mode Control Panel (MCP) speed recorded on the FDR was 132 kt. The 131 kt. target speed is used in this *Study*.

¹¹ The radio altitude measures the distance from the ground to the bottom of the main landing gear.

¹² The “speedbrake armed light” parameter recorded on the FDR is also consistent with the speedbrake being armed prior to touchdown. A description of the Boeing 737 speedbrake system can be found at <http://www.b737.org.uk/flightcontrols.htm>.

The throttles commanded idle reverse thrust on both engines at about 09:02:35, immediately after touchdown, and detent 2 reverse thrust¹³ at about 09:02:37. Between 09:02:41 and 09:02:55, maximum reverse thrust¹⁴ was commanded on both engines and maintained until the airplane came to rest at 09:02:59.3. Reverse thrust N1 of about 74% was achieved at 09:02:40, and about 81% at 09:02:42.

The right wheel brake pressure was steady near 0 psi until 09:02:34, and then rose to about 600 psi at 09:02:35 and then to 800 psi at 09:02:39 before jumping to 3,000 psi (corresponding to full manual braking) at 09:02:41, and remaining there until 09:02:58, a second before the airplane came to rest. The left wheel brake pressure was steady near 400 psi until about 09:02:36, and then rose steadily, reaching and maintaining 3,000 psi at about the same time as the right brake pressure. Consequently, maximum brake pressure on both left and right brakes was achieved at about 09:02:41, or about 6 seconds after touchdown.

During the landing roll, N752SW tracked within 13 ft. of the runway centerline until 09:02:47, when, 5,020 ft. from the threshold and with 782 ft. of runway remaining, it started to move left of centerline.¹⁵ The deviation to the left continued until the airplane crossed the left edge of the runway at 09:02:52, 5,590 ft. from the threshold, and 212 ft. from the runway end. The airplane passed the end of runway 8 at 09:02:55, 24 ft. to the left of the runway edge, and at a ground speed of 37 kt. At 09:02:56.4, N752SW entered the EMAS, about 102 ft. to the left of the runway centerline (27 ft. to the left of the runway edge) and 5,875 ft. from the runway threshold, at a ground speed of 30 kt. The airplane came to rest at 09:02:59.3, about 71 ft. into the EMAS.

The forces contributing to the deceleration of the airplane were aerodynamic drag, reverse thrust, and tire braking friction. The braking friction force on each tire is equal to the normal (vertical) force on the tire, multiplied by the braking friction coefficient (μ_B) between the tire and the runway. The calculation of μ_B from FDR data is described in detail below; here it suffices to note that the driving parameter in the calculation is the longitudinal load factor (n_x) recorded on the FDR, which is a measure of the airplane's deceleration.

At 09:02:38, about three seconds after touchdown, the n_x was about -0.3 G's.¹⁶ Starting at 09:02:43, the n_x decreased (deceleration increased), reaching about -0.42 G's at about 09:02:45, and oscillating between -0.4 and -0.26 G's between 09:02:45 and 09:02:52. After the airplane crossed the left runway edge onto ungrooved pavement, the n_x increased

¹³ The detent 2 reverse thrust corresponds to a throttle resolver angle of about 10°.

¹⁴ Maximum reverse thrust corresponds to a throttle resolver angle of about 6°.

¹⁵ The record of the Captain's interview with NTSB investigators (Reference 22) states that the Captain "saw the large area at intersection D1 [and] thought he might be able to make the turnoff at D1. He tried to use the left rudder and tiller to turn the aircraft but didn't feel like it was responding, so he continued into the EMAS."

¹⁶ Load factors are measured in units of acceleration (distance/time²), normalized by the acceleration due to gravity (32.17 ft./s.²), expressed in "G's." On the runway, positive n_x denotes acceleration (increasing speed), and negative n_x denotes deceleration (decreasing speed).

(deceleration decreased) to between -0.008 and -0.022 G's. After the airplane entered the EMAS, the deceleration increased significantly, with n_x reaching -0.6 G's at 09:02:57.

As noted above, the achieved μ_B during the landing roll lies between the μ_B levels specified in transport category airplane certification standards for ungrooved and grooved wet runways, and generally matches the μ_B predicted by the NASA model and assumed in the FCOM/PWB. At 09:02:40, about 5 seconds after touchdown, the computed μ_B was about 0.14. Starting at about 09:02:43, the μ_B increased, reaching 0.3 at about 09:02:45, and increasing further to 0.4 at 09:02:51. After the airplane crossed the left runway edge onto ungrooved pavement, the μ_B decreased to about 0.1, before starting to increase again at 09:02:55. As shown in Figure 2b, the airplane is on a white-colored pavement while to the left of the runway, but before the runway end; and over a darker-colored pavement in the 73 ft. section between the end of the runway and the beginning of the EMAS. The friction characteristics of these pavements are likely different, and might account for the increase in μ_B before the airplane enters the EMAS at 09:02:56.4. In the EMAS itself, the effective "friction coefficient" is as high as 0.7 (though the deceleration provided by the EMAS arises mainly from the energy required to break down and displace the EMAS material, not just from frictional forces between the bottom of the tires and the material supporting the tires). The calculation of μ_B , and comparisons of the achieved μ_B with the μ_B levels underlying the FCOM landing distances and with various μ_B models for wet runways, are treated at length in Sections D-V and D-VII.

D. DETAILS OF THE INVESTIGATION

I. The Boeing 737-7H4 Airplane

The Boeing 737-7H4 is a 737-700, with the "H4" designation identifying the delivery customer (in this case, Southwest Airlines). Figure 1 shows a 3-view image of the Boeing 737-700, taken from Reference 4. Table 1 provides some dimensions of the airplane, as well as relevant mass properties for N752SW on the incident flight. The airplane weight at landing was determined from the FDR, and the center of gravity (C.G.) is an estimate based on interpolating takeoff weight and zero-fuel weight C.G. values reported on the flight's Weight and Balance Report to a C.G. corresponding to the landing weight.

Item	Value
<i>Reference dimensions:</i>	
Wing area	1,341 ft. ²
Wing span	112.58 ft.
Mean Aerodynamic Chord (MAC)	12.98 ft.
<i>Mass properties for N752SW:</i>	
FDR-recorded weight at landing	120,600 lb.
Takeoff weight and C.G. per Weight and Balance Report	125,700 lb. / 22.8% MAC
Takeoff fuel load per Weight and Balance Report	17,400 lb.
Zero-fuel weight and C.G. per Weight and Balance Report	108,300 lb. / 19.3% MAC
Estimated center of gravity (C.G.) position at landing weight	21.8% MAC

Table 1. Dimensions of the Boeing 737-700 airplane, and relevant mass properties for N752SW.

II. Ground Scars and Markings

KBUR runway 8 is asphalt, 5,802 ft. long and 150 ft. wide, grooved, with a threshold elevation of 727.4 ft. The elevation of the departure end of the runway is 697.3 ft., giving the runway an average gradient of -0.5% (downhill). For additional details about KBUR and its runways, see Appendix A.

Neither the NTSB nor the FAA traveled to KBUR following the incident, and so no on-scene activities, such as surveys of the runway and EMAS, were conducted by these organizations. However, a photograph of N752SW at rest in the EMAS published by news media (KTLA) is shown in Figure 2b. Based on this photograph, the airplane's C.G. is estimated to have come to rest 71 ft. into the EMAS, 144 ft. past the end of runway 8, and about 107 ft. to the left of the runway centerline.

III. Surveillance data

N752SW was tracked by both ground-based radar stations, and by the Automatic Dependent Surveillance – Broadcast (ADS-B) system. ADS-B capability enables aircraft to broadcast their three-dimensional position (latitude, longitude, and altitude) to other ADS-B equipped aircraft and to ADS-B ground stations. ADS-B latitude and longitude are determined using Global Navigation Satellite System (GNSS) signals, including those from Global Positioning System (GPS) satellites, and altitudes determined both barometrically and by GNSS are included in ADS-B messages. The GNSS positions are very accurate compared to radar data; radar range uncertainty alone (without even considering azimuth uncertainty) is about $\pm 1/16$ nmi, or ± 380 ft., and GNSS positions are generally accurate to within 60 ft. (see Reference 23). Furthermore, ADS-B data is available at a higher frequency (typically 1 sample/second) than radar data (at best, 1 sample every 4.5 seconds). Consequently, only the ADS-B surveillance data for N752SW are presented in this *Study*. The ADS-B positions are used to confirm the latitude and longitude parameters recorded on the FDR, and the kinematically consistent airplane positions computed through mathematical integration of the load factors (accelerations) recorded by the FDR, as described in Section D-V.

The recorded ADS-B data includes the following parameters:

- UTC time of the ADS-B report, in hours, minutes, and seconds. PST = UTC – 8 hours.
- Aircraft identifying information.
- Latitude and longitude, to a resolution of 0.01 arc-seconds (≈ 1 ft.)
- Pressure altitude in feet, to the nearest 25 ft. (an uncertainty band of ± 12.5 ft.)
- Geometric (GNSS) altitude in feet, to the nearest 25 ft.
- North-south and east-west components of ground speed, to a resolution of 1 kt.
- Rate of climb, to a resolution of 1 ft./min.
- Numerous parameters documenting the quality and accuracy of each reported GNSS position.

The sample rate of this data is a consistent 1 sample / sec (1 Hz). The ADS-B data is presented along with recorded flight data in subsequent sections of this *Study*.

IV. 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 2. The paraphrased version of the selected CVR events listed in Table 2 are also presented along with other information in various Figures throughout this *Study*. For the complete transcript and CVR report, see Reference 6.

FDR time (EDT)	Selected CVR items full transcript text	Paraphrased text on plots
09:01:26.8	[HOT-2] that's twenty knots on the butt.	[HOT2] [FO comments on tailwind]
09:01:36.2	[BUR] wind two seven zero at one one.	[BUR] wind 270 at 11.
09:01:51.6	[HOT-2] alright we got eleven nots. You want to call it good?	[HOT2] [FO questions captain ...]
09:02:01.8	[CAM] [sound similar to autopilot disconnect]	[CAM] [... autopilot disconnect]
09:02:22.0	[CAM] one hundred. [automated voice]	[CAM] 100. [automated voice]
09:02:25.2	[CAM] fifty. [automated voice]	[CAM] 50. [automated voice]
09:02:27.5	[CAM] thirty. [automated voice]	[CAM] 30. [automated voice]
09:02:30.7	[CAM] 10. [automated voice]	[CAM] 10. [automated voice]
09:02:34.8	[CAM] [sound similar to speedbrake handle]	[CAM] [... speedbrake handle]
09:02:35.4	[CAM] [sound similar to landing gear touchdown]	[CAM] [... landing gear touchdown]
09:02:36.5	[CAM] [sounds similar to thrust reverser deployment]	[CAM] [... thrust reverser...]

Table 2. Full CVR transcript text corresponding to paraphrased text on plots in this *Study*. Audio sources are: [CAM] = Cockpit Area Microphone; [HOT2] = First Officer's hot microphone; [BUR] = Burbank Aircraft Control Tower.

Correlation of FDR, CVR, and ADS-B Times

The FDR, CVR, and ADS-B system 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 (FDR time), converted into PST.

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:

$$(\text{Seconds elapsed since midnight PST}) = (\text{FDR SRN}) - 65414.707 \text{ seconds} \quad [1]$$

Equivalently,

$$09:00:00 \text{ PST FDR time} = 97814.707 \text{ FDR SRN} \quad [2]$$

The correlation between the FDR and CVR times is described in Reference 5. The CVR transcript provided in Reference 6 uses the FDR PST time.

The ADS-B time is aligned with the FDR time using pressure altitude. Pressure altitude is recorded on both the FDR and in the ADS-B data stream; to align the ADS-B pressure altitude with the FDR pressure altitude, 0.4 seconds were subtracted from the times recorded in the ADS-B file (see Figure 3). Consequently,

$$(\text{FDR time in PST}) = (\text{ADS-B time in PST}) - 0.4 \text{ seconds} \quad [3]$$

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 content was recorded. The content portrayed on the plots is not the verbatim CVR transcript text, but rather a paraphrase or shorthand code for this text. The full CVR transcript text associated with each paraphrase or code is shown in Table 2.

V. 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 errors¹⁷ 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 120,600 lb. and 21.8% MAC, respectively. Further details about 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:

- Static pressure errors during the landing flare and rollout that introduce errors in the recorded calibrated airspeed and pressure altitude.
- Accelerometer bias errors.
- Magnetic heading errors.

¹⁷ “Measurement error” in this context means the difference between the actual true value of the property 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, or from the necessity of measuring a property that is only approximately equal to the desired property (for example, the static pressure measured at the airplane’s static ports may not exactly equal the freestream static pressure, which is the desired property).

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

- True airspeed and altitude.
- Kinematically consistent positions and velocities from accelerometer integration.
- Wind speed and direction while airborne, and headwind / tailwind on the ground.
- Braking friction coefficient developed during the ground roll.

The results of these corrections and derivations for the period from the airplane's descent through 1,100 ft. above the runway to its at-rest location in the EMAS are presented in Figures 2 – 15.¹⁸

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 5 shows the results of the true airspeed calculation, compared with the indicated (calibrated) airspeed recorded by the FDR. Figure 4 shows that the airplane crossed the runway threshold at 09:02:25.3. At this time, Figure 5 shows that the FDR airspeed is 136.8 knots calibrated airspeed (KCAS) as recorded, and 140.4 KCAS after correcting for static port pressure errors (this correction is described below). The recorded and corrected true airspeeds are within a knot of the corresponding calibrated airspeeds. Figure 5 also shows the ground speed recorded by the FDR, and the ground speed computed from integration of the accelerometer data (this calculation is also described below); the integrated ground speed differs from the FDR ground speed in places because it is forced to be kinematically consistent with the latitude and longitude positions recorded by the FDR and the known at-rest point. The recorded ground speed is not necessarily kinematically consistent with the FDR positions, and is non-zero at the time that recorded load factor evidence indicates that the airplane came to rest (see discussion below).

During the time the airplane is rolling down the runway, the ground speed is about 13 to 18 kt. greater than the corrected true airspeed, indicating a tailwind in this range. This tailwind component is consistent with winds recorded by the ASOS on the field; however, the tailwind reported to the flight crew by the Burbank Air Traffic Control (ATC) tower and through the Automatic Terminal Information Service (ATIS) was only about 5 to 11 kt. The METAR observations and ASOS winds surrounding the time of the incident (from Reference 8) are presented in Tables 3 and 4, respectively; and the wind reports to the

¹⁸ 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.

crew (from Reference 3) are shown in Table 5. A more rigorous calculation of the winds during the approach and rollout is described below, and presented in Figure 11.

Parameter / Report	KBUR METAR 07:53 PST	KBUR METAR 08:53 PST	KBUR METAR 09:53 PST
Sky condition	1,100 ft. broken, 1,700 ft. broken, 4,700 ft. overcast	400 ft. few, 1,300 ft. overcast	200 ft. few, 2,600 ft. broken, 4,800 ft. overcast
Visibility	1.25 statute miles	1.5 statute miles	2.5 statute miles
Winds	290° @ 5 kt.	280° @ 11 kt.	290° @ 5 kt.
Temperature / Dew Point	9°C / 9°C	8°C / 8°C	8°C / 7°C
Altimeter setting	29.86 "Hg	29.91 "Hg	29.96 "Hg
Precipitation	Heavy rain, mist	Heavy rain, mist	Heavy rain, mist

Table 3. METAR weather observations at KBUR surrounding the time of the incident. Wind directions are relative to true north.

Time, PST	2 minute average wind, kt.	Max 5-second wind, kt.	Weather	Precipitation amount, inches
08:45	265° 14	259° 17	R+	0.00
08:46	264° 15	261° 16	R	0.00
08:47	261° 14	260° 16	R	0.01
08:48	259° 14	256° 17	R+	0.01
08:49	259° 14	260° 17	R+	0.01
08:50	266° 15	268° 16	R+	0.01
08:51	270° 14	266° 16	R+	0.01
08:52	273° 13	276° 14	R+	0.02
08:53	278° 11	275° 13	R+	0.02
08:54	278° 10	282° 13	R+	0.01
08:55	276° 11	269° 16	R+	0.01
08:56	274° 13	281° 19	R+	0.01
08:57	269° 14	268° 16	R+	0.02
08:58	267° 14	267° 17	R+	0.01
08:59	268° 16	267° 19	R+	0.01
09:00	269° 16	268° 18	R+	0.02
09:01	273° 15	275° 18	R+	0.01
09:02	279° 14	284° 18	R+	0.00
09:03	282° 14	276° 19	R+	0.01
09:04	281° 13	273° 16	R+	0.01
09:05	279° 13	274° 18	R+	0.01
09:06	275° 15	269° 19	R+	0.00
09:07	273° 17	271° 21	R+	0.01
09:08	273° 19	271° 21	R+	0.01
09:09	274° 17	276° 20	R+	0.01
09:10	279° 14	279° 16	R+	0.02
09:11	282° 12	280° 15	R+	0.01
09:12	284° 11	281° 14	R+	0.02
09:13	284° 12	278° 15	R+	0.02
09:14	284° 11	273° 13	R+	0.02
09:15	290° 8	267° 10	R+	0.01
09:16	299° 7	303° 9	R+	0.02

Table 4. ASOS weather observations at KBUR surrounding the time of the incident, from Reference 8. In the "Weather" column, R = moderate rain, R+ = heavy rain. Precipitation amounts are precipitation collected over 1 minute. Wind directions are relative to true north.

Time	Source	Wind direction / velocity
08:22	07:53 KBUR METAR via ACARS ¹⁹	290° true / 278° mag @ 5 kt.
08:59	KBUR ATC tower controller	260° @ 9 kt.
09:01	KBUR ATC tower controller	270° @ 10 kt.
09:02	KBUR ATC tower controller	270° @ 11 kt.

Table 5. KBUR surface wind information provided to the flight crew. Wind directions reported by the tower are relative to magnetic north. Magnetic variation at KBUR is 12° E.

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 N752SW, 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 solution of the hydrostatic equation is shown in Figures 2 and 3 as the blue line labeled "Target for accelerometer integration." This result is modified and shifted upwards to match the known altitude of the airplane while it is over the runway, equal to the radio altitude plus the terrain elevation (the need for this shift results from static pressure measurement errors, as described below). Accounting for the lower-than-standard temperature of the day changes the rate of change of altitude with distance (Figure 2) or time (Figure 3) slightly, compared to the rate of change of pressure altitude.²⁰

The indicated altitude shown on the airplane's altimeters is obtained by adjusting the FDR pressure altitude to account for the 29.91" Hg altimeter setting reported in the 08:53 METAR (see Table 3). Note that the indicated altitude places the airplane below the terrain elevation during the time the airplane is on the ground; this is evidence that there is some error in the pressure measured at the airplane's static pressure ports. The solid magenta line in Figures 2 and 3 is the indicated altitude corrected for the static port pressure error (the correction is described below), and correctly places the airplane slightly above the terrain while on the ground. Note that the corrected indicated altitude deviates slightly from the hydrostatically derived altitude (blue line) as altitude increases; this deviation results from the nonstandard lapse rate of pressure with altitude.

¹⁹ The Aircraft Communications Addressing and Reporting System (ACARS) is a digital datalink system for transmission of short messages between aircraft and ground stations via airband radio or satellite.

²⁰ The standard-day temperature at the field elevation of 727 ft. is 13.6° C (56.4° F); at 8° C (46.4° F), the temperature was 5.6° C (10.0° F) lower than standard.

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 cooler-than-standard day, and temperature variations during the descent, the density altitude during the approach and landing was 500 to 800 ft. lower than the true MSL altitude.

True altitude based on radio altimeter and terrain elevation data

The green line in Figures 2 and 3 labeled “Terrain elevation + FDR radio altitude” is the altitude that results from adding the height of the airplane’s main gear tires above the ground (measured by the radio altimeter) to the elevation of the terrain underneath the airplane. An additional 11 ft. is added to this result to account for the distance from the bottom of the main gear tires to about the middle of the fuselage. The terrain elevation is determined by using the FDR latitude and longitude data to define the airplane’s track over the ground, and then by 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 coverage²¹. The resolution of the terrain data used in this *Study* is 1 arc-second.

Note that the “Terrain elevation + FDR radio altitude” altitude is well-behaved during the flare and touchdown, whereas the FDR pressure altitude exhibits unrealistic “waviness” in this area. The waviness of the FDR pressure 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 FDR pressure altitude during the landing flare and rollout, on approach the radio altimeter-based data shows oscillations that are likely due to the resolution of the radio altitude data and to undulations in the terrain or other terrain features (such as buildings), and do not indicate variations in the airplane’s MSL altitude. The oscillations are reduced near the runway, where the terrain is flatter. In turn, the FDR pressure altitude is well-behaved at higher altitudes, but exhibits unrealistic waviness near touchdown. Consequently, a better estimate of the altitude during the entire approach and landing would use a pressure-based altitude during the approach, transitioning to the radio-based altitude near the runway; this is the method used to construct the blue “Target for accelerometer integration” line in Figures 2 & 3. However, the altitude constructed in this way may not be entirely kinematically consistent with the load factor data recorded on the FDR. In addition, while the FDR ground speed parameter is relatively accurate, it may not be entirely kinematically consistent with the FDR load factor data or the FDR and ADS-B position data. “Kinematically consistent” means that the mathematical relationships between acceleration (measured by load factor parameters), speed (measured by the ground speed and heading parameters), and position (measured by the FDR and ADS-B position parameters) hold in the three dimensions of the airplane’s motion. In practice, the FDR parameters as recorded are only approximately kinematically consistent, as a result of inherent measurement errors and

²¹ See <http://viewer.nationalmap.gov/viewer/>.

uncertainties (such errors are obvious in the FDR position data, as shown in the bottom plot of Figure 4a).

In light of these errors and uncertainties, a better, kinematically consistent solution for the airplane's altitude, position, and speed throughout the approach and landing can be 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 “Accelerometer integration” is the altitude that results from integrating²² 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 pressure-based altitude data.

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 integration.²³ 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 N752SW's approach, landing, and rollout, the flight path was divided into three segments (approach, landing, and rollout), and the accelerometer data was integrated separately for each segment. For the rollout segment, the “target” positions for the accelerometer integration are those resulting from an integration of the FDR ground speed and track angle, after the ground speed has been “corrected” to read zero at the time the FDR n_x data indicates the airplane came to rest, and the FDR heading has been corrected to match the runway heading. For the approach and landing segments, the “target” positions for the accelerometer integration are defined by the FDR data points shown in Figure 4, and by the blue “Target for accelerometer

²² In the following discussion, “integrating” the load factor data refers to mathematical integration with respect to time, per the theorems of Calculus.

²³ For details about the equations to be integrated and the bias correction technique described in this *Study*, see Appendix A of Reference 7.

integration” line shown in Figure 3. In addition, the solution is forced to be continuous (no discontinuities in position or speed) at the boundaries between segments. The integration is solved in “reverse,” starting at the end of the data (with the airplane at rest in the EMAS), and progressing backwards in time, ending at about 1,980 ft. MSL altitude. Solving the problem in reverse makes it easier to match the known end point in the EMAS.

The dashed green line in the top plot of Figure 5 shows the “corrected” FDR ground speed; it matches the recorded ground speed until about 09:02:55, and then is made to deviate below the recorded ground speed, and reach a value of zero at 09:02:59.3. This is the time the airplane came to rest in the EMAS, as determined by the jump in n_x from about -0.6 G’s to about 0.1 G’s shown in Figure 6.

The dashed black line in the bottom plot of Figure 7 shows the corrected FDR magnetic heading. The resulting corrected true heading using a magnetic variation of 12° E is shown as the solid blue line. Note the corrected true heading approximately matches the runway true heading of 90.93° , making it consistent with surveillance video footage of the landing that shows the airplane tracking the runway centerline. The corrected magnetic heading is shifted $+2^\circ$ from the recorded magnetic heading. The true track angle is computed by adding the FDR drift angle to the corrected true heading.

The corrected ground speed and computed true track angle are combined to obtain north and east components of the ground speed, and these components are integrated to produce the target east and north coordinates for the rollout segment of the accelerometer integration.

For the rollout segment, the constants of integration (the initial ground speed, track angle, and rate of climb) are zero since the integration starts with the airplane at rest. For the landing and approach segments, the constants of integration are defined by the end values of the corresponding parameters in the previous segment. Since the integration is performed in reverse, the “initial” conditions for the rollout segment are those in the EMAS (the actual end of the rollout); the initial conditions for the landing segment are those at the start of the rollout; and the initial conditions for the approach segment are those at the start of the landing. The accelerometer biases in each segment 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 path and target path coincide at the end of the integration over each segment.

The approach segment starts at about 1,982 ft. MSL and ends at 1,264 ft. MSL; the landing segment starts at the end of the approach segment, and ends shortly after the FDR weight on wheel parameter switches to the “on ground” state; and the rollout segment starts at the end of the landing segment, and ends with the airplane at rest in the EMAS. The beginning and end times, constants of integration, and accelerometer biases used for the three segments are shown in Table 6. The constants of integration for the rollout segment are expressed as increments, or biases, on the initial ground speed, track, and rate of climb that would be computed using the target trajectory (and are zero in this case, since the target trajectory ends at rest in the EMAS). For the landing and approach segments,

the initial ground speed and rate of climb are set equal to the values of these parameters at the boundary with the adjacent segment, and so the increment or bias is not applicable.

Segment	Start time (EDT)	End time (EDT)	Speed bias, knots	Track bias, degrees	Rate of climb bias, ft/min	n_x bias, G's	n_y bias, G's	nlf bias, G's
Approach	09:01:00	09:01:50	n/a	n/a	n/a	-0.01932	0.00081	-0.01168
Landing	09:01:50	09:02:38	n/a	n/a	n/a	-0.00945	0.00273	-0.00935
Rollout	09:02:38	09:02:59.3	0	0	0	-0.02061	0.00250	-0.01084

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

Accelerometer integration results and consequent ILS deviations

The airplane position and altitude resulting from the final integrated trajectory for all three segments (approach, landing and rollout) are shown in Figures 2, 3, and 4 as the lines with the “Accelerometer integration” label. The ground speed and rate of climb resulting from the integrated trajectory are plotted in Figure 5.

The corrected load factors are compared to the load factors recorded by the FDR in Figure 6. Figures 2 and 4 indicate that the path over the runway resulting from the accelerometer integration is in generally good agreement with both the FDR and ADS-B position data, and is therefore a satisfactory solution.

The dashed gray lines in the bottom plot of Figure 2 depict the runway 8 Instrument Landing System (ILS) glide slope 1 and 2 “dot” deviation boundaries. The instrument approach plate for the KBUR ILS runway 8 approach itself is presented in Figure 8. The computed deviations from the localizer and glideslope beams, in terms of “dots,” based on the accelerometer integration positions are compared to the deviations recorded on the FDR in Figure 9. The definition of the ILS beam geometry and the measurement of deviation from the localizer and glide slope beams in terms of “dots” is described below.

ILS beam geometry definition – localizer: When an aircraft is on the centerline of the glide slope and localizer beams, its ILS radio receivers will sense a “null,” or 0 μA , signal. As the aircraft deviates from the centerline of the beams, the receivers start to sense signals that will deflect the cockpit instrument localizer and glide slope needles.

The localizer heading may be aligned with the runway heading, or it may be offset by a few degrees. The aircraft localizer receiver will sense a 90 Hz signal if the aircraft is left of the (localizer) centerline and a 150 Hz signal if it is right of centerline. The strength of the signal varies with the angular displacement from the center of the localizer beam. The signal is null (0 μA) at the center and increases with angular deflection from center. The width of the localizer is defined by the angular deflection between a 150 μA “fly right” (airplane left of centerline) signal and a 150 μA “fly left” (airplane right of centerline) signal. The signal strength corresponding to a given localizer needle deflection on the cockpit instrument depends on the specific instrument used, but for the 737 and large aircraft in general, a 150 μA signal corresponds to a “2 dot” deflection of the needle. On these

aircraft, the localizer scale is two dots left and right, so a 2 dot or 150 μA signal corresponds to full scale needle deflection.

The angular displacements from the localizer centerline to the 150 μA “fly right” and “fly left” signals are not necessarily symmetric. The actual angles are defined by the localizer “Symmetry,” as follows:

$$\begin{aligned}\text{Angular deflection to 150 } \mu\text{A “fly right” signal} &= (\text{Course Width}) * (\text{Symmetry}) \\ \text{Angular deflection to 150 } \mu\text{A “fly left” signal} &= (\text{Course Width}) * (1 - \text{Symmetry})\end{aligned}$$

The “Symmetry” is a number between 0 and 1. A symmetrical localizer will have a “Symmetry” of 0.5 or 50%.

ILS Beam Geometry Definition – glide slope: The centerline of the glide slope beam is set at the “glide slope angle” from the runway. The altitude of the beam at a given point depends on the distance from the glide slope antenna, the height of the antenna above the runway, and the glide slope angle. The curvature of the Earth must also be taken into account when determining the altitude of the beam.

The aircraft glide slope receiver will sense a 90 Hz signal if the aircraft is above the beam centerline and a 150 Hz signal if it is below the centerline. The strength of the signal varies with the angular displacement from the center of the glide slope beam. The signal is null (0 μA) at the center of the beam and increases with angular deflection from the center. The width of the glide slope is defined by the angular deflection between a 75 μA “fly up” signal and a 75 μA “fly down” signal. The signal strength corresponding to a given glide slope needle deflection on the cockpit instrument depends on the specific instrument being used, but for the 737 and large aircraft in general, a 75 μA signal corresponds to a “1 dot” deflection of the needle. On these aircraft, the glide slope scale is two dots up and down, so a 1 dot or 75 μA signal corresponds to a half scale needle deflection.

The angular displacements from the glide slope centerline to the 75 μA “fly up” and “fly down” signals are not necessarily symmetric. The actual angles are defined by the glide slope “Symmetry,” as follows:

$$\begin{aligned}\text{Angular deflection to 75 } \mu\text{A “fly down” signal} &= (\text{GS Width}) * (\text{Symmetry}) \\ \text{Angular deflection to 75 } \mu\text{A “fly up” signal} &= (\text{GS Width}) * (1 - \text{Symmetry})\end{aligned}$$

The “Symmetry” is a number between 0 and 1. A symmetrical glide slope will have a “Symmetry” of 0.5 or 50%.

The parameters that define the localizer and glide slope geometry for the ILS at K BUR runway 8 are presented in Table 7, based on an FAA ILS inspection report dated 11/20/2018. Note that the localizer antenna is located *before* the runway threshold, as opposed to the usual location beyond the end of the runway (the reason for this might be space limitations beyond the end of runway 8). The computed localizer deviations

are not valid past the x-runway coordinate of localizer antenna, and the computed glide slope deviations are not valid past the x-runway coordinate of the glide slope antenna.

Figure 9 indicates that the computed ILS beam deviations based on the accelerometer integration positions match the deviations recorded by the FDR relatively well. Note that the linear deviations (distances from centerline) corresponding to the angular deviations plotted in this Figure decrease as the distance from the ILS antennas decreases (0.5 “dots” of deviation represents a much smaller linear distance near the antenna than far from the antenna). The top plot in Figure 9 shows the airplane deviating above the glide slope starting at about 09:02:10.

Runway and localizer data	
Runway heading (degrees true)	90.93°
Localizer heading (degrees true)	90.93°
Runway x-coordinate of localizer antenna	-.1657 nm (ahead of runway threshold)
Localizer course width	5.13°
Localizer symmetry (applied to “fly right”)	49.3%
Number of dots for full scale deflection	2
Glide slope data	
Elevation of glide slope antenna	725.2 ft.
Effective glide slope antenna height (to obtain RDH)	-2.25 ft.
Reference Datum Height (RDH) (height above threshold)	723 ft.
Glide slope angle	3.01°
Runway x-coordinate of glide slope antenna	0.2018 nm
Glide slope half-width	0.63°
Glide slope symmetry (applied to “fly down”)	45.9%
Number of dots for full scale deflection	2

Table 7. KBUR ILS runway 8 geometry data.

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

The flight path angle is defined by

$$\gamma = \sin^{-1} \left(\frac{\dot{h}}{V} \right) \quad [4]$$

where γ is the flight path angle, $\dot{h}$ is the rate of climb, and V is speed. Using true airspeed gives γ relative to the airmass, and using ground speed gives γ relative to the Earth. If $\dot{h}$ and V from the pressure-based altitude²⁴ and true airspeed calculations described above are used in Equation [4], the resulting γ is very noisy (i.e., it contains unrealistic “spikes” and oscillations). A better (smoother) calculation of γ results from using $\dot{h}$ and V from integrated accelerometer data. The γ relative to the Earth using $\dot{h}$ and ground speed from the accelerometer integration is shown as the red line in the top plot of Figure 7. The γ relative to the airmass using the same $\dot{h}$ and the corrected true airspeed described above

²⁴ This is the altitude labeled “Target for accelerometer integration” in Figures 2 and 3.

is shown as the green line in the top plot of Figure 7. The $\dot{h}$ used in these calculations is shown as the red line in the bottom plot of Figure 5.

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 10). This angle is required to resolve the airspeed of the airplane into components along each of the airplane's axes, which in turn are 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 (while the airplane is airborne) 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 (δ_r):

$$C_Y = \frac{Y}{\frac{1}{2}\rho V^2 S} = \frac{\partial C_Y}{\partial \beta} \beta + \frac{\partial C_Y}{\partial \delta_r} \delta_r + \{\text{smaller terms}\} \quad [5]$$

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 [5] can be solved for an estimate of β :

$$\beta \cong \frac{C_Y - \frac{\partial C_Y}{\partial \delta_r} \delta_r}{\frac{\partial C_Y}{\partial \beta}} \quad [6]$$

The derivatives $\partial C_Y / \partial \beta$ and $\partial C_Y / \partial \delta_r$ are aerodynamic characteristics of the airplane.

The side force Y can be calculated using

$$Y = (W)(n_y) \quad [7]$$

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, as is the rudder angle δ_r . Consequently, Y and β are also very small. 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 :

$$\alpha = \tan^{-1} \left(\frac{\tan \theta}{\cos \phi} \right) - \sin^{-1} \left(\frac{\sin \gamma + \sin \beta \cos \theta \sin \phi}{\cos \beta \sqrt{1 - \cos^2 \theta \sin^2 \phi}} \right) \quad [8]$$

Note that when $\beta = \phi = 0$, Equation [7] simplifies to the well-known result that

$$\alpha = \theta - \gamma \quad [9]$$

As shown in Figure 7, during the approach $|\phi| < 5^\circ$, and so Equation [9] is an excellent approximation (the difference between the results of Equations [8] and [9] is at most 0.02°). The α resulting from Equation [9], using γ relative to the airmass based on $\dot{h}$ from the accelerometer integration, is presented as the blue line in the top plot of Figure 7.

Static pressure error correction

The static pressure measurement error used in this *Study* is defined as

$$\Delta P = P_{TRUE} - P_{MEASURED} \quad [10]$$

where P_{TRUE} is the actual freestream static pressure, and $P_{MEASURED}$ is the static pressure sensed at the airplane static ports, as determined from the FDR pressure altitude data.

To calculate P_{TRUE} , the known static pressure on the ground and the altitude resulting from the accelerometer integration are used in the hydrostatic equation to compute the lapse of static pressure with altitude. As noted above, the hydrostatic equation describes the pressure increment across a differential element of air required to balance the weight of the element:

$$dP = -(\rho)(g)dh \quad [11]$$

Where dP is the differential pressure change, g is gravitational acceleration, dh is the differential altitude change, and ρ is air density:

$$\rho = \frac{P}{RT} \quad [12]$$

Where P is the static pressure, T is the static temperature, and R is the gas constant of air. Substituting Equation [12] into Equation [11] gives

$$dP = -\left(\frac{P}{RT}\right)(g)dh \quad [13]$$

Equation [13] can be integrated to obtain P_{TRUE} as a function of altitude using the initial P on the ground, T from the FDR data, and dh from the accelerometer integration.

The error in the total pressure (P_{TOTAL}) sensed by the airplane's pitot tubes is assumed to be small. The total pressure can be calculated correctly from the uncorrected static pressure measurement and FDR calibrated airspeed.

Once P_{TRUE} and P_{TOTAL} have been calculated, the Mach number, static temperature, speed of sound, and true airspeed calculations can be redone. The results are shown in Figures 2, 3, 5 and 11 as the data labeled "corrected for static pressure error."

Wind calculations

Airspeed, ground speed, and wind are related as follows:

$$\vec{V}_W = \vec{V}_G - \vec{V} \quad [14]$$

where $\vec{V}$ is the airspeed vector, $\vec{V}_G$ is the ground speed 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 10, are related to α and β as follows:

$$u = V \cos(\beta) \cos(\alpha) \quad [15a]$$

$$v = V \sin(\beta) \quad [15b]$$

$$w = V \cos(\beta) \sin(\alpha) \quad [15c]$$

where in the present case $\beta \cong 0$ and α is computed using Equation [9]. Once the components of $\vec{V}_W$ in the airplane body axes are computed using Equation [15], they can be transformed into Earth axes using the known θ , ϕ , and true heading (ψ_{THDG}). The results of the wind calculations are shown in Figure 11. Note that the total wind speed and direction are computed using V *uncorrected* for the static pressure measurement error.

Once the airplane is on the ground, it is hard to determine the true value of β , and so Equations [14] and [15] cannot be used to determine the winds. Consequently, the wind calculation in Figure 11 ends when the airplane reaches the runway. However, in the present case what is of most interest (affecting landing distance) is the tailwind component, which on the runway can be computed as

$$V_{TAIL} = V_{GROUND} - V_{TRUE} \quad [16]$$

Where:

V_{TAIL} = tailwind

V_{GROUND} = ground speed

V_{TRUE} = true airspeed

Figure 11 presents the results of computing V_{TAIL} using V_{GROUND} from the accelerometer integration, and values of V_{TRUE} both uncorrected for the static pressure error (blue line in the top plot of Figure 11) and corrected for this error (red line in Figure 11).²⁵ The total wind speed computed without the static pressure correction matches the FDR wind speed well. However, accounting for the static pressure error reduces the computed V_{TAIL} by

²⁵ The results of using Equation [16] to compute V_{TAIL} are plotted in Figure 11 even for the time when the airplane is airborne (not on the runway). During the airborne portion, Equation [16] is only a valid approximation for V_{TAIL} when the wind is close to a direct tailwind; a direct crosswind would increase V_{GROUND} above V_{TRUE} , and Equation [16] would attribute the difference (incorrectly) to V_{TAIL} , which in that case would in fact be zero. The computed and FDR wind directions are plotted in the middle plot of Figure 11.

about 4 kt. on final approach. The V_{TAIL} on the runway itself, computed using the corrected V_{TRUE} , is 13 to 18 kt.

Per Table 5, the final wind report transmitted to the flight crew by the KBUR ATC tower (at 09:02) was wind from 270° (magnetic) at 11 knots. The magnetic heading of runway 8 is approximately 080°, so a direct tailwind for runway 8 would be from 080° + 180° = 260°. Hence, the 09:02 wind report, with winds from 270°, was only 10° away from a direct tailwind, and the tailwind component computed from this report would have been

$$V_{TAIL} = V_{WIND} \cos(\psi_{WIND}) = (11 \text{ kt.}) \cos(10^\circ) = 10.8 \text{ kt.} \quad [17]$$

So the tail wind indicated by the 09:02 wind report from the tower exceeded the SWA B737NG AOM tailwind limit of 10 knots.²⁶

The corrected tailwind speeds plotted in Figure 11 agree well with the 2-minute average tailwinds computed from the recorded ASOS data. As noted above, these wind speeds are 3 to 5 kt. higher than those reported by the tower.

Braking friction calculations

Considering the lower-than-expected braking friction coefficient (μ_B) achieved in previous landing overrun accidents and incidents investigated by the NTSB and by foreign agencies, it is of interest to determine the μ_B generated on the runway in this incident, 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 B737-700 FCOM and computed by the Southwest Airlines PWB.²⁷ This sub-section presents various FDR parameters relevant to the braking system operation and performance, and describes a method for computing μ_B using FDR-based parameters and additional information about the airplane provided by Boeing. The results of the μ_B calculation are also presented. The computed μ_B is compared with μ_B levels assumed in the FCOM, PWB, and various wet-runway friction models in Section D-VII.

Several FDR parameters relevant to the airplane's braking and deceleration performance are presented in Figures 12 and 13, including:

- Speedbrake armed light discrete and speedbrake handle position
- Flight control positions
- Ground spoiler deployment discrete and spoiler positions
- Throttle resolver angle (TRA) and engine N1
- Thrust reverser deployed and in-transition discrettes
- Autobrake applied discrete and left and right wheel brake pressures
- Wheel braking friction coefficient (μ_B) and airplane braking coefficient (μ_{AP})

²⁶ The record of the Captain's interview with NTSB investigators (Reference 22) states that "tower made a call of winds 270/11 when they passed 1000 ft – somewhere between 500 and 1000 ft. [The Captain] and the FO acknowledged this call and agreed that the tailwind component was 9-10 kt. and it was within limits."

²⁷ The FCOM and PWB landing distances are described further in Section D-VII.

The calculations of μ_B and μ_{AP} are described below. The results of the calculations are presented along with the FDR engine N1 speeds, the left and right brake pressures, and the n_x achieved during the landing roll in Figure 13. As described further below, the engine thrust, which is measured by N1, and the achieved n_x are used in these calculations.

The μ_B can be computed from n_x , engine N1, and knowledge of the airplane's aerodynamic and thrust characteristics. Figure 14 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 14 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:

$$F_N = \mu_N N_N \quad [18]$$

$$F_M = \mu_B N_M \quad [19]$$

$$\sum F_x = W n_x + W_x = W(n_x - \sin \theta) \quad [20]$$

$$\sum F_z = W n_z + W_z = W(n_z + \cos \theta) \quad [21]$$

$$\sum M_y = 0 \quad [22]$$

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 0.02,²⁸ Equations [18]-[22] can be reduced to three equations for the three unknowns N_N , N_M , and μ_B . As is evident in Figure 14, the geometry of the landing gear, thrust line, CG location, and aerodynamic reference

²⁸ Boeing uses a rolling μ of 0.0125 at the speeds relevant in this *Study*; another aircraft manufacturer, Embraer, uses a rolling μ of 0.03. Hence, the value of 0.02 used here is about an "average" of the values used by these manufacturers.

point of the airplane must be known. This geometry, as well as aerodynamic coefficient and thrust data for the B737-700, were provided to the NTSB by Boeing.

For the μ_B calculation, the θ recorded on the FDR was used, and a runway gradient of -0.5% was assumed (downhill, as determined from the runway threshold elevations at each end). Tables of forward and reverse thrust as a function of Mach number and engine N1 for the pressure and temperature conditions of the incident were provided by Boeing. The engine N1 and thrust reverser position data shown in Figure 13, and the Mach number computed from the FDR calibrated airspeed and static pressure, were used with these tables to compute the forward and reverse thrust from both engines during the ground roll.

The result of solving Equations [18]-[22] for μ_B is shown in Figure 13, and in several subsequent Figures discussed in Section D-VII.

The airplane braking friction coefficient (μ_{AP}) plotted in Figure 13 is similar to the wheel braking friction coefficient (μ_B) in that it quantifies the runway friction force acting on the airplane's tires, but it differs in that it is a simpler calculation that it does not isolate the braking forces and corresponding friction on the braked main gear alone, but accounts for the total frictional forces acting on the airplane, which result from both the braked main gear and the rolling nose gear:

$$\mu_{AP} = \frac{F_M + F_N}{N_M + N_N} = \frac{\mu_B N_M + \mu_N N_N}{N_M + N_N} \quad [23]$$

Whereas, from Equation [19],

$$\mu_B = \frac{F_M}{N_M}$$

Note that as μ_B approaches the rolling friction coefficient μ_N , $\mu_B \cong \mu_N$, $F_M \cong \mu_N N_M$ and

$$\mu_{AP} \cong \frac{\mu_N N_M + \mu_N N_N}{N_M + N_N} = \frac{\mu_N (N_M + N_N)}{N_M + N_N} = \mu_N \cong \mu_B \quad [24]$$

For the μ_B values and C.G. position of this incident, Figure 13 indicates that μ_B is about 16% greater than μ_{AP} during much of the landing roll.

The results of research into runway friction (as documented in Reference 9) is presented in terms of the wheel braking friction coefficient (μ_B), not the airplane braking friction coefficient (μ_{AP}). Likewise, regulation and guidance concerning runway friction (discussed below) specify values of μ_B , not μ_{AP} , and so this *Study* analyzes the friction on the runway in terms of μ_B . However, the runway friction values underlying the stopping distances published in the B737-700 FCOM are based on μ_{AP} , so the computation of μ_{AP} is presented in Figure 13 for comparison with these values.

VI. Regulations and guidance concerning operations on wet runways

Overview

Section D-VII of this *Study* compares the actual μ_B achieved during the landing roll (as described above and presented in Figure 13) with the μ_B that would be 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 underlying the unfactored²⁹ landing distances published in the B737-700 FCOM, for different runway “reported braking action” levels³⁰ and braking effort settings³¹ under the weight, wind, temperature, and pressure conditions of the incident. Braking action levels are not associated with particular runway surface conditions directly; however, different runway conditions will result in different braking action levels, and the methodology in the FCOM assumes that the braking action for a particular landing will be reported to the flight crew by ATC or other means, if warranted.

In addition, since October 2016, within the U.S.A. runway surface conditions and associated braking performance have been described and reported using the Takeoff And Landing Performance Assessment (TALPA) Runway Condition Assessment Matrix (RCAM) framework, which differs from the “braking action” level framework used in the FCOM. Operators must use an accepted method to “translate” RCAM “Runway Condition Codes” (RwyCCs) into the FCOM reported braking action levels and associated landing distances. One such method, used by SWA, employs a third-party application, hosted by AeroData and configured to SWA specifications, to compute landing distances based on information in a Boeing-provided operational performance computing module called the Boeing Landing Module (BLM).

The BLM contains the same calculations and data as the certified B737-700 Airplane Flight Manual - Digital Performance Information (AFM-DPI) computer software, but can also compute additional operational landing distance information. In the case of FAA-certified and registered aircraft, the AFM-DPI does not contain contaminated (non-dry, non-wet) landing distances; however, the BLM does, and this information is available through SWA’s implementation of AeroData’s application.

The additional operational landing distance information available in the BLM is a combination of 1) data based on contaminant type, contained in the AFM-DPI of European-certified and registered aircraft, and 2) braking-action-based landing distance information, contained in the Boeing FCOM. Operators can customize the operational landing distance information provided by the BLM by specifying certain options such as the assumed air distance for the landing (the distance from the runway threshold to touchdown), and different braking coefficient options. SWA’s implementation of AeroData’s application includes these customizations as a part of its use of the BLM.

²⁹ 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.

³⁰ The FCOM reported braking action levels are Dry Runway, Good, Medium, and Poor.

³¹ The FCOM braking effort settings are Max Manual, Autobrake Max, Autobrake 3, Autobrake 2, and Autobrake 1.

The RCAM levels, FCOM braking actions, PWB system options, and the μ_B models they imply are described in Section D-VII. The relevance of the μ_B models, their associated landing distances, and of the landing distances published in the FCOM is determined both by the accuracy of these models and data, and by how this information is used to operate the airplane.

The B737 is certificated to the transport category airworthiness standards specified in 14 CFR Part 25,³² and is typically used for Part 121 “Domestic, Flag, and Supplemental” operations (as in this incident). Part 25 dictates that landing distance data must be published in the Airplane Flight Manual (AFM).³³ As discussed below, the AFM landing distances are based on maximum-performance (minimum possible distance) landings conducted on smooth, dry runways during flight testing. Part 121 requires that these distances, with applied factors, be used during flight planning and dispatch to establish the minimum runway length required at the destination and alternate airports, or alternatively, the maximum takeoff weight at departure.

The landing distances published in the FCOM (for different braking efforts and runway conditions) are not required by FAA regulations, but are “advisory” data³⁴ provided by the manufacturer to assist flight crews in conducting en-route landing distance assessments (after the airplane has taken off) in case conditions at the destination airport change. (However, some foreign regulators *do* require that the AFM contain landing distances for contaminated runways, as discussed below.) The advisory data in the FCOM (and BLM) does not need to be established by flight test, but can be determined by calculation.

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 required landing distance data presented in the AFM, the advisory data provided in the FCOM, and the operating regulations and guidance that govern how these data sources are to be used.

³² 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.

³³ The AFM is a document approved by the FAA as part of the airplane’s certification (see the following footnote for a definition of FAA “approval”). The FCOM is a document authored by Boeing to assist flight crews in operating the airplane. The FCOM is not part of the airplane’s certification, like the AFM is, but its content is consistent with the AFM.

³⁴ “Advisory” data provided by an aircraft manufacturer can be contrasted with data “approved by” the regulator. In this context, “approved by” means the data is required to be and has been reviewed and formally approved by the FAA (or appropriate Civil Aviation Authority). Approvals are granted only by letter, by a stamp of approval, or by other official means. “Advisory” data is not subject to these requirements.

Required AFM landing distance data for Part 25 transport category airplanes

14 CFR §25.1587, “Performance Information,” dictates the landing distance information that must be presented in the Airplane Flight Manual (AFM) of airplanes certificated under Part 25. The regulation reads, in part:

(b) Each Airplane Flight Manual must contain the performance information computed under the applicable provisions of this part (including §§25.115, 25.123, and 25.125 for the weights, altitudes, temperatures, wind components, and runway gradients, as applicable) within the operational limits of the airplane, and must contain the following:

...

(3) The following performance information (determined by extrapolation and computed for the range of weights between the maximum landing weight and the maximum takeoff weight):

...

(iii) Landing distance.

The landing distance is defined in §25.125 as “the horizontal distance necessary to land and come to a complete stop ... from a point 50 feet above the landing surface.” Furthermore, §25.125(c) states that “for landplanes and amphibians, the landing distance on land must be determined on a level, smooth, dry, hard-surfaced runway.”

These landing distances are established by flight testing without using reverse thrust, and represent the minimum distance required to land and stop the airplane without reverse thrust. For the B737-700, the landing distance data required by §25.125 is contained in the AFM-DPI, which is part of the approved AFM.

For Part 25 airplanes intended to be operated on contaminated runways in Europe, contaminated landing distances must be presented in the European AFM and computed per the methods described in the European Aviation Safety Agency (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). FAA regulations do *not* require the publication of landing distances on other than dry runways, though applicants may choose to present this information as “advisory” data in order to satisfy foreign regulations that do require this information (this is the case with the B737-700 AFM-DPI). The wet and contaminated runway data is not necessarily based on flight tests (largely because of the difficulty of achieving a consistent “wet” or “contaminated” runway surface), but is derived from calculations such as those specified in AMC 25.1591.

It should be noted that a runway that is merely wet (not flooded with at least 3 mm of standing water³⁵) 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.

However, 14 CFR §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; however, Part 25 does not prescribe the μ_B to be used when calculating the *landing* distance on a wet runway. 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.

In December 2015, the FAA published AC 25-32, titled *Landing Performance Data for Time-of-Arrival Landing Performance Assessments* (Reference 24). This AC prescribes using the §25.109 μ_B model for computing wet landing distances that are (optionally) provided in Part 25 AFMs, and is discussed in greater detail below.³⁶

³⁵ 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.

³⁶ In April 2009, the Takeoff and 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 were ultimately implemented through ACs 25-31 and AC 25-32, which are non-regulatory documents.

Operational regulations concerning dispatch and arrival landing distance assessments

The incident flight was conducted under the provisions of Part 121. The corresponding regulation governing the runway lengths required at a destination airports is §121.195, “Airplanes: Turbine engine powered: Landing limitations: Destination airports,” which states, in part,

(a) No person operating a turbine engine powered transport category airplane may take off that airplane at such a weight that (allowing for normal consumption of fuel and oil in flight to the destination or alternate airport) the weight of the airplane on arrival would exceed the landing weight set forth in the Airplane Flight Manual for the elevation of the destination or alternate airport and the ambient temperature anticipated at the time of landing.

(b) Except as provided in paragraph (c), (d), or (e) of this section, no person operating a turbine engine powered 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 distance set forth in the Airplane Flight Manual for the elevation of the destination airport and the wind conditions anticipated 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 the B737-700 AFM are based on the actual (unfactored) landing distances for a dry runway, multiplied by the 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 121 operations, the factored dry distances in the AFM are used during flight planning and dispatch to determine the dry-runway field length required and / or the maximum allowable takeoff weight.

If, prior to takeoff, the destination runway is not forecast to be dry, then §121.195(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 takeoff a turbojet powered airplane when the appropriate weather reports and forecasts, or a combination thereof, 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 the AFM, 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 $((\text{unfactored distance} / 0.6) \times 1.15 \cong \text{unfactored distance} \times 1.92)$. 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.

The B737-700 BLM module used by the SWA PWB includes advisory data (which is also in the EASA version of AFM-DPI) based on EASA CS 25.1591/AMC 25.1591. This data provides landing distances for runways covered with wet ice, compacted snow, standing

water, slush and snow.³⁷ However, this advisory data is not required to be used for flight planning or dispatch; for dispatch purposes, the additional 15% safety factor prescribed by §121.195(d) is considered sufficient to address all “slippery” (i.e., contaminated – neither dry nor wet) runways. Instead, the advisory data in the BLM are primarily intended to be used by the flight crew to perform en-route landing distance assessments when conditions at the destination have deteriorated from those assumed at dispatch. Nonetheless, the SWA flight planning process uses the PWB “5 – GOOD” runway condition as the default for all flights (vs. “6 – DRY”), and the advisory data in the PWB system for worse runway conditions when warranted (per the SWA Dispatch Operations Manual (Reference 13)).

En-route landing distance assessments: CAT.OP.MPA.300 & FAA SAFOs 06012 & 19001

European operational regulation CAT.OP.MPA.300 requires what amounts to an en-route landing distance assessment, i.e., a determination by the pilot while in flight as to 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,” CAT.OP.MPA.300 does not provide guidance for making the determination. Challenges pilots 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 FCOM guidance material.

There is no equivalent to CAT.OP.MPA.300 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)*. 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.

³⁷ The runway condition options included in the SWA PWB en-route landing distance calculation are described below.

The SAFO also notes that “the FAA has undertaken rulemaking that would explicitly require the practice described above.” In December 2015, the FAA issued ACs 25-31 and 25-32 in lieu of the rulemaking contemplated in SAFO 06012.

SAFO 06012 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, FCOM 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 FCOM 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.”

Reference 9 discusses NTSB recommendations concerning en-route landing distance assessments and SAFO 06012, as well as NTSB comments on the content of ACs 25-31 and 25-32.

SAFO 06012 was cancelled and replaced by SAFO 19001, published on March 11, 2019. SAFO 19001 updates the information presented in SAFO 06012 to incorporate the TALPA RCAM framework and the corresponding contaminated runway performance guidance provided in ACs 25-31 and 25-32. As stated in SAFO 19001,

After a Boeing 737-700 runway overrun accident at Chicago Midway Airport in December 2005, the FAA convened the Takeoff and Landing Performance Assessment (TALPA) Aviation Rulemaking Committee (ARC). The Federal Aviation Administration (FAA) adopted certain recommendations of the ARC (which became known as “TALPA”), and implemented them into the National Airspace System on October 1, 2016. This SAFO provides information and guidelines to airplane operators on utilizing the safety benefits TALPA provides.

In addition,

The TALPA ARC discovered significant gaps in information needed to determine if a safe landing can be made. The ARC produced consistent terminology and runway assessment criteria, and recommended usage of non-dry, non-wet [i.e., contaminated] performance data for takeoff and time of arrival landing calculations. The TALPA ARC did not recommend any changes in the *preflight* landing distance requirements.³⁸

Like SAFO 06012, SAFO 19001 recommends a conservative approach to assessing landing distance requirements, including using the most adverse reliable braking action

³⁸ A subsequent Aviation Rulemaking Advisory Committee (ARAC) has in fact recommended an addition to preflight (or dispatch) landing distance requirements, to account for the shortfall in the expected runway friction observed in a number of wet runway landing overruns; see Section D-VII.

report or runway condition code, values for air distances and approach speeds that are representative of actual operations, and a safety margin of at least 15%. However, compliance with SAFOs is not mandatory, and so the FAA can only “encourage” operators to adopt the practices recommended in the SAFO:

There is no specific regulation requiring operators to assess landing distance requirements at time of arrival, however the FAA encourages operators to adopt such procedures to ensure that a safe landing can be made. Additionally, the FAA highly encourages operators to use their FAA-approved landing performance data and any associated manufacturer-provided supplemental/advisory data in concert with the AC 91-79-generated RCAM Braking Action Codes to conduct an adequate landing distance assessment at the time of arrival. This is particularly important when the landing runway is contaminated or not the same runway analyzed for preflight calculations.

Southwest Airlines Flight Operations Manual Requirements

The certification of air carriers in the USA is governed by 14 CFR Part 119 §119.33, which states in part that “a person may not operate as a direct air carrier 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.

SWA holds operations specifications (OpsSpecs) for its air carrier operations conducted under 14 CFR Part 121. SWA’s Flight Operations Manual (FOM, Reference 14) states that

Operators must comply with Operations Specifications (OpSpecs) and the Code of Federal Regulations (CFR), which comprise a contract between the FAA and the Company specifying requirements, limitations, conditions, and other provisions regarding how an operation shall be conducted. Requirements in the OpSpec are mandatory and must be brought to the attention of all Crew Members and Dispatchers.

In addition, sections of the FOM and other SWA manuals define limitations, policies and recommendations. Policies

are defined as broad specifications about the manner in which Southwest Airlines management expects tasks to be performed. Pilots are expected to adhere to policies.

The dispatch landing distances and associated limitations on landing weight are specified in the SWA Dispatch Operations Manual (DOM, Reference 13), and satisfy the requirements of 14 CFR §121.195. In addition, the DOM uses a default runway condition of “5 – GOOD” (which describes a wet runway) for all flights.

Furthermore, the SWA FOM states that it is SWA policy that for every flight, “a landing distance assessment must be made within one hour of [the Estimated Time of Arrival].” This assessment is normally performed by the flight crew using the PWB system. As noted in Reference 3 and described above, the incident crew received a Landing Data Report from the PWB system via ACARS at 08:24, or about 39 minutes before landing.

The runway length remaining number cited in the Landing Data Report provided by the PWB includes a 15% safety margin (i.e., the actual required landing distance computed

by the BLM is multiplied by 1.15, and the result is used to compute the runway length remaining). Consequently, the en-route landing distance assessment required by SWA policy, and the 15% safety margin included in the PWB system calculations, comply with the recommendations of SAFOs 06012 and 19001.

Guidance concerning braking performance on wet runways: SAFOs 15009 and 19003

Reference 9 presents the μ_B achieved in six accidents in which the airplane overran the runway after landing in wet conditions. In all of these accidents, the achieved μ_B was significantly lower than the μ_B predicted by industry-standard models, and the μ_B required to match the manufacturer's published unfactored, wet-runway landing distances.

In recognition of the unexpectedly low μ_B achieved in some of the accidents described in Reference 9 (among others), the FAA issued SAFOs 15009 and 19003 in August 2015 and July 2019, respectively. SAFO 15009 "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 the wet-runway overrun events described in Reference 9. 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."

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 in the overrun accidents described in Reference 9.³⁹

³⁹ For one of the accidents described in Reference 9, it is not possible to exclude drainage and puddling problems or rubber deposits on the runway as contributors to the accident, though dynamic hydroplaning in that event can be ruled out (dynamic hydroplaning is described below).

SAFO 15009 states 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.” The SAFO 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.”

SAFO 19003 “cancels and replaces SAFO 15009 and warns airplane operators and pilots that the advisory data for wet runway landings may not provide a safe stopping margin especially in conditions of Moderate or Heavy Rain.” This language is nearly identical to that in SAFO 15009, but specifies that the loss of friction might be associated with moderate or heavy rain conditions. In addition, SAFO 19003 updates the discussion in SAFO 15009 to refer to SAFO 19001 (which replaced SAFO 06012) and address the TALPA RCAM framework, and focuses on the risk of heavy rain events transitioning runways from a “wet” condition to a flooded (“contaminated”) condition:

These [landing] incidents/accidents occurred on both grooved and un-grooved runways. The data indicates that applying a 15% safety margin to wet runway time-of-arrival advisory data, as recommended by SAFO 19001 (or current guidance), may be inadequate in certain wet runway conditions. Takeoff and Landing Performance Assessment (TALPA) procedures implemented by the FAA on October 1, 2016, added new insight as to how flightcrews can evaluate runway braking performance prior to landing. TALPA defines WET as “includes damp and 1/8-inch depth or less of water,” while CONTAMINATED is “greater than 1/8-inch of water.”

Discussion: These overruns have occurred on grooved and smooth runways during periods of moderate to heavy rain. Analysis of these incidents/accidents indicates that the braking coefficient of friction in each case was significantly lower than expected, and that 30 to 40 percent of additional stopping distance may be required if the runway transitions from wet to contaminated based on the rainfall intensity or reported water contamination (greater than 1/8-inch depth). For the operational in-flight landing assessment, determining whether the runway is wet or potentially contaminated is the pilot’s responsibility.

In this incident, it is not likely that the runway “transition[ed] from wet to contaminated based on the rainfall intensity” present shortly before the landing, because the rainfall rate of about 1 in./hr. (see Reference 8) combined with the runway texture depth provided by grooving, the surveillance video of the landing, and (most significantly) the achieved μ_B during the landing roll are not consistent with a water depth close to or above 1/8 inch.

SAFO 19003 continues:

The FAA recommends that airports report “Wet” conditions. However, airports are not required to report when a runway is only wet. Further, an airport may not be able to generate a Field Condition NOTAM (FICON) for sudden rain showers that result in water on the runway more than 1/8 of an

inch in depth (contaminated). Rainfall intensity may be the only indication available to the pilot that the water depth present on the runway may be excessive. The 1/8-inch threshold that separates a wet runway with a RWYCC of 5 from runway contaminated with water depth greater than 1/8-inch a RWYCC of 2 is based on possibility of dynamic hydroplaning. This can be especially true in moderate rain if the runway is not properly crowned, grooved, constructed with a porous friction course (PFC) overlay, or when water run-off becomes overwhelmed. During heavy rain events, this may be true even on a properly maintained grooved or PFC runway.

The TALPA RCAM recommends using landing performance data associated with medium to poor braking or RwyCC of 2, if greater than 1/8-inch of water is anticipated to be on the runway. When planning to land on a smooth runway under conditions of moderate or heavy rain, or when landing on a grooved or PFC runway under heavy rain, pilots should consider that the surface may be contaminated with water at depth greater than 1/8 inch and adjust their landing distance assessment accordingly. Pilots should use all available resources to determine what condition they may expect upon landing to include Air Traffic Control (ATC), FICONs (as some airports do report Wet conditions), flight visibility, and/or onboard weather radar.

Note: A Special Weather Observation (SPECI) will only be generated if a Thunderstorm begins. A SPECI is not generated when rainfall rates simply change.

Knowing ahead of time whether your aircraft can or cannot stop within the Landing Distance Available if runway conditions deteriorate to a medium to poor condition (RwyCC = 2) is critical when operating in moderate or heavy rain. Go-around, holding, or diversion may be necessary if rainfall intensity increases beyond what might be acceptable for the intended operation.

...

Unless the pilot or operator is knowledgeable of the runway's maintenance program, and that the runway is grooved or is a PFC surface that can provide good runway friction during periods of active moderate or heavy rain, they should consider basing their time-of-arrival assessment on the above recommendations. Aircraft operators should also clarify their reporting needs to the airport operator as it relates to "Wet" runway conditions.

Significantly, SAFO 19003 notes that pilots cannot rely on the airport to know of and / or inform them of flooded (standing water) conditions resulting from heavy rainfall, and it is the rainfall intensity itself that "may be the only indication available to the pilot that the water depth present on the runway may be excessive." Hence, the pilot's observation of heavy rain and recognition of its potential effect on braking performance is the last line of defense against sudden flooded conditions that can defeat the dispatch landing distance safety factors required by 14 CFR §121.195 and the operator's Flight Operations Manual.

Flight Test Harmonization Working Group wet runway regulatory recommendations

As indicated by SAFOs 15009 and 19003, 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 10) 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 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.

Because the tasking assigned to the FTHWG was very broad, the FTHWG decided to conduct the technical deliberations on each topic individually, and adopted the topic numbers from the original list of topics as identifiers for each topic. Wet runway landing performance was identified as “Topic 9.”⁴⁰

The FTHWG started its review of wet runway stopping performance and associated μ_B models in September, 2015. In March 2018, the FTHWG published its final report on this topic, titled *FAA Aviation Rulemaking Advisory Committee FTHWG Task 9: Wet Runway Stopping Performance Final Report: Recommendation Report, March 16, 2018* (Reference 12). The report recommends the creation of a new 14 CFR Part 25 transport airplane certification requirement (§25.126) to determine landing distances on wet runways, to supplement the existing requirement to determine landing distances on dry runways (§25.125). In addition, the report proposes modifying the 14 CFR 121.195 operating rule to account for the wet runway landing distances required by the new §25.126 rule when dispatching airplanes to runways forecast to be wet at the time of arrival.

⁴⁰ See Reference 11.

In general, the wet landing distances required by the recommended new §25.126 rule would have to be determined by calculation, assuming the μ_B defined by §25.109(c), and incorporate a 10% safety margin (see Reference 12 for details about exceptions to this requirement, such as the use of μ_B values determined by flight test). In addition, reverse thrust could be used when determining the wet-runway landing distances (in contrast to the dry-runway landing distances required by §25.125, which must be determined without the use of reverse thrust).

The recommended change to the §121.195 operating rule would require that to dispatch a flight to a runway forecast to be wet at the time of arrival, the landing distance available must be at least 115% of the wet-runway landing distance determined per the recommended new §25.126 rule. Hence, the landing distance required at dispatch to a wet runway would be equal to the unfactored landing distance determined using the μ_B defined by §25.109(c) and including the effect of reverse thrust, multiplied by a total safety factor of $1.1 \times 1.15 = 1.265$. (The 1.1 factor is from the recommended new §25.126 rule, and the 1.15 factor is from the recommended change to §121.195.)

If the incident flight had been required to comply with these FTHWG recommendations, N752SW could not have been dispatched to KBUR runway 8 assuming the weight and arrival conditions of the incident landing. Table 10 (described below) indicates that at the nominal flaps 40 approach speed of 131 KCAS and with a 5 kt. tailwind, the SWA PWB system computes a non-factored landing distance of 4,645 ft. with a “5 – GOOD” runway condition (this condition uses the μ_B defined by §25.109(c)). The required wet-runway dispatch distance under the new recommendations would therefore be $4,645 \text{ ft.} \times 1.265 = 5,876 \text{ ft.}$, which is 74 ft. greater than the 5,802 ft. runway length available. However, per the dispatch release, the winds at landing were predicted to be from 120° (true) at 8 knots, which result in a 7 kt. headwind for runway 8 (as opposed to a 5 kt. tailwind). Hence, it is likely that with these winds, the incident flight would have complied with the new FTHWG recommendations.

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

Overview

This Section presents several methods for modeling the μ_B achievable on wet runways, and compares the μ_B achieved during the incident landing roll (presented in Section D-V) with the μ_B that would be predicted using several wet-runway friction models. These models include the μ_B assumed in the TALPA Runway Condition Assessment Matrix (RCAM) for wet runway conditions, and the μ_B implicit in the various “reported braking action” levels associated with the landing distances published in the B737-700 FCOM and computed by the SWA PWB system. This Section also summarizes the historical development of the TALPA RCAM in the context of other TALPA recommendations, and its presentation in AC 25-32.

In addition, this Section compares the landing distance that would be required given the actual μ_B achieved during the landing roll to the distances computed using the FCOM and

PWB system data. The corresponding furthest touchdown point from the runway threshold that would allow the airplane to stop on the runway is also presented.

It will be shown that the computed μ_B is between the values defined by §25.109 for smooth (ungrooved) and grooved runways (KBUR runway 8 is grooved), and that the computed μ_B matches the μ_B predicted by a NASA model based on runway friction measurements.⁴¹ Since the μ_B underlying the “5 – GOOD” runway condition used in the PWB landing distance computations corresponds to the §25.109(c) model for smooth runways, the computed μ_B is higher than that assumed in the PWB, and the airplane achieved better braking performance than assumed in the PWB (until it crossed the left side of the grooved runway onto ungrooved pavement).

Consequently, the achieved μ_B in this incident is not a concern, unlike in the other events discussed in Reference 9. While the achieved μ_B on this grooved runway is less than the grooved runway μ_B modeled in §25.109(d) (see below), operators cannot take credit for the higher μ_B specified in §25.109(d) for landing operations, and so this observation is of primarily academic interest. Accordingly, this *Study* does not discuss the physics underlying the reduction of friction on wet runways, the computation of water depth on a runway, or hydroplaning. Readers interested in these topics are referred to Reference 9.

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 ,⁴² and then bring the airplane back to a stop in the remaining runway length.⁴³ §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 course 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:

⁴¹ The NASA model also successfully predicts the μ_B achieved in other accident landings investigated by the NTSB (see Reference 9).

⁴² 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.”

⁴³ 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	$\mu_{t/g_{MAX}} = -0.0350 \left(\frac{V}{100} \right)^3 + 0.306 \left(\frac{V}{100} \right)^2 - 0.851 \left(\frac{V}{100} \right) + 0.883$
100	$\mu_{t/g_{MAX}} = -0.0437 \left(\frac{V}{100} \right)^3 + 0.320 \left(\frac{V}{100} \right)^2 - 0.805 \left(\frac{V}{100} \right) + 0.804$
200	$\mu_{t/g_{MAX}} = -0.0331 \left(\frac{V}{100} \right)^3 + 0.252 \left(\frac{V}{100} \right)^2 - 0.658 \left(\frac{V}{100} \right) + 0.692$
300	$\mu_{t/g_{MAX}} = -0.0401 \left(\frac{V}{100} \right)^3 + 0.263 \left(\frac{V}{100} \right)^2 - 0.611 \left(\frac{V}{100} \right) + 0.614$

Where—

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

$\mu_{t/g_{MAX}}$ = 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

$$\mu_B = (\mu_{t/g_{MAX}})(\eta_{AS}) \quad [25]$$

Where $\mu_{t/g_{MAX}}$ (or μ_{max})⁴⁴ and the anti-skid efficiency η_{AS} are defined in the rule as shown above.

FAA AC 25-7D, *Flight Test Guide for Certification of Transport Category Airplanes*, dated 05/04/2018 (Reference 15), describes the three types of anti-skid braking systems identified in §25.109.⁴⁵ The B737-700 is equipped with a “fully modulating” anti-skid system, and so the applicable η_{AS} is 0.80 for this airplane.

The history of the §25.109 μ_B model described above, and its development from a μ_B model documented in Reference 16, is described in Reference 17.

⁴⁴ Throughout this *Study*, $\mu_{t/g_{MAX}}$ and μ_{max} are used equivalently.

⁴⁵ See AC 25-7D, paragraph 4.3.7.4, “Classification of Types of Anti-Skid Systems.”

The nominal inflation pressure of the main tires for the B737-700 is 205 psi. Interpolating the $\mu_{t/gMAX}$ tables above for a tire pressure of 205 psi gives

$$\mu_{t/gMAX} = -0.0335 \left(\frac{V_G}{100}\right)^3 + 0.2526 \left(\frac{V_G}{100}\right)^2 - 0.6557 \left(\frac{V_G}{100}\right) + 0.6881 \quad [26a]$$

Where V_G is the ground speed in knots. The μ_B resulting from multiplying the $\mu_{t/gMAX}$ defined in Equation [26a] by the nominal η_{AS} of 0.80 (for a fully-modulating anti-skid braking system) is shown in Figure 15 as the blue dashed line labeled “14 CFR 25.109 smooth μ_B (RCAM 5), $\eta_{AS} = 0.8$.”

14 CFR §25.109(d) defines the μ_B to be assumed in the calculation of the accelerate-stop distance for wet runways that are grooved or treated with porous friction course material. The method is similar to that prescribed in §25.109(c) for smooth wet runways, except that the polynomials defining $\mu_{t/gMAX}$ as a function of V_G for different tire pressures are 5th order rather than 3rd order. The polynomial coefficients specified in §25.109(d) are presented in Table 8. As in §25.109(c), the $\mu_{t/gMAX}$ defined in §25.109(d) must be multiplied by η_{AS} (“appropriate for a grooved or porous friction course wet runway”) to obtain μ_B , per Equation [25]. Alternatively, μ_B may assumed to be “70 percent of the dry runway braking coefficient of friction used to determine the dry runway accelerate-stop distance.”

Tire pressure, psi	V_G terms					
	$\left(\frac{V_G}{100}\right)^5$	$\left(\frac{V_G}{100}\right)^4$	$\left(\frac{V_G}{100}\right)^3$	$\left(\frac{V_G}{100}\right)^2$	$\left(\frac{V_G}{100}\right)^1$	$\left(\frac{V_G}{100}\right)^0$
50	0.1470	-1.050	2.673	-2.683	0.403	0.859
100	0.1106	-0.813	2.130	-2.200	0.317	0.807
200	0.0498	-0.398	1.140	-1.285	0.140	0.701
300	0.0314	-0.247	0.703	-0.779	-0.00954	0.614

Table 8. Polynomial coefficients and terms defining $\mu_{t/gMAX}$ in 14 CFR §25.109(d).

Interpolating the coefficients in Table 8 for a 205 psi tire, the polynomial for $\mu_{t/gMAX}$ on a grooved runway is:

$$\mu_{t/gMAX} = 0.0489 \left(\frac{V_G}{100}\right)^5 - 0.390 \left(\frac{V_G}{100}\right)^4 + 1.118 \left(\frac{V_G}{100}\right)^3 - 1.260 \left(\frac{V_G}{100}\right)^2 + 0.1325 \left(\frac{V_G}{100}\right) + 0.697 \quad [26b]$$

AC 25-7D notes that “airplane operators who wish to use the grooved or PFC runway accelerate-stop distances will need to determine that the design, construction, and maintenance aspects are acceptable for each runway for which such credit is sought.” The TALPA RCAM (described below) makes no reference to grooved or PFC runways, and consequently does not distinguish between smooth and grooved/PFC runways in designating the RwyCCs associated with various contaminants, including water.

The μ_B resulting from multiplying the $\mu_{t/gMAX}$ defined in Equation [26b] by the nominal η_{AS} of 0.80 is shown in Figure 15 as the black dashed line labeled “14 CFR 25.109 grooved μ_B , $\eta_{AS} = 0.8$.”

Comparison of achieved and modeled μ_B , and corresponding landing distances

Figure 15 compares the μ_B achieved during the incident landing roll (“Computed μ_B from FDR / aero / thrust data,” also plotted as a function of time in Figure 13) with the μ_B defined by various friction models. The §25.109 μ_B models are described above; the other μ_B lines plotted in Figure 15 are described below.

The value of μ_B at each point on the “14 CFR 25.109 smooth μ_B (RCAM 5), $\eta_{AS} = 0.8$ ” line in Figure 15 is computed using Equations [25] and [26a], with V_G equal to N752SW’s ground speed at the corresponding point in the plot. Similarly, the value of μ_B at each point on the “14 CFR 25.109 grooved μ_B , $\eta_{AS} = 0.8$ ” line in Figure 15 is computed using Equations [25] and [26b], with V_G equal to the ground speed at the corresponding point.

Note that the computed μ_B based on the incident data in Figure 15 matches the “14 CFR 25.109 smooth μ_B (RCAM 5), $\eta_{AS} = 0.8$ ” line fairly well between 2,900 ft. and 4,400 ft. from the threshold, though it is slightly below the line between 3,700 ft. and 4,350 ft., and above the line from 4,350 ft. to 5,600 ft. (the computed μ_B drops sharply after the airplane crosses over the left edge of the runway onto ungrooved pavement). The computed μ_B is generally between the §25.109 smooth and grooved lines past 4,350 ft., and even a bit higher than the grooved line between 4,600 ft. and 4,800 ft.

The “requested μ_B ” lines in Figure 15 represent the effective μ_B commanded by the left and right brake pressures (the calculation of these values is described below). Note that the total requested μ_B is consistently above the achieved μ_B from 3,300 ft. from the threshold onwards (corresponding to a time of 09:02:38 onwards).

The FDR “autobrake applied” parameter plotted in Figure 12 toggles from 0 to 1 at 09:02:35.6 for 1 sample, but toggles back to 0 at 09:02:36.6, suggesting that the autobrake system engaged after touchdown at 09:02:34.8, but then disengaged almost immediately as the result of pressure applied to the brake pedals by one of the pilots.

Figure 16 plots μ_B (in the top graph) and ground speed (in the bottom graph) vs. distance from the runway 8 threshold for the incident data (accelerometer integration), and compares this curve with those corresponding to simulated ground rolls that assume different μ_B models for the runway. The initial condition for the simulations is the following point in the incident data:

- Time = 09:02:37.0 (2.2 seconds after touchdown)
- Runway x coordinate = 3,057 ft.
- Ground speed = 144 kt.

A tailwind of 14 knots is assumed for all the simulations, consistent with the corrected tailwind component on the runway shown in Figure 11.

The bottom plot of Figure 16 indicates that the airplane achieved a stopping performance roughly equal to that corresponding to the §25.109 smooth μ_B level, and slightly better

than that corresponding to the $\mu_{AP} = 0.2$ assumed in the FCOM “Good” braking action landing distances, even with the μ_B drop following the departure of the airplane from the grooved pavement. The dashed red lines in Figure 16 are the μ_B and corresponding ground speed obtained assuming the airplane had remained on the grooved runway, and the μ_B had continued to increase with decreasing ground speed per the §25.109 models. The simulation of this case indicates that with the increase, rather than decrease, in μ_B over the final portion of the runway shown in the top graph of Figure 16, the airplane might have come to rest 5,831 ft. from the threshold, 29 ft. beyond the runway end, but 44 ft. before the start of the EMAS.

If the airplane had consistently achieved the μ_B corresponding to the §25.109(d) model for a *grooved* runway, it would have stopped about 5,454 ft. from the threshold, with 348 ft. of runway remaining.

The results of these simulations are used to determine the furthest touchdown point from the threshold that would still allow the airplane to stop before the end of the runway, for various μ_B assumptions. These points are presented below in Table 10.

NASA μ_B model based on Continuous Friction Measurement Equipment (CFME) data

References 9 and 19 discuss the investigations of six other landing accidents or incidents on wet runways (all involving turbojet airplanes) in which the airplane did not achieve the μ_B implied in the manufacturer’s FCOM landing distances, or that would be predicted by the §25.109(c) (smooth runway) model. These six accidents are:

- The BAe 125-800A accident in Owatonna, MN (KOWA), on 7/31/2008 (NTSB #DCA08MA085) (Reference 17 is the *Airplane Performance Study* for this accident)
- The American Airlines flight 331 accident in Kingston, Jamaica, on 12/22/2009 (NTSB #DCA10RA017)
- The United Express flight 8050 accident in Ottawa, Ontario, on 6/16/2010 (NTSB #DCA10RA069)
- The Southwest Airlines flight 1919 incident in Chicago, IL (KMDW), on 4/26/2011 (NTSB #DCA11SA047)
- The EMB-505 accident in Conroe, TX (KCXO), on 9/19/2014 (NTSB #CEN14FA505) (Reference 19 is the *Airplane Performance Study* for this accident)
- The EMB-500 accident in Sugarland, TX (KSGR), on 11/21/2014 (NTSB #CEN15LA057)

The μ_B levels achieved in these events (and numerous events investigated by foreign agencies) are below those underlying the wet runway landing distances published in the airplanes’ FCOMs and the smooth-runway μ_B specified by 14 CFR §25.109. However, the achieved μ_B levels are generally consistent with the μ_B predicted using a National Aeronautics and Space Administration (NASA) model that is based on runway friction measurements taken with a Continuous Friction Measurement Equipment (CFME) device.

Significantly, however, the runways in five of these events were determined *not* to be flooded.⁴⁶ Furthermore, the NASA model fails to predict the almost total loss of braking friction experienced by a Miami Air International Boeing 737-800 during a May 3, 2019 landing overrun in Jacksonville, Florida on a runway that included areas that were likely very close to or over the 3 mm water depth that defines a “flooded” runway (see Reference 20). Since the achieved μ_B and video evidence of the incident landing indicate that KBUR runway 8 was *not* flooded, the good match between the NASA CFME μ_B and the achieved μ_B shown in Figure 15 is consistent with the results obtained in the other cases discussed in References 9 and 19. This sub-section of the *Study* describes the CFME μ_B model, the CFME tests performed on KBUR runway 8/26, and the resulting μ_B predicted by the CFME model and plotted in Figure 15.

The Operations department of KBUR provided the NTSB with the results of CFME runs conducted on runway 8/26 on December 5, 2018 (the day before the incident), using a Moventor BV-11 Skiddometer device.⁴⁷ The CFME runs were conducted at 40 mph, 10 ft. to the right of the centerlines of runways 8 and 26. The data from the run 10 ft. to the centerline of runway 8 is used in this *Study*, and presented in Figure 17. The k_B parameter plotted in Figure 17 is defined below.

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 the NTSB in support of the investigation of the Hawker Beechcraft BAe 125-800A accident in Owatonna, MN, on July 31, 2008 (NTSB #DCA08MA085). The method is also presented in Reference 18. The method 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 μ_{dry} for the test vehicle, and assuming that this ratio also applies to the μ_{wet}/μ_{dry} ratio of the braked airplane tires. The μ_{dry} of the airplane tires is a function of the tire inflation pressure. Appendix B lists μ_{dry} for the BV-11 Skiddometer as 1.10.

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 ($V_{p,spin\ down}$) of the test vehicle, and then applying that same ratio to the spin-down hydroplaning speed of the aircraft tires. The $V_{p,spin\ down}$ of both the test vehicle and airplane tires are a function of each vehicle’s tire inflation pressure (p):

$$V_{p,spin\ down} = 9\sqrt{p} \quad [27]$$

One product of this method, which is based on similarity of the μ_{wet}/μ_{dry} and $V_G/V_{p,spin\ down}$ ratios between the friction test vehicle and an airplane, is the maximum wet

⁴⁶ For the Ottawa accident, it is not possible to exclude drainage and puddling problems or rubber deposits on the runway as contributors to the accident, though dynamic hydroplaning in that event can be ruled out. The NASA CFME μ_B model overestimates the achieved μ_B in this accident, though it is much closer to the actual μ_B than the §25.109 model (see Reference 2).

⁴⁷ A description of the Skiddometer CFME device can be found at: <https://moventor.com/skiddometer-bv11-2/>.

friction coefficient that the runway can provide (μ_{max}), as a function of V_G for an airplane. As described in §25.109(c), the actual μ_B achieved by an aircraft is less than μ_{max} because the braking systems of aircraft are not 100% efficient. In the NASA method, μ_B is computed from μ_{max} using the following equations:

$$\text{For } \mu_{max} < 0.7: \quad \mu_B = 0.2 \mu_{max} + 0.7143 (\mu_{max})^2 \quad [28a]$$

$$\text{For } \mu_{max} \geq 0.7: \quad \mu_B = 0.7 \mu_{max} \quad [28b]$$

The computation of μ_B from μ_{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 $\mu_{t/gMAX}$ by η_{AS} (see Equation [25]). The η_{AS} implied in Equations [28a] and [28b] can be gleaned by dividing these equations by μ_{max} :

$$\text{For } \mu_{max} < 0.7: \quad \eta_{AS} = \mu_B / \mu_{max} = 0.2 + 0.7143 \mu_{max} \quad [29a]$$

$$\text{For } \mu_{max} \geq 0.7: \quad \eta_{AS} = \mu_B / \mu_{max} = 0.7 \quad [29b]$$

Note that the η_{AS} defined by these equations is a function of μ_{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 [29a] indicates that η_{AS} deteriorates with μ_{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. Reference 19 presents additional evidence that η_{AS} deteriorates with μ_{max} , contrary to the constant η_{AS} assumed in the §25.109 μ_B model.

Figure 17 indicates that the μ measured by the Skiddometer on KBUR runway 8 was not constant over the test run, but varied considerably during the run. Not surprisingly, this indicates that the μ_{max} available from a runway can depend on both speed *and* the location (runway x and y coordinates) in question. Of note, the Skiddometer run indicates a substantial reduction in μ between about 1,100 ft. and 2,000 ft. from the runway 8 threshold (during the incident landing, N752SW overflowed this “slippery” area, touching down 2,504 ft. from the threshold). The reduction in μ is in the “normal” touchdown area for runway 8, and might be the result of tire rubber buildup.

The Skiddometer test speed of 40 mph transforms into an airplane ground speed of 91 knots, using a Skiddometer tire pressure of 30 psi and an airplane tire pressure of 205 psi. Consequently, the test speed of 40 mph is not sufficient to determine the airplane μ_B at airplane ground speeds above 91 knots. As shown in Figure 5, the speed range of interest (while N752SW was on the pavement) is from 151 to 30 knots, so a substantial portion of the higher speed range is not covered by the Skiddometer test. Nonetheless, References 9 and 19 present a method for estimating the airplane μ_B across the entire speed range of interest based on a combination of the §25.109 model and CFME runs that address only part of the desired speed range. That method is used to here to estimate the airplane μ_B as a function of both airplane ground speed and position on the runway; the result of this calculation is shown in Figure 15 as the lines labeled “NASA CFME method, scaled from 25.109 smooth” and “NASA CFME method, scaled from 25.109 grooved” (the difference between these lines is explained below). The method itself is also described below, after

some preliminary discussion about how CFME μ thresholds defined in FAA AC 150/5320-12C are used to determine a need for runway pavement maintenance (these thresholds are the “NEW,” “MAINT,” and “MIN” friction levels depicted in Figure 17).

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

FAA AC 150/5320-12C 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 the AC. Three friction levels are defined, corresponding to the “NEW,” “MAINT,” and “MIN” lines shown in Figure 17.⁴⁸ The AC 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 [Table 3-2 of the AC]. 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] ... 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 ... for a distance of 1000 feet (305 m) or more, the airport operator should conduct

⁴⁸ Table 3-2 in AC 150/5320-12C defines the NEW, MAINT, and MIN μ levels for different CFME devices. The levels plotted in Figure 17 correspond to the BV-11 Skiddometer.

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 ... 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

The drop in μ measured by the Skiddometer between 1,100 and 2,000 ft. shown in Figure 17 (the black line in the top plot) is below the MAINT level for only about 400 ft., and so is close to satisfying the description in paragraph (a) above, which states that “no corrective action is required” but “the pavement friction is deteriorating” and “the airport operator should monitor the situation closely.”

Expected μ_B for incident landing based on combined NASA CFME and §25.109 models

As noted above, References 9 and 19 present a method for estimating the airplane μ_B across the entire speed range of interest based on a combination of the §25.109 model and CFME runs that address only part of the desired speed range. That method is described in this sub-section, and is used to estimate the (expected) airplane μ_B as a function of both airplane ground speed and position on the runway.

The Skiddometer run can be used to predict the expected airplane μ_B along the device's track at an airplane ground speed of 91 knots, per the NASA CFME method described above. The §25.109 model also predicts the airplane μ_{max} at these speeds, per Equation [26a] for a smooth runway (the resulting μ_{max} is independent of the position on the runway, unlike the CFME-based μ_B). The airplane μ_{max} for a grooved runway would be computed using Equation [26b]. The CFME prediction, which is based on measurements of the actual runway, can be used to compute an “effective” η_{AS} that should be applied to the §25.109 μ_{max} , which models runways in general. This effective η_{AS} , termed k_B , is defined as

$$k_B = \frac{\mu_{B,CFME}}{\mu_{max,25.109}} \quad [30]$$

Where:

$\mu_{B,CFME} = \mu_B$ obtained from the Skiddometer run using the NASA CFME method
 $\mu_{max,25.109} = \mu_{max}$ from the §25.109 model (Equations [26a] and [26b])

Since $\mu_{B,CFME}$ varies with position on the runway, k_B also varies along the runway. Figure 17 plots k_B computed using Equation [30] as a function of distance from the runway 8 threshold. The k_B computed using μ_{max} defined by Equation [26a] for a smooth runway is

labeled “Scaled from 25.109(c) (smooth);” the k_B computed using μ_{max} defined by Equation [26b] for a grooved runway is labeled “Scaled from 25.109(d) (grooved).”

The “NASA CFME method” lines plotted in Figure 15 are obtained by multiplying the μ_{max} from Equation [26a] (for a smooth runway) or Equation [26b] (for a grooved runway) by the corresponding k_B lines in Figure 17. Note that when k_B is greater than 0.8 (the η_{AS} assumed in Equation [25]), then the NASA CFME μ_B is greater than the §25.109 μ_B . Where the NASA CFME μ_B no longer oscillates (beyond 5,300 ft. and below 70 kt. in Figure 15), there is no Skiddometer measurement for the corresponding point on the runway (see Figure 17) and the last available k_B value is “held.” In general, the NASA CFME μ_B lies between the §25.109(c) and §25.109(d) μ_B levels, and matches the computed μ_B attained during the landing roll well. As discussed further below, the μ_B associated with the “5 – GOOD” runway condition assumed in the PWB system for the Landing Data Report calculations corresponds to the §25.109(c) model for a smooth runway. Consequently, in this case, unlike in the other overrun events mentioned above, the μ_B achieved by the airplane is consistent with the μ_B assumed in the landing distance calculations, and the friction provided by the runway is not a concern. However, it is noteworthy that the achieved μ_B does fall below the level modeled in §25.109(d) for grooved runways, indicating that both grooved and smooth runways can fall short of the friction modeled in §25.109. Hence, the development of tools with which airport operators can reliably predict and report the performance of their individual runways over a range of rainfall intensities would help ensure safety while maximizing the use of runways in wet conditions. To this end, the NASA CFME μ_B model has consistently matched the μ_B achieved during non-flooded wet runway overrun events, and consequently could be used to predict the μ_B that would be available on any given runway when wet. However, as the Jacksonville B737-800 overrun demonstrates, the NASA model fails to predict the μ_B available on a flooded (or nearly flooded) runway, so additional research to establish the range of rainfall rates and runway water depths for which the NASA model is valid would be beneficial.

μ_B “requested” via brake application

The FDR recorded left and right brake pressure parameters, which measure the brake pressure commanded by the pilots’ brake pedals upstream of the anti-skid system. The anti-skid system modulates the pressure actually delivered to the brake calipers, reducing it intermittently in order to prevent locking up the wheels and skidding the tires. The lower the μ_B , the lower the brake pressure at the calipers required to lock the wheels, and so in reduced friction conditions (such as in this case) the actual pressure delivered to the calipers might be far below the pressure commanded by the brake pedals.

Although the anti-skid system likely reduces the pressure delivered to the brake calipers, the recorded brake pressures can be used to determine the braking level – effectively, the μ_B – “requested” by the pilots through the brake pedals. Where this “requested” μ_B exceeds the achieved μ_B , it is reasonable to conclude that the anti-skid system is reducing the pressure delivered to the brakes, and the airplane’s braking is “friction limited” – that is, the anti-skid system is extracting as much braking performance from the runway as

possible, and any increase in pressure at the brakes would result in a skid, with a resultant further drop in μ_B and, possibly, directional control problems.

The requested μ_B is that value of μ_B that results in a frictional force at the tire that generates a torque about the wheel axle that exactly balances the torque the brakes are able to apply to the wheel with the commanded brake pressure. Boeing provided the NTSB with a table defining the applied brake torque as a function of brake pressure. With this information, for the left and right brakes we can write

$$T_L = f(p_L) = \mu_{reqL} \left(\frac{N_M}{4} \right) r_{TIRE} \quad [31a]$$

$$T_R = f(p_R) = \mu_{reqR} \left(\frac{N_M}{4} \right) r_{TIRE} \quad [31b]$$

Where:

T_L = Torque applied by the brakes on one of the two left wheels

T_R = Torque applied by the brakes on one of the two right wheels

$f(p_x)$ = Brake torque as a function of brake pressure p_x , per Boeing table; x indicates left (L) or right (R) brakes

μ_{reqx} = Requested μ_B by brake system x (L or R)

N_M = vertical reaction at main gear

r_{TIRE} = effective radius of main gear tires

Equation [31] is the torque about *one* wheel. The two left wheels are assumed to develop the same braking torque as a function of p_L , and the two right wheels are assumed to develop the same braking torque as a function of p_R . The vertical reaction force N_M is assumed to be distributed evenly across all four main gear tires. Solving Equation [31] for μ_{reqx} ,

$$\mu_{reqL} = \frac{4f(p_L)}{r_{TIRE}N_M} \quad [32a]$$

$$\mu_{reqR} = \frac{4f(p_R)}{r_{TIRE}N_M} \quad [32b]$$

The results of evaluating Equation [32] are shown in Figure 15 as the lines labeled “Left brake requested μ_B ” and “Right brake requested μ_B .” The “Brake torque limit μ_B ” line in the Figure is the result of evaluating Equation [32] with the maximum brake pressure that can be commanded from the pedals (3,000 psi); this is the maximum μ_B that the brakes would be able to sustain. Any higher μ_B on the runway would overcome the brakes, increasing the wheel speed.

Figure 15 indicates that the total requested μ_B is consistently above the achieved μ_B from 3,300 ft. from the threshold onwards (corresponding to a time of 09:02:38 onwards). The corresponding average brake pressure at 09:02:38 is about 750 psi, suggesting that this is the maximum pressure that the anti-skid system can command (at the speed in question) without locking the wheels. Consequently, the fact that the PF did not command the full brake pressure of 3,000 psi until 09:02:41 (about 6 seconds after touchdown) did

not significantly delay achieving the maximum available braking performance available from the runway.

The TALPA RCAM and AC 25-32

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.” According to the order, the objectives and scope of the 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; these recommendations are presented in detail in Reference 19. Reference 19 also describes internal disagreements between TALPA ARC participants representing Part 91K, 125, and 135 operators on the one hand, and the FAA and most other TALPA ARC participants on the other, concerning the operational assumptions and safety margins to be used for landing distance assessments on contaminated runways.

As described in Reference 19, the regulatory changes proposed by 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, CFME measured friction coefficient values, airplane wheel braking coefficient values, and pilot braking action reports. 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; 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 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.

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.” A 15% safety margin would be added to the computed operational landing distance to determine the runway length required for landing.

The FAA declined to pursue rulemaking to codify the TALPA ARC recommendations, deciding instead to encourage adoption of the practices recommended by the TALPA ARC through non-regulatory means (see Reference 19 for a detailed description of this evolution). These efforts culminated in the publication of AC 25-32, *Landing Performance Data for Time-of-Arrival Landing Performance Assessments*, in December 2015.⁴⁹ This AC provides 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 contaminated runway landing performance data for transport category airplanes. In addition, the AC includes a Runway Condition Assessment Matrix (RCAM) that is the outgrowth of the “Runway Condition and Braking Action Reports” table proposed by the TALPA ARC. The RCAM promotes the use of consistent terminology for runway surface conditions used among data providers and FAA personnel, and is presented here as Figure 18. The FAA officially started reporting runway conditions for Part 139 airports using the RCAM in October 2016.

Note that while AC 25-32 provides guidance for the development of airplane landing performance data on contaminated runways, it does not include any operational guidance as to how this data should be used for en-route landing distance assessments, or recommend that any specific safety factor be applied to the data (whereas the TALPA ARC specifically recommended *requiring* that a safety margin of 15% be added to landing distance assessments). Similarly, the 15% safety margin and en-route landing distance assessment practice is *recommended* by SAFO 19001, but is not *required*. The NTSB expressed concern regarding these points, and about the non-regulatory approach to the TALPA ARC recommendations in general, in comments submitted to the FAA during the AC 25-32 draft comment period (see Reference 19).

The runway condition code (RwyCC) and corresponding μ_B model listed in Figure 18 that is most relevant to the N752SW incident is RwyCC 5. This RwyCC is associated with a pilot-reported braking action of “good,” and includes a runway surface that is “wet (includes damp and $\frac{1}{8}$ ” (3 mm) depth or less of water).” This condition describes KBUR runway 8 at the time of the incident, and is the “default” runway condition assumed in the SWA PWB system for dispatch landing distance calculations. It is also the condition used for the en-

⁴⁹ At the same time, the FAA published *Advisory Circular AC 25-31, Takeoff Performance Data for Operations on Contaminated Runways*, containing guidance for developing takeoff performance data on contaminated runways.

route PWB landing distance assessment performed by the flight crew prior to the incident landing.

For a RwyCC 5 runway, Figure 18 indicates that the μ_B should be computed “per [the] method defined in §25.109(c).” As stated above and discussed in detail in References 2 and 19, and acknowledged in SAFOs 19003 and 15009, the §25.109(c) μ_B model can significantly overestimate the μ_B available on some wet runways. In comments on the draft versions of ACs 25-31 and 25-32 (Reference 21), the NTSB expressed 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

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 results of the ARAC task mentioned in these comments are the FTHWG wet runway regulatory proposals discussed in Section D-VI. In their response to the NTSB’s comments, the FAA also noted that “FAA Flight Standards (AFS-200) has also addressed this topic to some degree in SAFO 15009, dated 8/11/15.”

Boeing 737-700 FCOM & SWA PWB landing distances for the incident conditions

Perhaps the most relevant μ_B models, from an operational point of view, are those underlying the wet-runway stopping distances in the B737-700 Flight Crew Operating Manual (FCOM) and the PWB system Landing Data Report. These sources contain performance data that operators can use to ensure compliance with dispatch requirements and to perform en-route landing distance assessments.

During the investigation of the Miami Air International B737-800 overrun in Jacksonville, Boeing described⁵⁰ some of the differences between the FCOM and the Onboard Performance Tool (OPT) computing device used by Miami Air. Both the Miami Air OPT and the SWA PWB system use the Boeing Landing Module to perform landing distance calculations, and so Boeing’s description of the OPT calculation methods also applies to the SWA PWB system:

⁵⁰ In an email to the NTSB Aircraft Performance specialist dated June 10, 2020.

For the 737NG, a software called Airplane Flight Manual - Digital Performance Information (AFM-DPI) replaces the airplane performance charts in section four (4) of the airplane flight manual as the sole source of AFM certified performance. OPT uses the operational performance databases for takeoff and landing which are created from the "AFM-DPI" databases. AFM-DPI and OPT use the same calculation engine, Boeing Takeoff Module (BTM) & Boeing Landing Module (BLM), to perform the takeoff and landing calculations.

In OPT, the calculation is a first principle 'point' calculation, taking into account all of the variables including their interactions. For example, if there is runway slope the calculation takes into account the runway slope for the given weight, temperature, wind, etc. being used in the calculation. First principles means the fundamental equations of motion and the parameters defining the airplane (thrust, lift, drag, etc.) are used to calculate the performance directly, yielding a more exact solution. Advanced mathematical optimization techniques are used in order to maximize the performance available. In addition, the user can customize the calculation for calculating the operational landing distance via the OPT Administrator tool. For example, the operator can choose to apply a factor to the final operational landing distance calculation i.e. 15%, or/and change the flare distance used by fixing the flare value (i.e. 1,500 ft.)

The reason why the normal and non-normal landing distances calculated using OPT might not match the distances obtained from the tables in the QRH [Quick-Reference Handbook] is because the FCOM-QRH normal landing distance data is based off a reference weight, maximum manual braking with no adjustments, and does not take credit for thrust reversers. The FCOM-QRH adjustments are then run independent from each other, and are based on varying a single parameter such as weight or wind, and observing the change in runway required relative to the reference conditions. As such, when multiple adjustments are made, there is usually a difference between the FCOM/QRH results and the OPT/BLM results.

The OPT/BLM results would be considered more representative of the combined effects of multiple parameters being changed relative to the reference conditions than would the FCOM/QRH results.

The FCOM and PWB advisory data for landing distances corresponding to different runway conditions and braking action reports also differ in the μ_B and other parameters assumed in the underlying calculations. The landing distance for a given airplane weight and approach speed depends not only on the achieved μ_B , but also on the air distance (from 50 ft. above the runway threshold to touchdown) and the time required to engage the deceleration devices (wheel brakes, speedbrakes, and reverse thrust), and these quantities are not always the same for the FCOM and PWB. For example, the FCOM assumes a fixed air distance of 1,000 ft., but the PWB assumes 1,500 ft.

Table 9 shows the values of various parameters used in the FCOM and OPT calculations.

Item (times are from touchdown)	FCOM	Southwest Airlines PWB
Touchdown distance from threshold	1,000 ft.	1,500 ft. (SWA option)
Speed reduction from approach speed to touchdown speed	$V_{touchdown} = (0.9902)V_{approach}$	$V_{touchdown} = (0.9902)V_{approach}$
Time to wheel brake application (autobrakes)	0 sec.	0 sec.
Time to wheel brake application (manual wheel brakes and auto speedbrakes)	1 sec.	1 sec.
Time to wheel brake application (manual wheel brakes and manual speedbrakes)	2 sec.	2 sec.
Time to speedbrake deployment (auto speedbrakes)	1 sec.	1 sec.
Time to speedbrake deployment (manual speedbrakes)	2 sec.	2 sec.
Time to reverse thrust selected	2 sec.	2 sec.
Time to full reverse thrust deployment	4 sec.	4 sec.
Reverse thrust detent used (normal landing)	Detent 2	Detent 2
Reverse thrust reduced / removed	Starting @ 60 kt., decrease to reverse idle by 30 kt.	Starting @ 60 kt., decrease to reverse idle by 30 kt.
Safety factor applied	None	15% (SWA option)

Table 9. Assumptions used in the calculation of FCOM and PWB system landing distances.

The FCOM predates the TALPA ARC and AC 25-32, and so the different runway conditions considered in the FCOM not described in terms of the TALPA RwyCCs listed in Figure 18, but in terms of “reported braking action.” Constant μ_{AP} values are assumed for each braking action: 0.4 for “dry,” 0.2 for “good,” 0.1 for “medium,” and 0.05 for “poor.”⁵¹ The results of an NTSB simulation of a landing roll for the incident conditions with a constant 0.2 μ_{AP} is shown in Figure 16 as the green line labeled “ $\mu_{AP} = 0.2$ (Boeing ‘good’).” The FCOM landing distances for different combinations of approach speed and tailwind, and the resultant furthest touchdown points that permit stopping on the runway, are shown in Table 10.

As noted in Table 9, the PWB adds a 15% safety factor to the landing distances computed by the BLM, whereas the FCOM distances shown in Figure 19 do not include any safety factor. The 15% safety factor has been removed from the PWB distances shown in Table 10 to render them comparable to the corresponding FCOM distances.

The invariant conditions for the landing distances presented in Table 10 are as follows:

- Airport elevation 727 ft. MSL
- Runway slope -0.5% (downhill)
- Temperature 9° C
- Airplane gross weight = 120,800 lb. (PWB & FCOM); 120,600 lb. (simulations)⁵²

⁵¹ The dry runway μ_B is actually a Boeing proprietary model based on flight test data; the same data is used to build both the BLM calculator and the FCOM tables. For a typical 737-700 landing, the dry runway μ_{AP} is approximately 0.40. The non-dry braking action μ_{AP} values are in fact modeled as the constants indicated.

⁵² Per the FCOM, a 200 lb. difference in weight changes the landing distance by about 4 ft.

- Flaps 40
- $V_{REF40} = 126$ KCAS
- Maximum manual braking
- Auto speedbrakes

Data source	Approach speed, kt.	Tailwind, kt.	Total distance, ft.	Air distance, ft.	Ground roll, ft.	Latest touchdown point, ft.
PWB system	131	5	4645	1500	3145	2657
FCOM “good”	131	5	4132	1000	3132	2670
FCOM “good”	131	10	4442	1000	3442	2360
FCOM “good”	131	14	4690	1000	3690	2112
FCOM “good”	141	14	4990	1000	3990	1812
Simulation, $\mu_{AP} = 0.2$	141	14	5994	2504	3490	2312
Simulation, $\mu_B = \S 25.109(c)$	141	14	5934	2504	3430	2372
Simulation, $\mu_B = \S 25.109(d)$	141	14	5453	2504	2949	2853
Simulation, achieved μ_B	141	14	5831	2504	3327	2475

Table 10. Stopping distances and consequent latest touchdown points for various conditions and models. The actual touchdown point was 2,504 ft. from the threshold. Runway 8 is 5,802 ft. long.

The FCOM and PWB account for non-zero wind conditions using wind factors prescribed by §25.125(f), which states

The landing distance data must include correction factors for not more than 50 percent of the nominal wind components along the landing path opposite to the direction of landing, and not less than 150 percent of the nominal wind components along the landing path in the direction of landing.

Hence, the 5, 10, and 14 kt. FCOM and PWB tailwind data presented in Table 10 correspond to *actual* tailwind values of 7.5, 15, and 21 kt., respectively. To determine the FCOM and PWB distances corresponding to actual tailwinds of 5, 10, and 14 kt., the calculations should be performed using tailwind values of 3.3, 6.7, and 9.3 kt., respectively. The respective FCOM distances would be 103, 207, and 289 ft. shorter than those presented in Table 10. However, in operational practice the FCOM and PWB distances are always computed using the factored wind values.

Table 10 indicates that based on the (actual) landing distance required computed by the PWB using the inputs provided by the flight crew prior to landing (131 kt. approach speed and 5 kt. tailwind), the airplane could have touched down 2,657 ft. from the threshold (153 ft. past the actual touchdown point) and still stopped on the runway. This point is only 13 ft. less than that predicted by the FCOM for similar conditions. However, the actual approach speed over the threshold was 141 KCAS (corrected for the static pressure error), and the tailwind over the runway was about 14 kt., not 5 kt. Under these conditions, the FCOM indicates that the latest touchdown point is 1,812 ft. from the threshold, or 312 ft. past the SWA nominal touchdown point of 1,500 ft., but 692 ft. short of the actual touchdown point of 2,504 ft. from the threshold.

The simulation of the rollout with the actual speed and tailwind conditions and the achieved μ_B indicates that if the airplane had maintained the runway centerline (instead of crossing over the left edge onto ungrooved pavement) and the μ_B had continued increasing with decreasing ground speed, then the airplane would have come to rest in between the end of the runway and the EMAS (see Figure 16). The latest touchdown point in Table 10 corresponding to this condition is 2,475 ft., only 29 ft. short of the actual touchdown point.

Even if the airplane had been at the nominal approach speed of 131 kt. ($V_{REF} + 5$ kt.) over the threshold, with a 10 kt. tailwind (presumably what the crew was expecting based on the latest wind report from the ATC tower), per the FCOM the latest touchdown point would have been 2,360 ft., or 144 ft. shorter than the actual touchdown point.

If the μ_B had achieved the level specified by §25.109(d) for a grooved runway (Equation [26b]), then Table 10 indicates that the latest touchdown point would have been 2,853 ft. from the threshold, or 349 ft. past the actual touchdown point.

The results in Table 10 indicate that the faster than nominal approach speed, the higher than expected tailwind, and the longer than normal touchdown point all contributed to the overrun. However, of the three, the long touchdown is the most significant contributor. The airplane could have stopped on the runway with the high approach speed and 14 kt. tailwind even if the touchdown had been 312 ft. longer than the nominal 1,500 ft.; however, with the actual touchdown point of 2,504 ft. from the threshold, either the tailwind or faster approach speed by themselves would have prevented a stop on the runway. In addition, the simulation results indicate that the airplane might have stopped before entering the EMAS if it had remained on the grooved runway surface instead of deviating to the left off of this surface, which resulted in a significant loss of friction.

Comparison of incident flare and touchdown with previous flaps 40 landings

As noted above, the long touchdown, 2,504 ft. from the threshold, was probably the most significant contributor to the runway overrun. Consequently, it is of interest to determine why the airplane touched down 1,000 ft. past the PWB nominal touchdown point of 1,500 ft. from the threshold. Figure 19 compares the flare and touchdown of the incident landing with those of two prior flaps 40 landings recorded on the FDR. Previous landing #1 was performed on runway 2L at John Wayne Airport in Santa Anna, California (KSNA), and previous landing #2 was also on KBUR runway 8.

Figure 19 plots the following parameters vs. the distance from the runway threshold in each case:

- Radar altitude
- The difference between ground speed and target approach airspeed, defined as

$$\Delta V = V_G - V_{TARGET} \quad [33]$$

- Pitch angle
- Left engine N1

In addition, circle symbols in the radar altitude plot (top plot in Figure 19) indicate the touchdown points for each landing, and are labeled with the time from the threshold crossing to touchdown, in seconds.

Figure 19 shows that flight 278 crossed the threshold about 20 ft. higher in radio altitude than during the previous landings, and took more than twice as long to touch down after crossing the threshold. Furthermore, flight 278's ΔV over the threshold was about 25 kt., whereas in the previous landings ΔV was -1 kt. and -2 kt. Flight 278's higher altitude over the threshold necessitated more time to descend to the runway; and the additional time, at a high groundspeed, resulted in much more distance over the runway before touchdown.

Figure 19 also shows that the peak pitch attitude during flight 278's flare (about 2.5°) is reached at about 1,800 ft. from the threshold, or 300 ft. past the nominal touchdown point, while the airplane is still airborne. Given the small stopping margin provided by the PWB system (245 ft.), the airplane state at this point should have prompted a go-around per section 11.8.1 of the AOM, since "the aircraft [would touch] down beyond 1,500 ft. with an insufficient PWB System-computed stopping margin." In addition, Figure 19 shows that 1,200 ft. from the threshold, the engine N1 is only beginning to reduce from 60%. During the previous landings, the engine N1 is reduced below 60% well before the 400 ft. mark.

In summary, the higher altitude and ground speed of flight 278 over the threshold compared to the previous flaps 40 landings, without any adjustment in thrust to compensate, resulted in its delayed touchdown and long touchdown point.

Boeing RAAS and RSAT Flight Deck Enhancements

The summary of the Captain's interview with NTSB investigators (Reference 22) states that he and the FO acknowledged the ATC tower's report of winds from 270° at 11 knots as the airplane was "somewhere between 500 and 1000 ft." (above the field), and that "he and the FO acknowledged this call and agreed that the tailwind component was 9-10 knots and it was within limits." In fact, as noted above, the tailwind component was 10.8 kt. and therefore just above the 10 kt. limit. In addition, Reference 22 records that the Captain stated that "they touched down between 1,300 and 1,500 feet down the runway," when in fact the touchdown occurred 2,504 ft. from the threshold. The Captain's statements indicate that he and the FO might not have been fully aware of the airplane's true ground speed (because the tailwind was higher than they believed) or position on the runway (as indicated by the large discrepancy between the actual touchdown point and the point reported by the Captain).

As described in a 2011 Boeing *AERO* magazine article (Reference 25), Boeing has developed "flight deck enhancements" that "provide crew information and awareness that promote runway safety and operational efficiency," that can "can reduce the risk of runway incursion, confusion, and excursion, resulting in safer and more efficient taxi, takeoff, approach, and landing operations." One of the flight deck enhancements described in the article is the runway awareness and advisory system (RAAS). RAAS "provides voice

callouts for pilot awareness when approaching, entering, or on a runway, and voice and visual alerts for taxiway takeoffs and short runways.”

RAAS can help prevent runway overruns by providing “callouts (e.g., runway distance remaining) and alerts (e.g., short runway) to provide awareness of overrun risk.” The *AERO* article, written in 2011, also lists the following “future excursion enhancements under consideration:”

- Landing performance calculation and display.
- HUD cues on primary flight displays.
- Stabilized approach, landing, and braking performance displays.
- Unstable approach (e.g., too high or too fast), long landing, predicted overrun, and taxiway landing alerts.
- Optimized runway exiting for a graphical indication of estimated braking performance and a dynamic indication of stopping performance during landing (see [Figure 20]).

In response to an NTSB request, Boeing provided the following update on the “future excursion enhancements” listed above:

In addition to the Boeing RAAS features noted in the *Aero Magazine* articles the following Boeing runway situational awareness tools (RSAT) features have been available on newly manufactured 737NG and 737MAX airplanes since 2016.

- Boeing RSAT Overrun Warning
 - Provides in-air and on-ground aural and visual warnings to indicate a potential runway excursion
- Boeing RSAT Speedbrake Warning
 - Provides an aural and a visual warning during landing rollout or rejected takeoff that the speedbrakes are not deployed
- Boeing RSAT Perspective Runway on HUD (if HUD is installed)
 - Provides enhanced awareness of airplane position relative to the FMC-selected runway through the addition of “pilot perspective” runway symbols

Retrofit options for these features are available on 737NG airplanes with compatible wiring, component, and software installations.

In response to an NTSB inquiry, SWA indicated that

the RAAS is not currently implemented on any SWA aircraft, including the incident aircraft. Boeing’s Runway Situational Awareness Tools are not available for use on all of our existing -700 fleet due to compatibility limitations.

E. CONCLUSIONS

Execution of the approach and landing

The material in this *Study* supports a number of observations and conclusions regarding the performance of N752SW during its approach and landing on KBUR runway 8. Section C of this *Study* summarizes the motion of the airplane during the approach and landing, and notes that the approach was stabilized on the ILS glideslope and centerline, and close to the target approach airspeed, until shortly after the autopilot and autothrottle were disconnected at 09:02:01.8. Following the autopilot disconnect, N752SW started to drift above the glide slope, and the airspeed increased by up to about 7 knots just prior to the start of the flare. The airplane crossed the threshold at a higher radio altitude than in two previous flaps 40 landings recorded on the FDR, and, as a result of a 16 kt. tailwind, the ground speed over the threshold was about 25 kt. higher than the target airspeed. The higher altitude and ground speed of flight 278 over the threshold compared to the previous flaps 40 landings, without any adjustment in thrust to compensate, resulted in its delayed touchdown and a long touchdown point 2,504 ft. from the threshold.

The higher than expected tailwind, the longer than normal touchdown point, and to a lesser degree, the faster than nominal approach speed all contributed to the overrun. However, of the three, the long touchdown is the most significant contributor. The airplane could have stopped on the runway with the high approach speed and tailwind even if the touchdown had been 312 ft. longer than the nominal 1,500 ft. from the threshold; however, with the actual touchdown point of 2,504 ft. from the threshold, either the tailwind or faster approach speed by themselves would have prevented a stop on the runway. Per the SWA AOM, once the airplane overflowed the nominal 1,500 ft. touchdown point, the PWB landing distance calculations became “invalid” and “a go-around [was] the better option.”

Reported vs. actual wind conditions

The maximum tailwind allowed by the SWA AOM is 10 kt. The tailwind component corresponding to the wind report provided by the ATC tower at 09:02 (wind from 270° (magnetic) at 11 knots) is 10.8 kt., i.e., higher than the limit. However, the Captain stated in his interview that he and the First Officer “acknowledged this call and agreed that the tailwind component was 9-10 kt. and it was within limits.” The error in the crew’s estimate of the tailwind component is admittedly small (about 1 kt.); consequently, it is possible that if the winds reported by the tower had been more consistent with the winds recorded by the ASOS (and computed using the FDR data), which were 3 to 5 kt. higher than those reported by the tower, the crew might have recognized that the AOM tailwind limit was exceeded and abandoned the approach.

Anticipated and achieved runway friction

Simulation results indicate that the airplane might have stopped before entering the EMAS if it had remained on the grooved runway surface instead of deviating to the left off of this surface, which resulted in a significant loss of friction.

While the airplane was on the grooved runway, the μ_B achieved was consistent with the wet-runway μ_B assumed in the PWB system landing distance calculations and with the “good” braking action level assumed in the B737-700 FCOM, though the μ_B did not reach the level specified in §25.109(d) for a grooved runway. If the §25.109(d) μ_B had been achieved, then the airplane would have stopped 348 ft. before the end of the runway. However, since neither the FCOM nor the PWB system take credit for the higher μ_B modeled in §25.109(d), and the achieved μ_B is consistent with the models used to compute operational landing distances, the μ_B levels attained in this incident do not raise the same concern as the lower-than-expected μ_B levels achieved in the accidents described in Reference 9.

Nevertheless, the development of tools with which airport operators can reliably predict and report the expected μ_B performance of their individual runways over a range of rainfall intensities would help ensure safety while maximizing the use of runways in wet conditions. To this end, the NASA CFME μ_B model has consistently matched the μ_B achieved during non-flooded wet runway overrun events, including this flight 278 event, and consequently could be used to predict the μ_B that would be available on any given runway when wet. However, as the Jacksonville B737-800 overrun demonstrates, the NASA model fails to predict the μ_B available on a flooded (or nearly flooded) runway, so additional research to establish the range of rainfall rates and runway water depths for which the NASA model is valid would be beneficial.

Flight deck enhancements for increasing situational awareness near runways

Some of the Captain’s statements recorded in Reference 22 indicate that he and the FO might not have been fully aware of the airplane’s true ground speed (because the tailwind was higher than they believed) or position on the runway (as indicated by the large discrepancy between the actual touchdown point and the point reported by the Captain). The runway awareness and advisory system (RAAS) and runway situational awareness tools (RSAT) flight deck enhancements developed by Boeing are intended to alert the flight crew to the energy state of the airplane and the potential for a runway excursion, and might have provided additional cues to the pilots in this incident that could have made them more aware of the airplane’s ground speed and position over the runway. While the RSAT features are available for retrofit on some B737NG airplanes, SWA reports that the feature is not available for use on all of their existing -700 fleet due to compatibility limitations.

John O’Callaghan
National Resource Specialist – Aircraft Performance
Office of Research and Engineering

F. REFERENCES

1. The Boeing Company, *737-700/-800 Flight Crew Operations Manual*, Southwest Airlines Co., Document # D6-27370-7H4-SWA, Revision # 49, Revision date March 21, 2019.
2. Southwest Airlines, *B737NG Aircraft Operating Manual (B737NG AOM)*, Revision Number 18-07 dated 11/20/2018 (Southwest Airlines proprietary document).
3. National Transportation Safety Board, Office of Aviation Safety, *Human Performance / Operational Factors Factual Report, Southwest Airlines Flight 278, Boeing 737-700, N752SW, Burbank, California, December 6, 2018, NTSB Incident # DCA19IA036*. (Contact NTSB at pubinq@ntsb.gov.)
4. The Boeing Company, *737-600/700/700IGW(BBJ)/800/900 Airplane Recovery Document*, Document # D626A004, March 31 2016 (Boeing proprietary document).
5. National Transportation Safety Board, Office of Research and Engineering, *Flight Data Recorder Specialist's Factual Report, Southwest Airlines Flight 278, Boeing 737-700, N752SW, Burbank, California, December 6, 2018, NTSB Incident # DCA19IA036*. (Contact NTSB at pubinq@ntsb.gov.)
6. National Transportation Safety Board, Office of Research and Engineering, *Cockpit Voice Recorder Specialist's Factual Report, Southwest Airlines Flight 278, Boeing 737-700, N752SW, Burbank, California, December 6, 2018, NTSB Incident # DCA19IA036*. (Contact NTSB at pubinq@ntsb.gov.)
7. National Transportation Safety Board, Office of Research and Engineering, *Group Chairman's Aircraft Performance Study, American Airlines Flight 587, Airbus A300B4-605R, Belle Harbor, New York, November 12, 2001, NTSB Accident Number DCA02MA001, Docket Item 188* (Washington, DC: NTSB, October 10, 2002). (Contact NTSB at pubinq@ntsb.gov.)
8. National Transportation Safety Board, Office of Aviation Safety, *Meteorology Factual Report / Weather Study, Southwest Airlines Flight 278, Boeing 737-700, N752SW, Burbank, California, December 6, 2018, NTSB Incident # DCA19IA036*. May 13, 2009 (Contact NTSB at pubinq@ntsb.gov.)
9. O'Callaghan, John J., *Slippery When Wet: The Case for More Conservative Wet Runway Braking Coefficient Models*. Presented at the 16th American Institute of Aeronautics and Astronautics Aviation Technology, Integration, and Operations Conference, Washington, D.C., June 17, 2016. Paper # AIAA-2016-4364, available at <https://goo.gl/rWfoUc>
10. *Federal Register* Vol. 78, No. 46 / Friday, March 8, 2013 / Notices, page 15112.
11. Federal Aviation Administration (FAA) Aviation Rulemaking Advisory Committee (ARAC) Flight Test Harmonization Working Group (FTHWG): *Phase 2 Recommendation Report – REV A*, April, 2017. Available at: https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/09%20-%20FTHWG_Final_Report_Phase_2_RevA_Apr_2017.pdf.
12. Federal Aviation Administration (FAA) Aviation Rulemaking Advisory Committee (ARAC) Flight Test Harmonization Working Group (FTHWG), *Task 9: Wet Runway Stopping Performance Final Report, Recommendation Report*, March 16, 2018. Available at https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/FTHWG-%20Wet%20Runway%20Topic9%20Final%20Report.pdf.
13. Southwest Airlines, *Dispatch Operations Manual (DOM)*, Revision Number 18-06 dated 11/20/2018 (Southwest Airlines proprietary document).

14. Southwest Airlines, *Flight Operations Manual (FOM)*, Revision Number 18-05 dated 11/20/2018 (Southwest Airlines proprietary document).
15. Federal Aviation Administration, *Advisory Circular 25-7D – Flight Test Guide For Certification Of Transport Category Airplanes*, dated May 4, 2018. Available at: https://www.faa.gov/documentLibrary/media/Advisory_Circular/25-7D.pdf
16. Engineering Science Data Unit (ESDU) Item 71026, *Frictional and Retarding Forces on Aircraft Tyres, Part II: estimation of braking force (friction data updated – 1981)*, with Amendments A and B, August 1981. Sponsored by the Royal Aeronautical Society. For ESDU items see <https://ihsmarkit.com/index.html>.
17. National Transportation Safety Board, Office of Research and Engineering, *Group Chairman's Aircraft Performance Study Addendum #1 (Errata #2), Hawker Beechcraft BAe 125-800A, registration N818MV, Owatonna, MN, July 31, 2008*, NTSB Accident Number DCA08MA085 (Washington, DC: NTSB, February 25, 2011). Available at: <http://dms.nts.gov/pubdms/search/document.cfm?docID=344186&docketID=46427&mkey=68571>
18. Yager, Thomas J., Vogler, William A., & Baldasare, Paul, *Evaluation of Two Transport Aircraft and Several Ground Test Vehicle Friction Measurements Obtained for Various Runway Surface Types and Conditions: A Summary of Test Results From Joint FAA / NASA Runway Friction Program*. NASA Technical Paper 2917, NASA Office of Management, Scientific and Technical Information Division, February 1990.
19. National Transportation Safety Board, Office of Research and Engineering, *Group Chairman's Aircraft Performance Study, Embraer EMB-505, N322QS, Conroe, TX (Lone Star Executive Airport (KCXO)), September 19, 2014*, NTSB Accident Number CEN14FA505 (Washington, DC: NTSB, April 20, 2016). (Contact NTSB at pubinq@ntsb.gov).
20. National Transportation Safety Board, Office of Research and Engineering, *Aircraft Performance Study, Miami Air International Flight 293, Boeing 737-81Q, N752SW, Jacksonville, Florida, May 3, 2019*, NTSB Accident # DCA19MA143. (Contact NTSB at pubinq@ntsb.gov.)
21. NTSB letter to FAA transmitting comments on draft Advisory Circulars 25-31 and 25-32, March 4, 2015, accessible at http://www.nts.gov/safety/safety-recs/_layouts/nts.gov/Recsearch/Recommendation.aspx?Rec=A-07-057
22. National Transportation Safety Board, Office of Aviation Safety, *Attachment #1 to Human Performance / Operational Factors Factual Report: Interview Summaries, Southwest Airlines Flight 278, Boeing 737-700, N752SW, Burbank, California, December 6, 2018*, NTSB Incident # DCA19IA036. (Contact NTSB at pubinq@ntsb.gov.)
23. International Civil Aviation Organization (ICAO), *The Tenth Meeting of Automatic Dependent Surveillance – Broadcast (ADS-B) Study and Implementation Task Force (ADS-B SITF/10) Agenda Item 6: Review States' activities and interregional issues on trials and implementation of ADS-B and multilateration: ADS-B / GPS Accuracy (Presented by Australia)*. Singapore, 26-29 April 2011. Document available at https://www.icao.int/APAC/Meetings/2011_ADS_B_SITF10/IP10_AUS%20AI.%206%20-%20GPS%20Accuracy.pdf.
24. Federal Aviation Administration, *Advisory Circular No. 25-32: Landing Performance Data for Time-of-Arrival Landing Performance Assessments*, dated December 22, 2015. Available at https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1028656.
25. Clark, Sam, & Trampus, George, *Improving Runway Safety with Flight Deck Enhancements*, Boeing AERO magazine, issue QTR_01.11, available at: https://www.boeing.com/commercial/aeromagazine/articles/2011_q1/2/.

G. GLOSSARY

Acronyms

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance – Broadcast
AFM	Airplane Flight Manual
AFM-DPI	Airplane Flight Manual - Digital Performance Information
AMC	Acceptable Means of Compliance (EASA)
AOM	Aircraft Operating Manual
ARC	Aviation Rulemaking Committee
ARAC	Aviation Rulemaking Advisory Committee
ASOS	Airport Surface Observation System
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
BLM	Boeing Landing Module
CDI	Course Deviation Indicator
CFME	Continuous Friction Measurement Equipment
CFR	Code of Federal Regulations
CG	Center of Gravity
CS	Certification Specification (EASA)
CVR	Cockpit Voice Recorder
EASA	European Aviation Safety Agency
EU OPS	European operational regulation(s)
FAA	Federal Aviation Administration
FCOM	Flight Crew Operating Manual
FDR	Flight Data Recorder
FO	First Officer
FOM	Flight Operations Manual
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ILS	Instrument Landing System
KBUR	Bob Hope Airport, Burbank, California
MAC	Mean Aerodynamic Chord
METAR	Meteorological Terminal Air Report
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
OpsSpec	Operations Specification(s)
OPT	Onboard Performance Tool
PF	Pilot Flying
PST	Pacific Standard Time
QAR	Quick Access Recorder
RAAS	Runway awareness and advisory system
RCAM	Runway Condition Assessment Matrix
RFT	Dynatest Model 6875 Runway Friction Tester CFME device
RSAT	Runway situational awareness tools
RwyCC	RCAM runway condition code
SAFO	Safety Alert For Operators

SRN	Subframe Reference Number
SRTM	Shuttle Radar Topography Mission
STC	Supplemental Type Certificate
SWA	Southwest Airlines
TALPA	Takeoff And Landing Performance Assessment
TC	Type Certificate
TDZE	Touchdown Zone Elevation
TRA	Throttle resolver angle
USA	United States of America
USGS	United States Geological Survey
UTC	Coordinated Universal Time

English symbols

dh	Differential altitude element
F_N	Longitudinal reaction force at nose gear
F_M	Longitudinal reaction force at main gear
F_x	Force along body x-axis
F_y	Force along body y-axis
F_z	Force along body z-axis
g	Gravitational acceleration
h	Altitude
$\dot{h}$	Rate of climb
k_B	Effective η_{AS} for scaling §25.109(c) μ_{max} to μ_B from CFME runs
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	Air pressure
P_{TOTAL}	Total pressure at pitot tube
P_{TRUE}	True freestream static pressure (vs. static pressure at static ports)
p	Tire pressure, or atmospheric pressure (depending on context)
R	Gas constant of air
S	Wing reference area
T	Air temperature
u	Component of airspeed along body x-axis
v	Component of airspeed along body y-axis
V	Airplane speed (airspeed or ground speed depending on context)
$\vec{V}$	Airspeed vector
V_1	Takeoff decision speed
V_G	Ground speed
$\vec{V}_G$	Ground speed vector
V_{REF}	Landing reference speed
V_{REF40}	Flaps 40 landing reference speed
V_{TAIL}	Tailwind velocity
V_{TARGET}	Target approach airspeed

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
w	Component of airspeed along body z-axis
W	Airplane weight
W_x	Component of airplane weight along body x-axis
W_y	Component of airplane weight along body y-axis
W_z	Component of airplane weight along body z-axis
x	Runway x coordinate
Y	Side force
y	Runway y coordinate

Greek symbols

α	Angle of attack
β	Sideslip angle
δ_r	Rudder deflection
γ	Flight path angle
η_{AS}	Anti-skid braking system efficiency
θ	Pitch angle
μ	Friction coefficient
μ_{AP}	Airplane braking coefficient
μ_B	Wheel braking friction coefficient
μ_{CFME}	Runway μ measured by a CFME device
μ_{dry}	Dry-runway μ
μ_N	Rolling friction coefficient at nose gear
$\mu_{max}, \mu_{t/gMAX}$	Maximum μ available on runway
μ_{wet}	Wet-runway μ
ρ	Air density
ϕ	Roll angle
ψ_{DRIFT}	Drift angle
ψ_{THDG}	True heading angle
ψ_{TRK}	True track angle

FIGURES

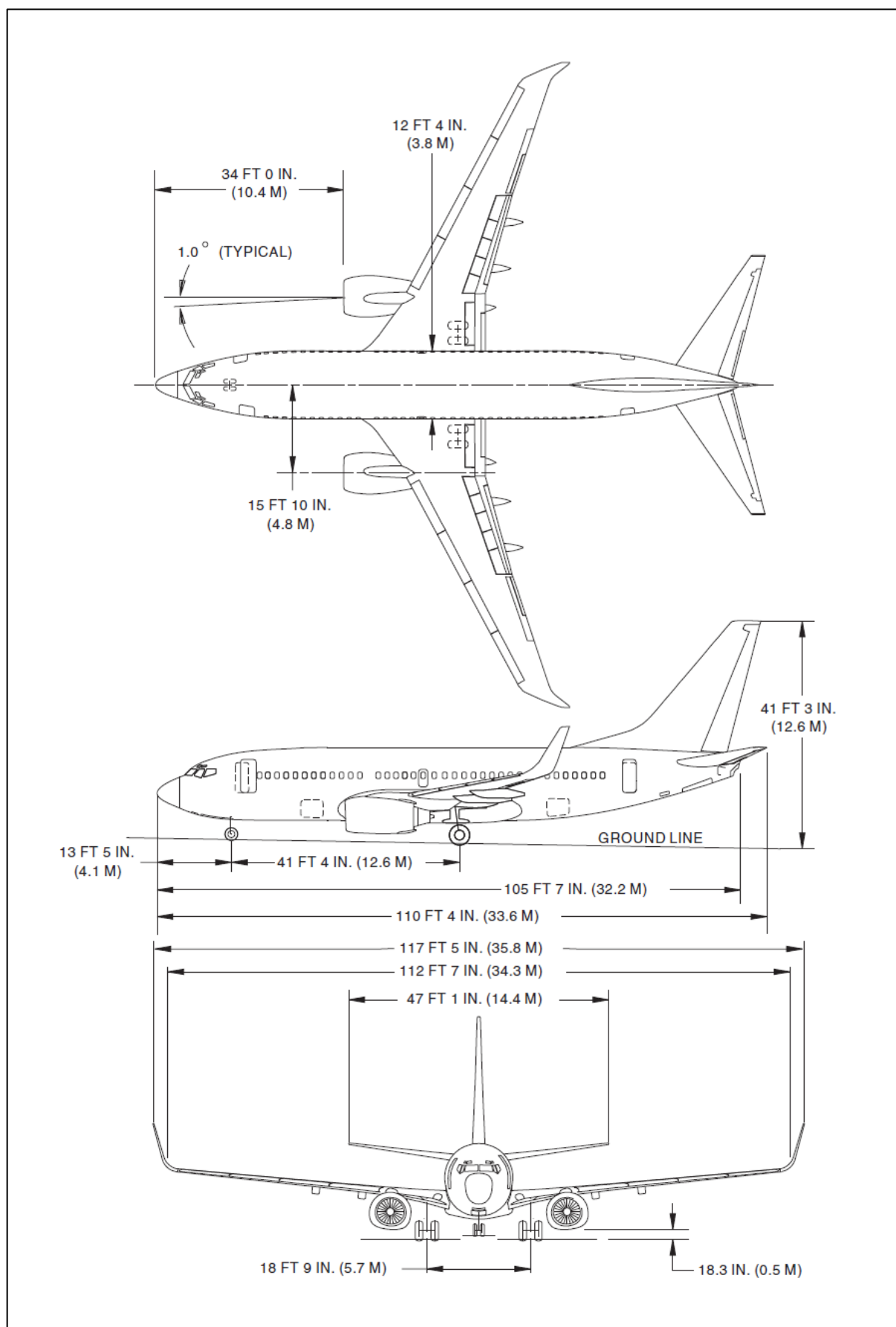


Figure 1. 3-view of Boeing 737-700 airplane (from Reference 4).

Figure 1 is an aerial map of the KBUR Runway 8 area. The map displays the Runway 8 outline in black. Blue dots represent FDR latitude/longitude points, and a yellow line represents the Accelerometer integration. The map includes a coordinate system with the x-axis ranging from -22000 to 6000 and the y-axis ranging from -2000 to 2000 ft. The legend indicates the following:

- FDR latitude / longitude points (Blue dots)
- Accelerometer integration (Yellow line)
- Runway 8 outline (Black line)



DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Plan view of ground track during landing and rollout (detail)

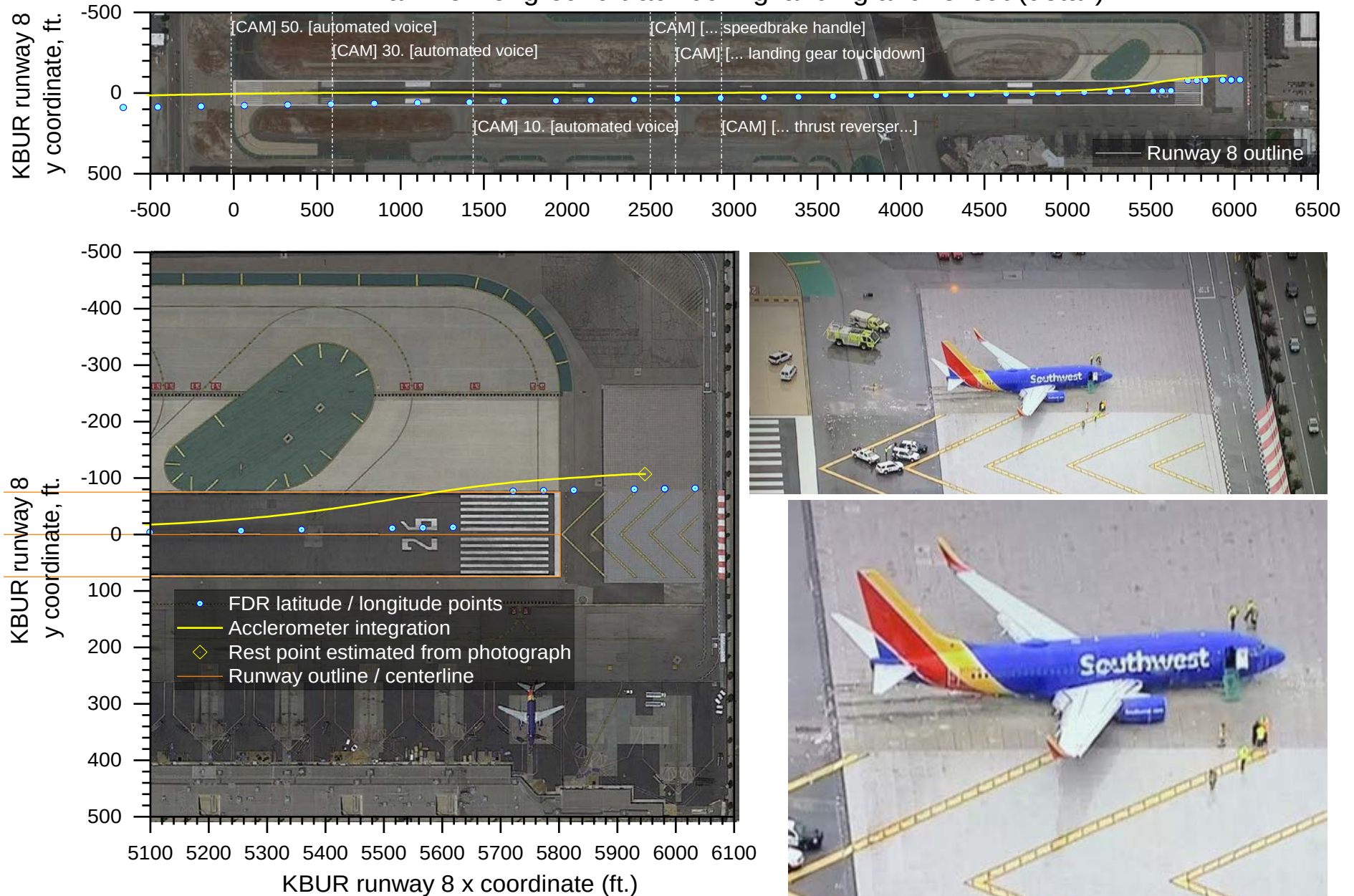
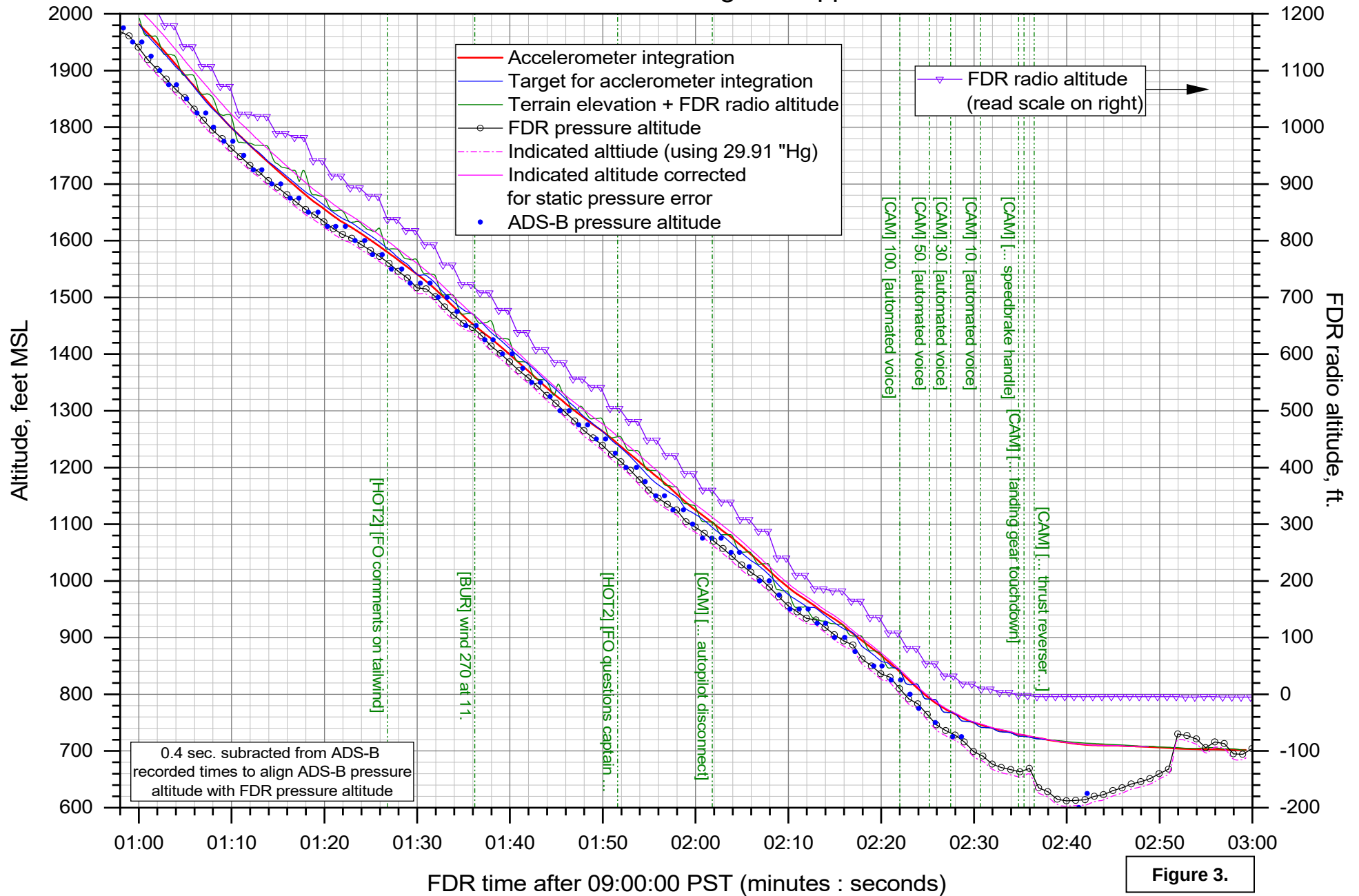


Figure 2b.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Altitude vs. time during final approach



DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Runway coordinates during final approach, landing, & rollout

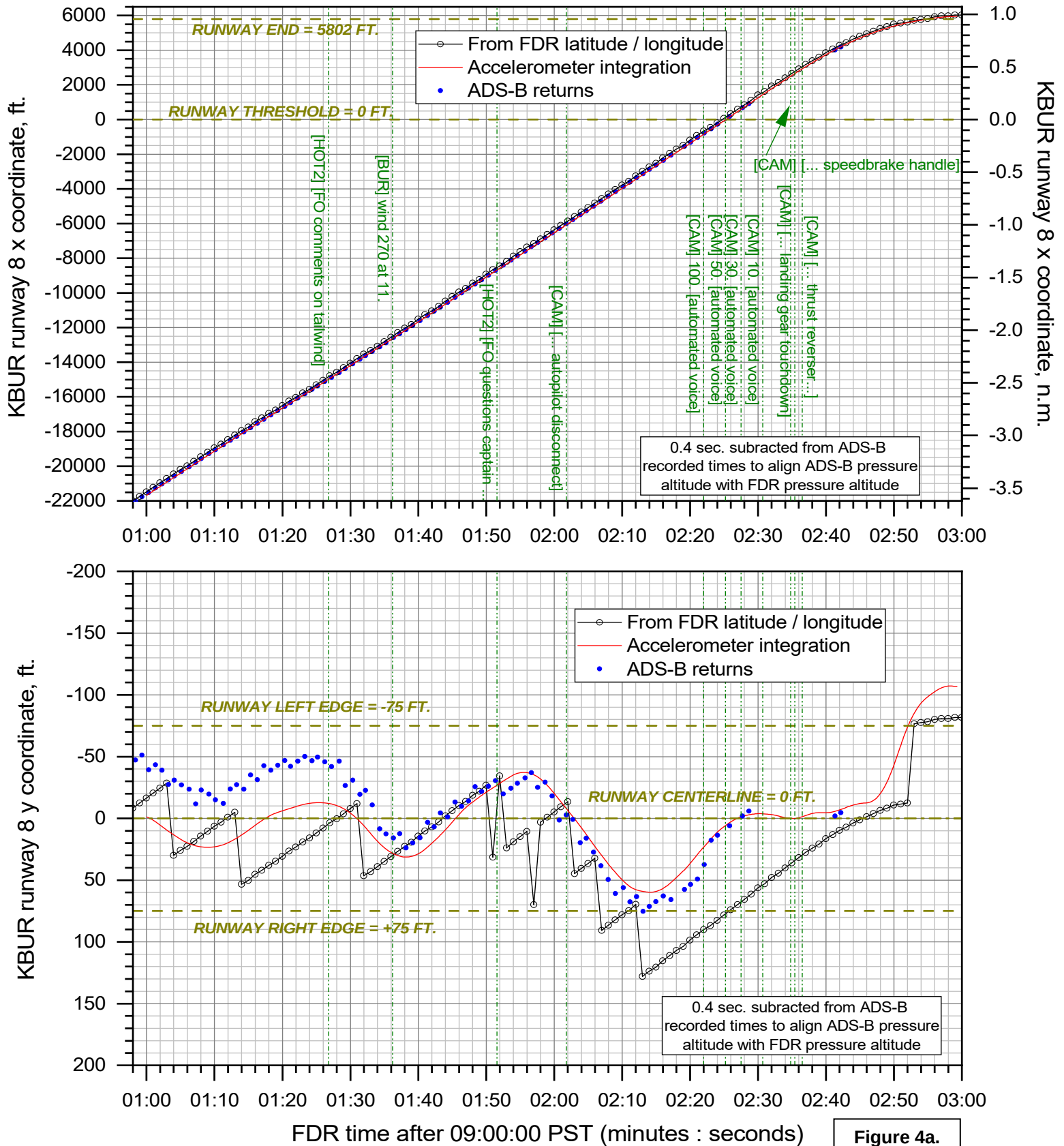


Figure 4a.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

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

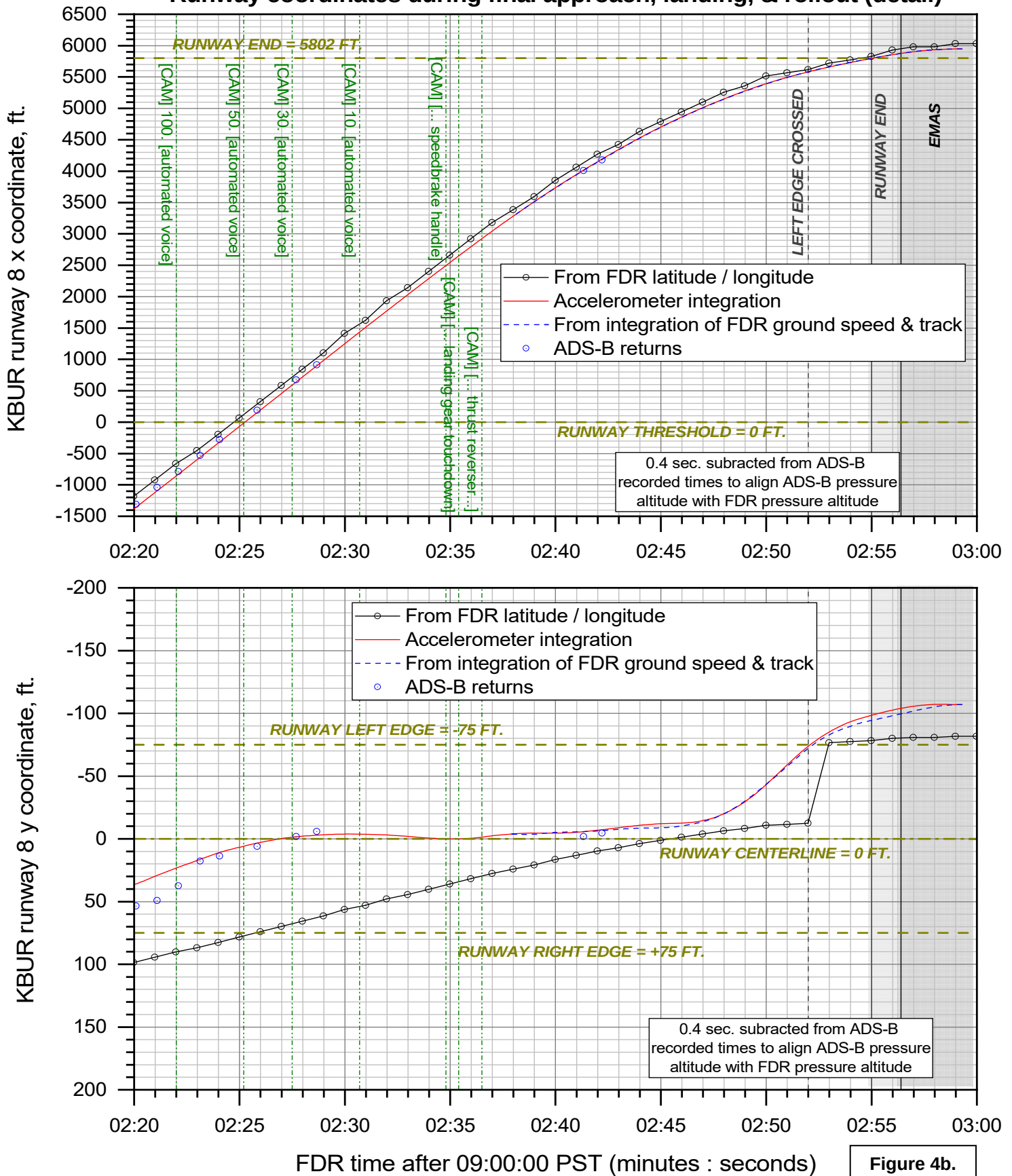


Figure 4b.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

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

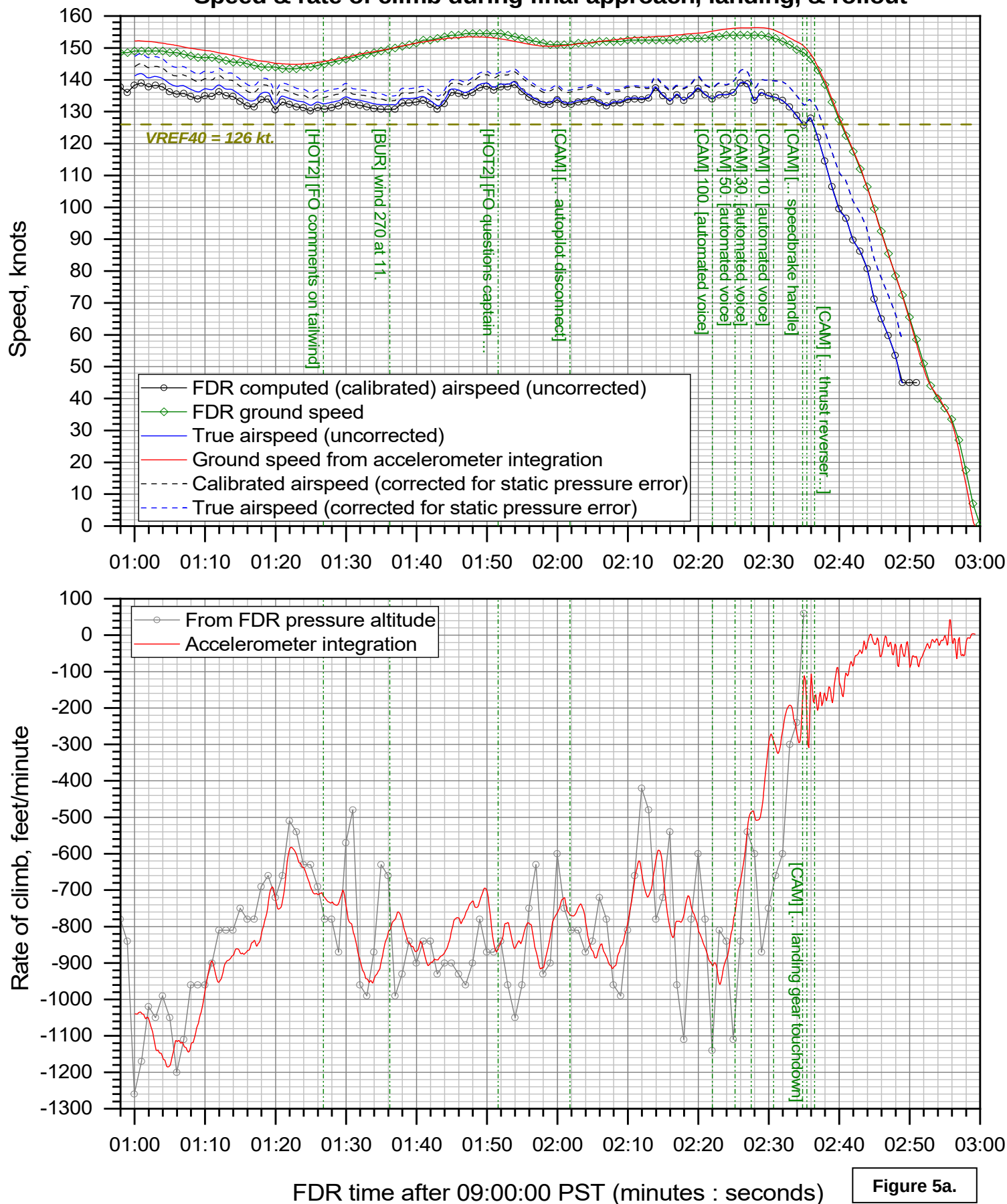


Figure 5a.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

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

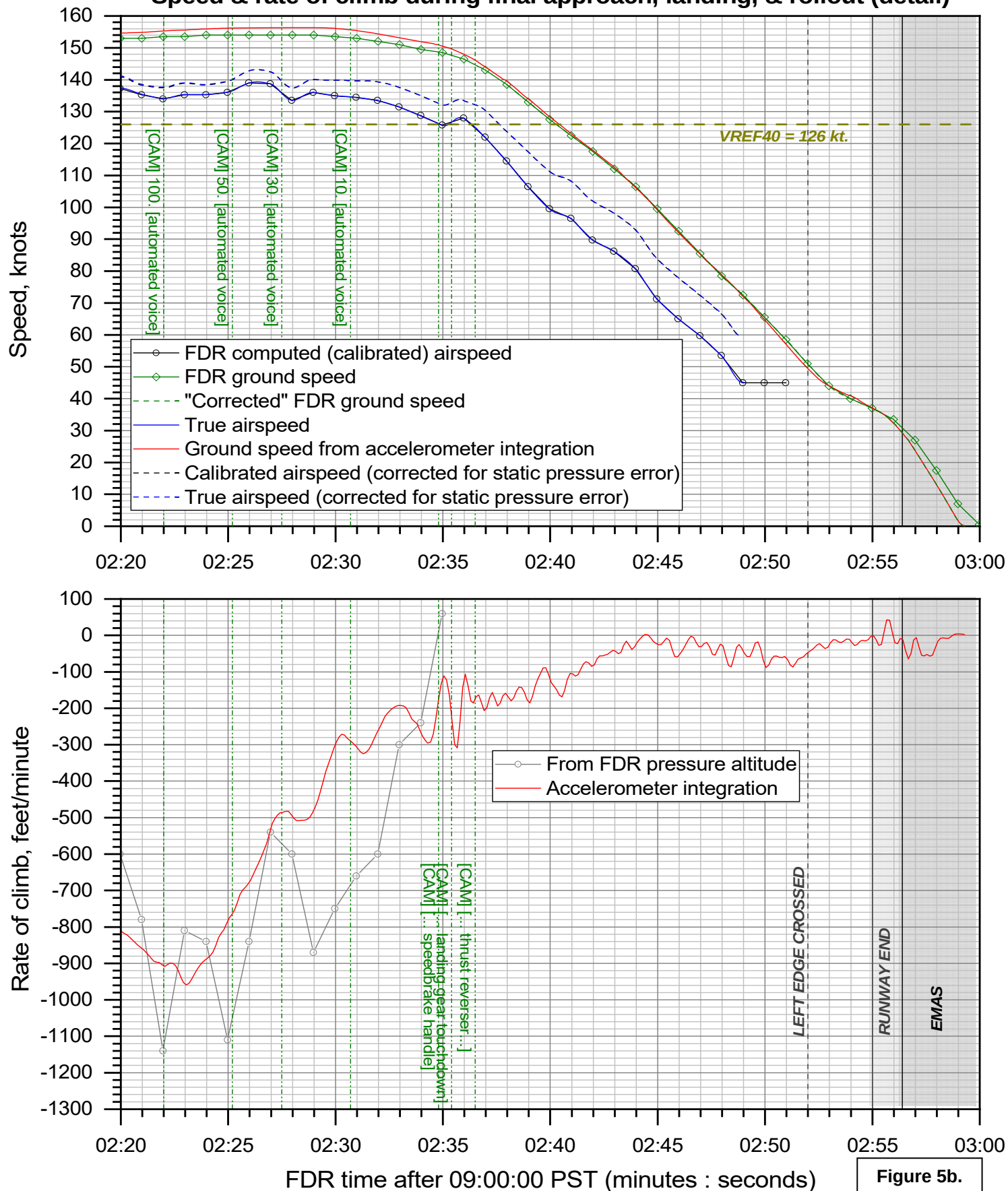
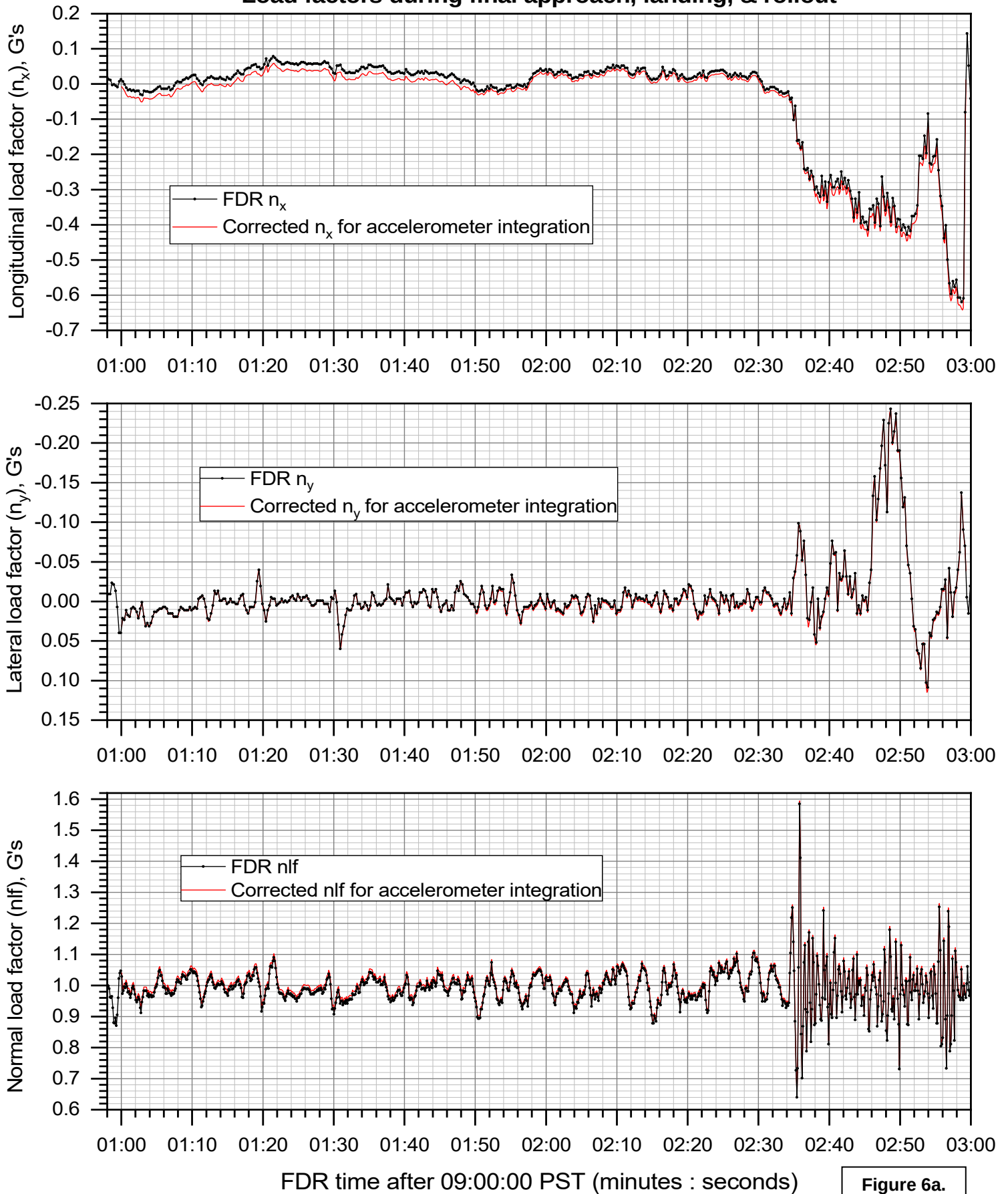


Figure 5b.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018**Load factors during final approach, landing, & rollout****Figure 6a.**

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

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

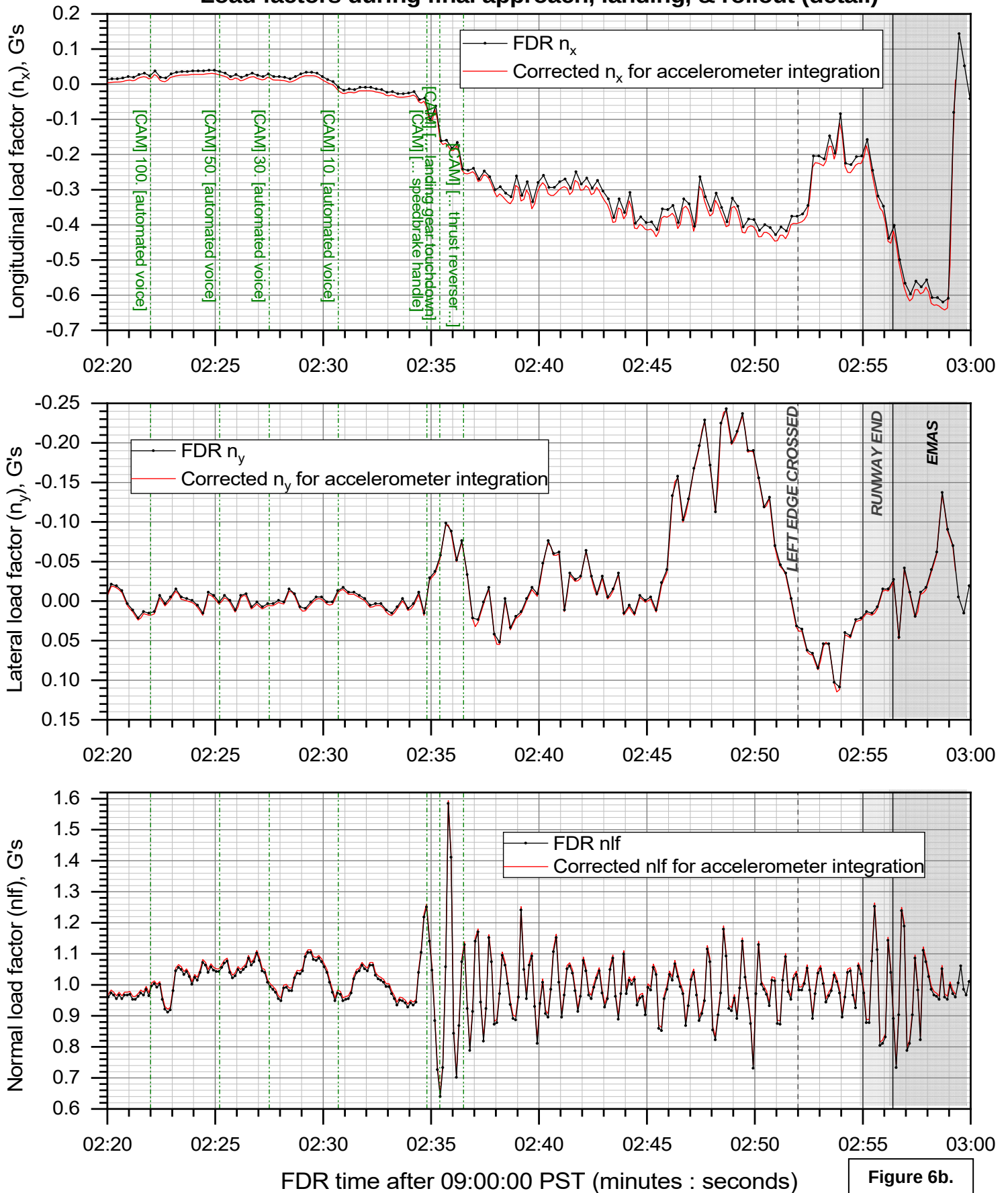


Figure 6b.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Euler angles during final approach, landing, & rollout

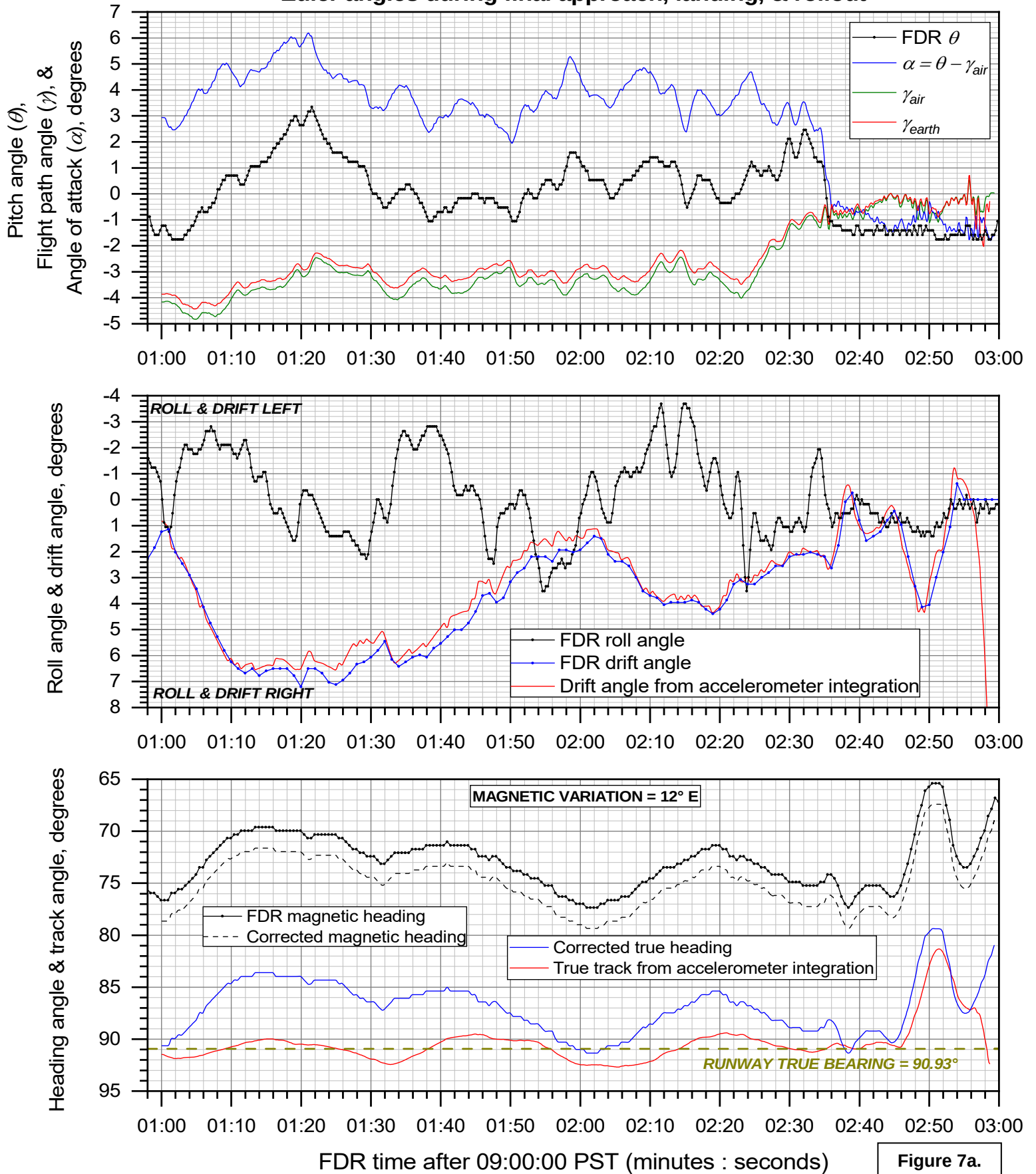


Figure 7a.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

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

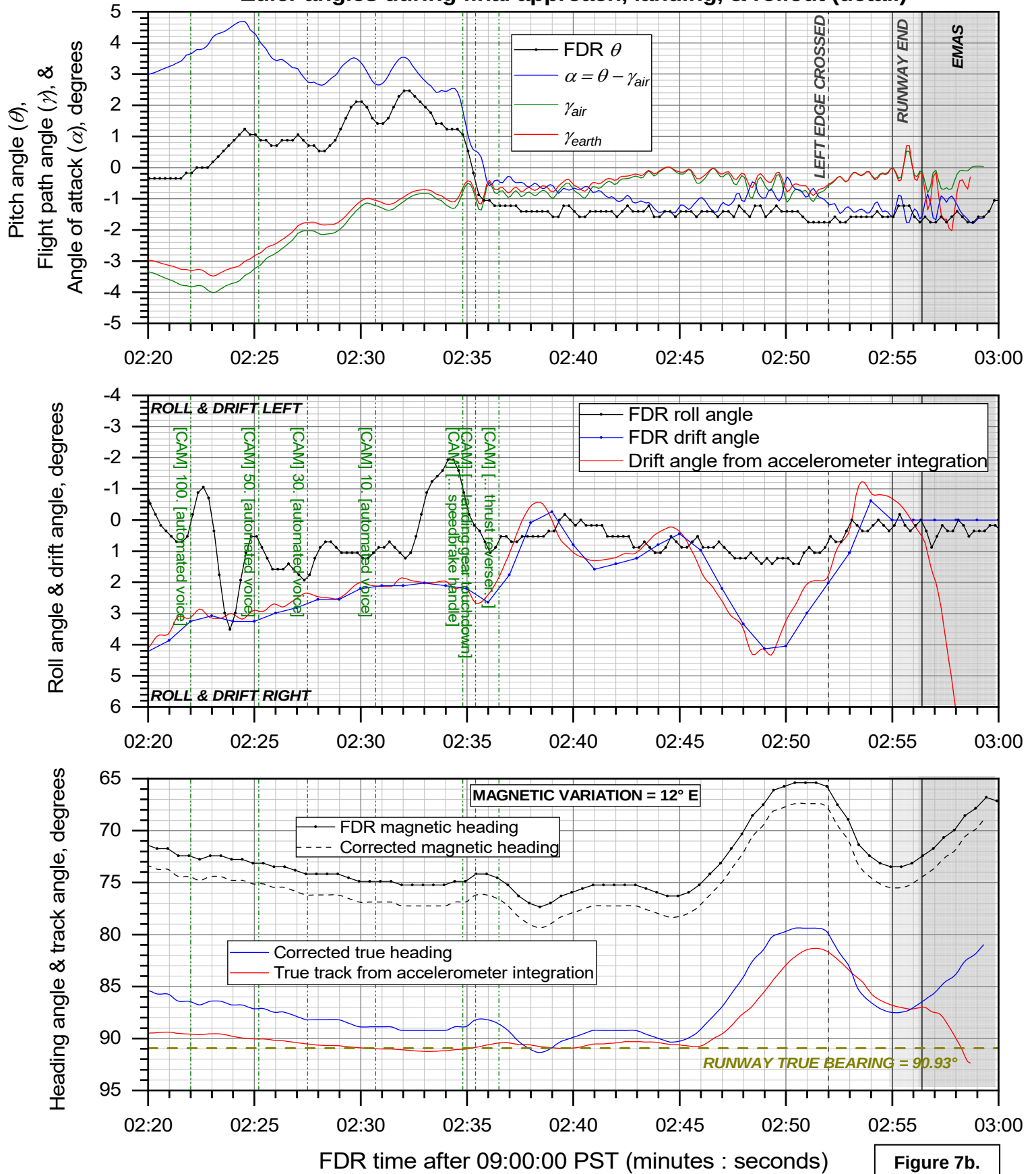
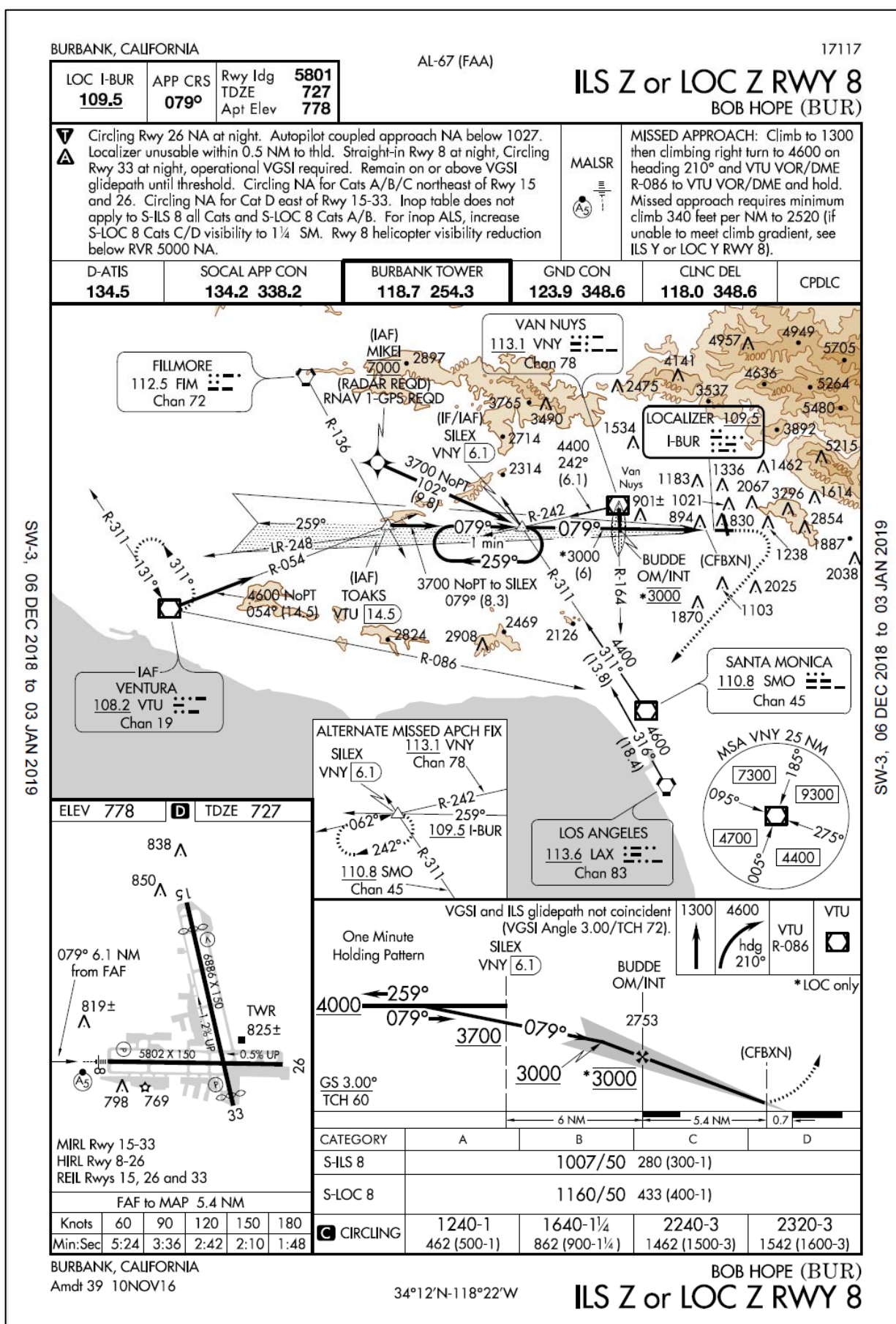
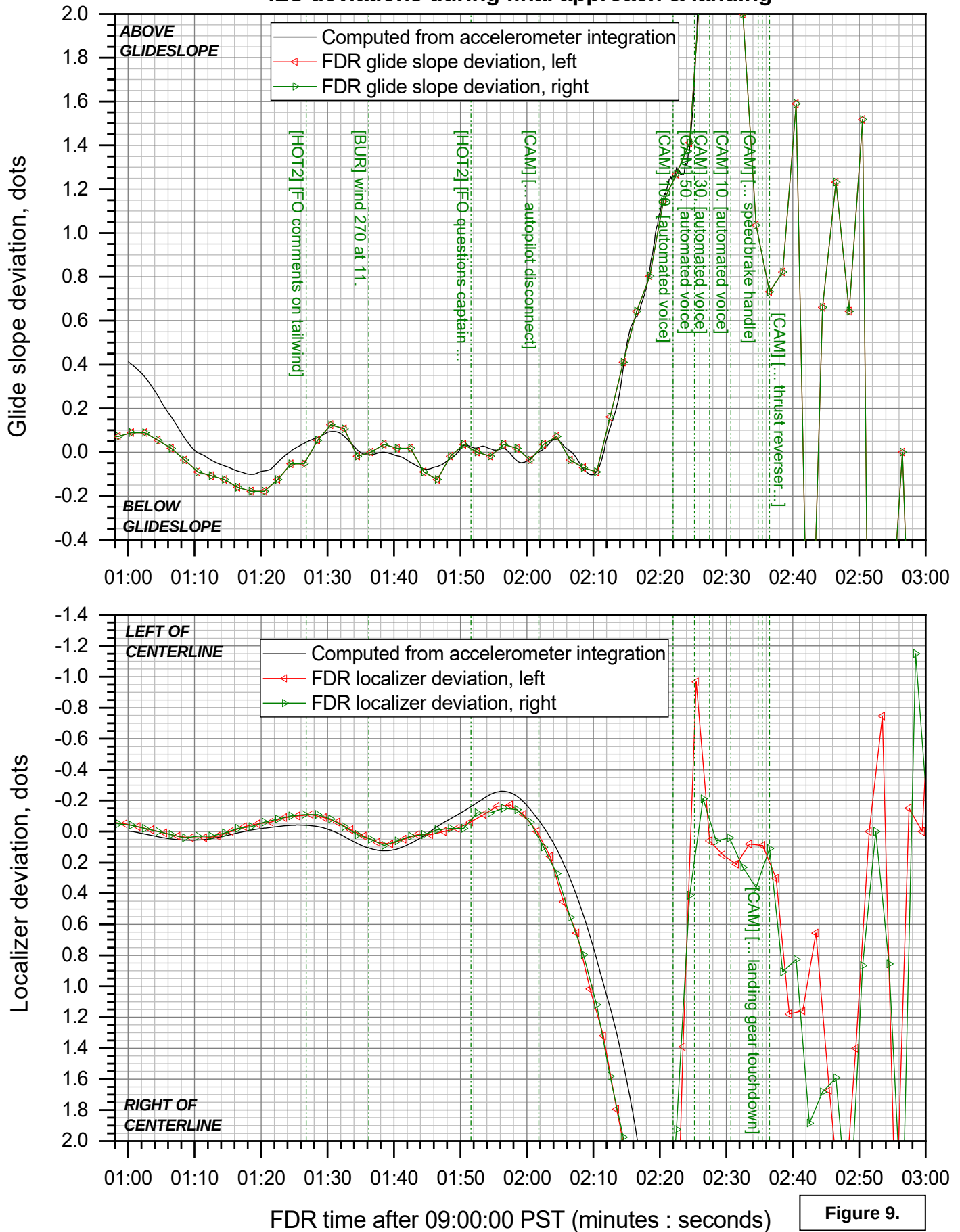


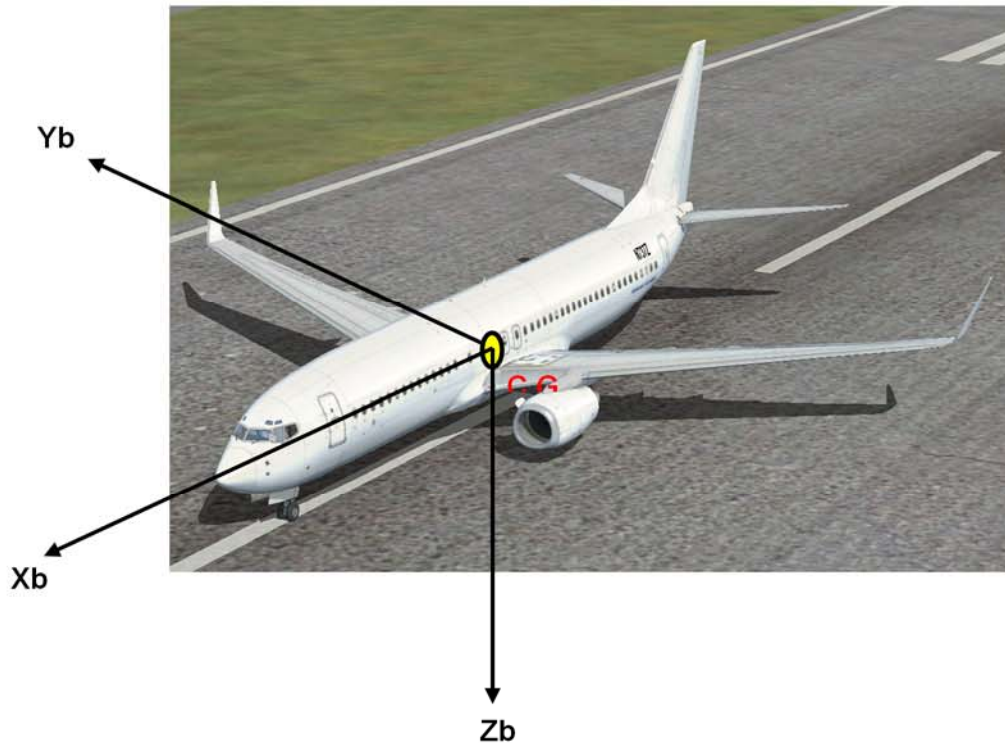
Figure 7b.



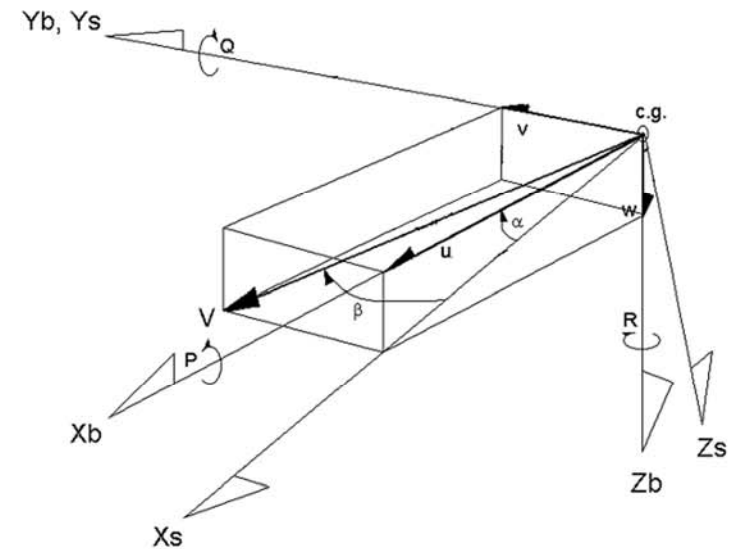
DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

ILS deviations during final approach & landing





C.G. = center of gravity
 $\{X_b, Y_b, Z_b\}$ = body axis system
 $\{X_s, Y_s, Z_s\}$ = stability axis system
 V = velocity vector
 α = angle of attack
 β = sideslip angle



P = body axis roll rate
 Q = body axis pitch rate
 R = body axis yaw rate
 u = component of V along X_b
 v = component of V along Y_b
 w = component of V along Z_b

Figure 10. Airplane body axis system, body-axis components of linear and angular velocities, and definitions of α and β .

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Winds during final approach, landing, & rollout

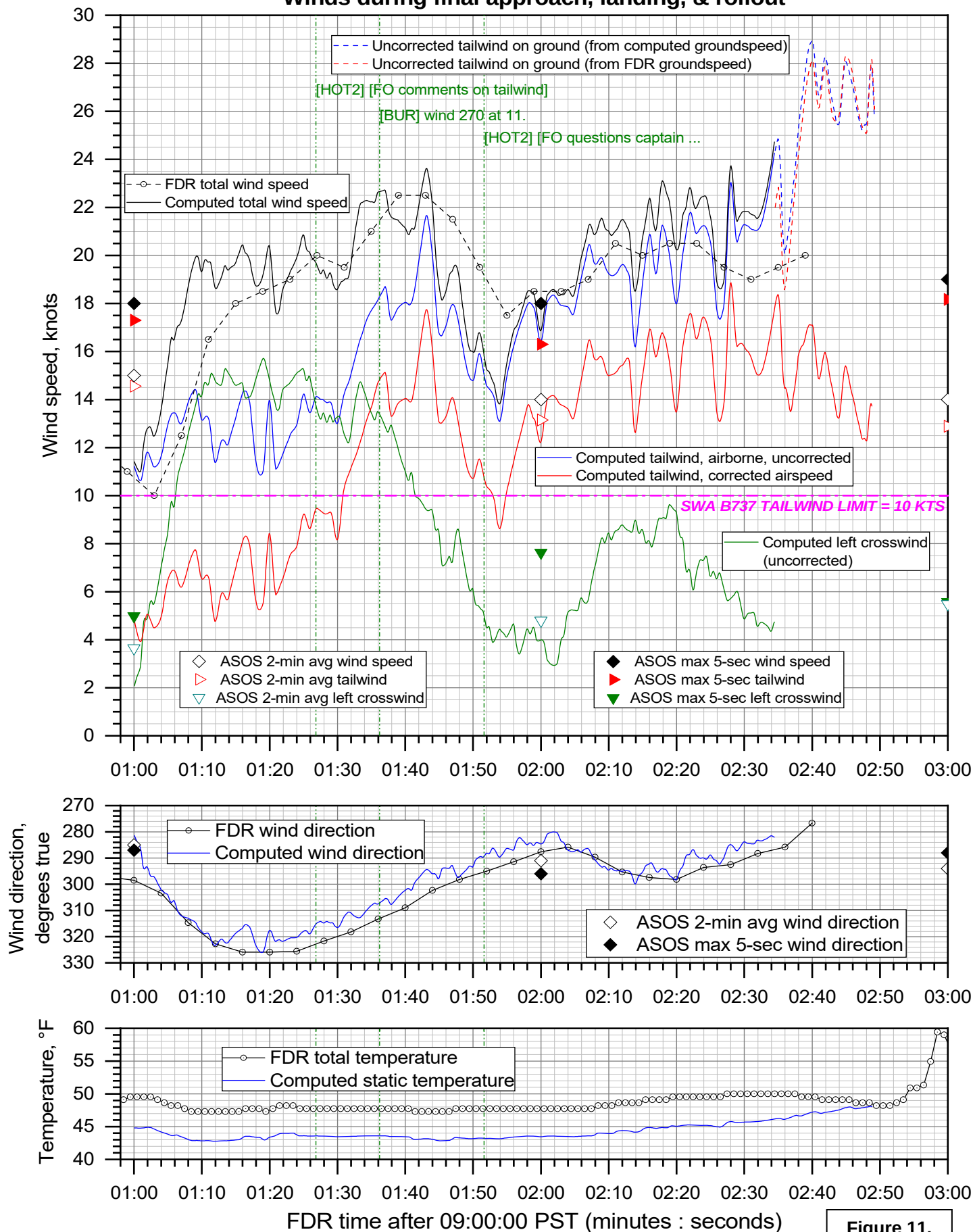
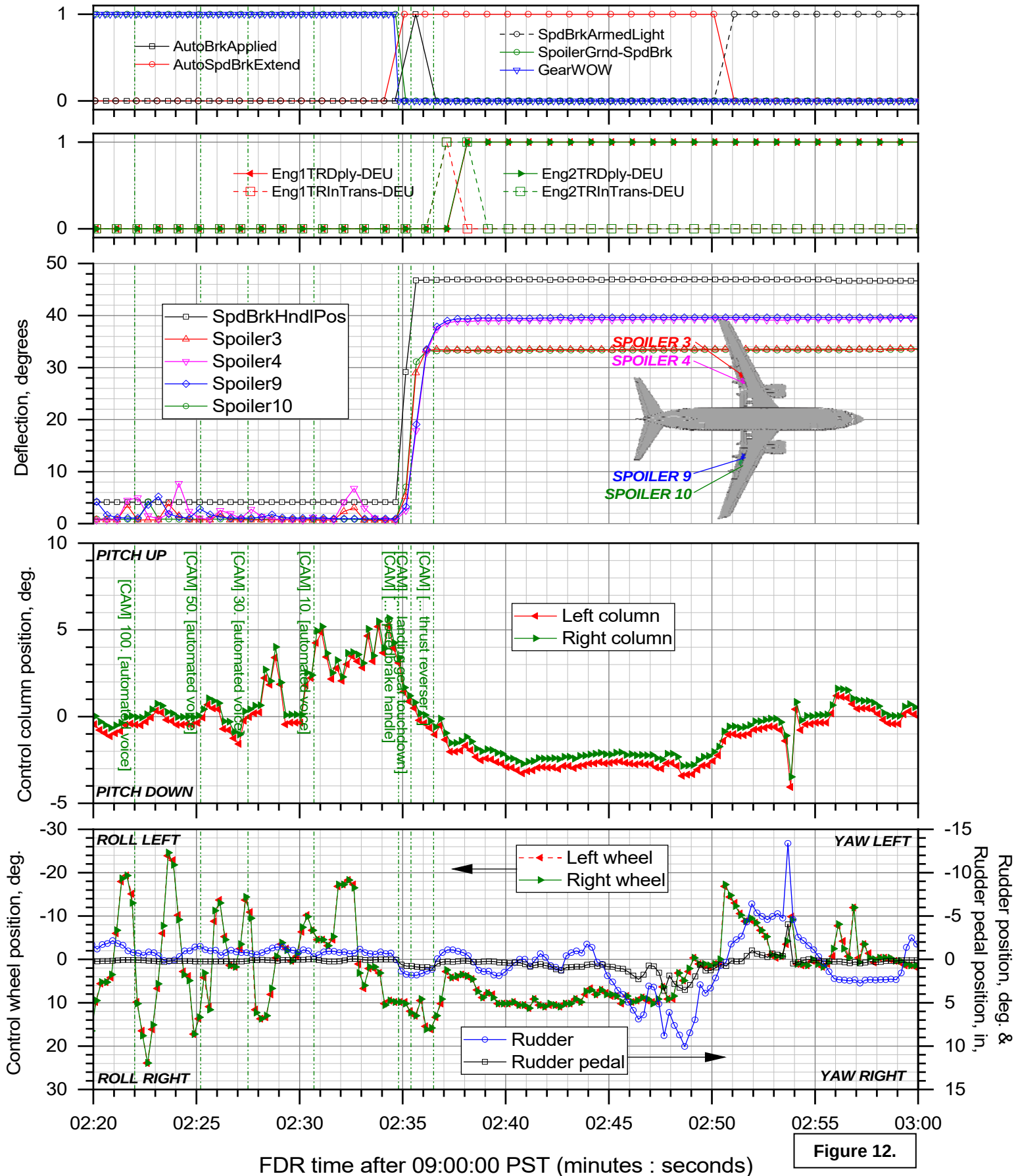


Figure 11.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Flight controls during landing & rollout



DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Deceleration performance during landing & rollout

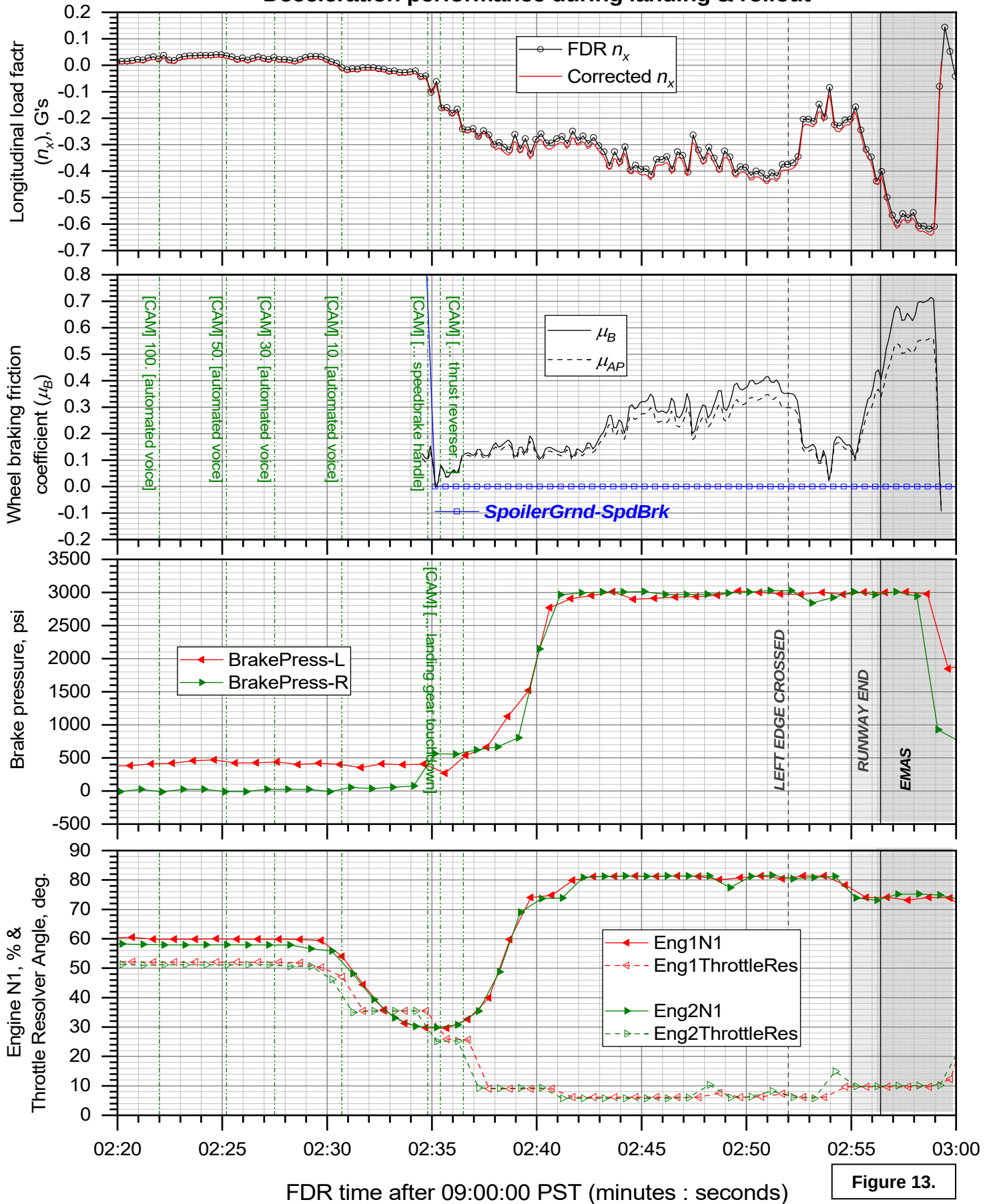


Figure 13.

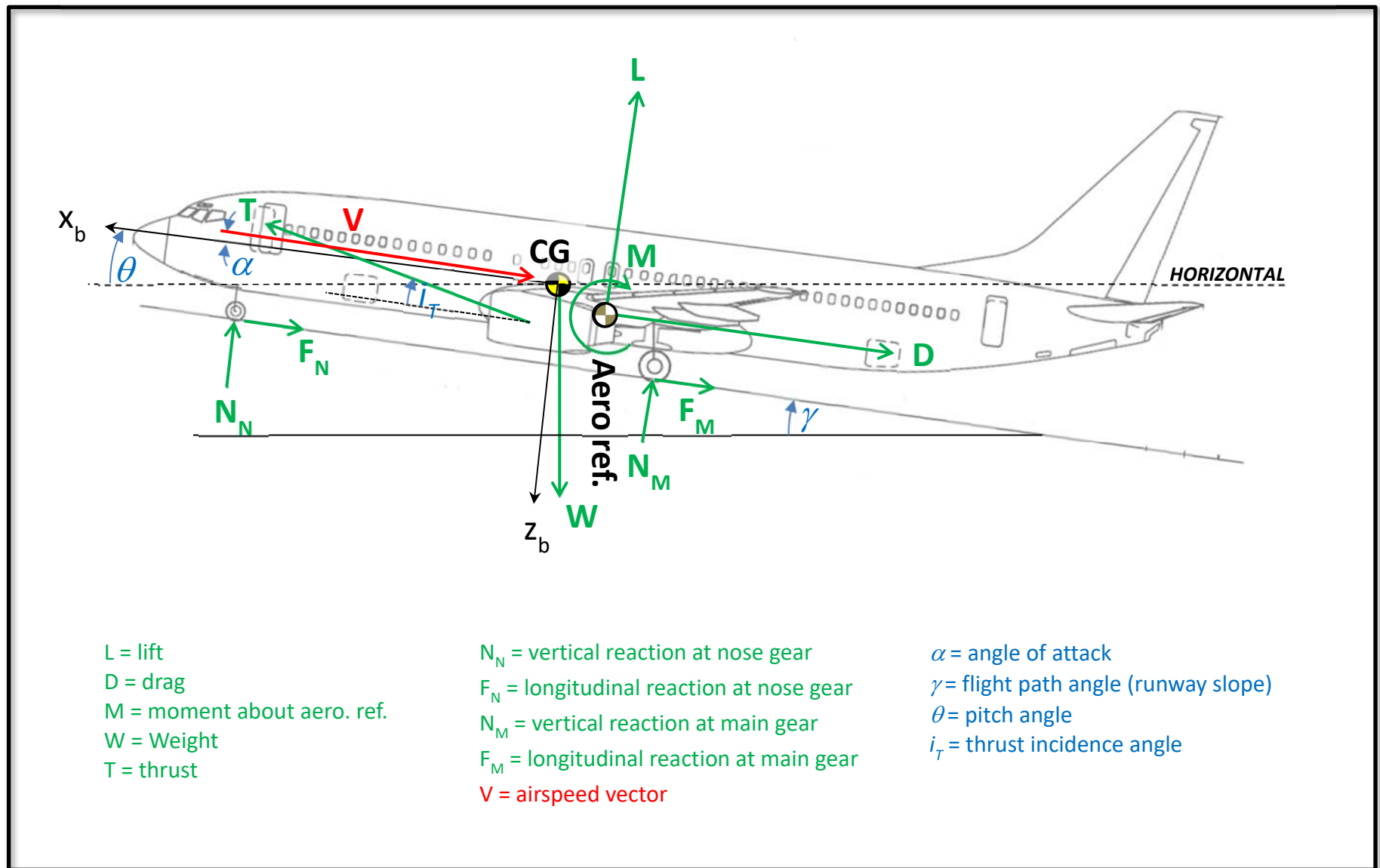


Figure 14. Free body diagram of forces on airplane during ground roll.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Wheel braking friction coefficient (μ_B) during landing rollout

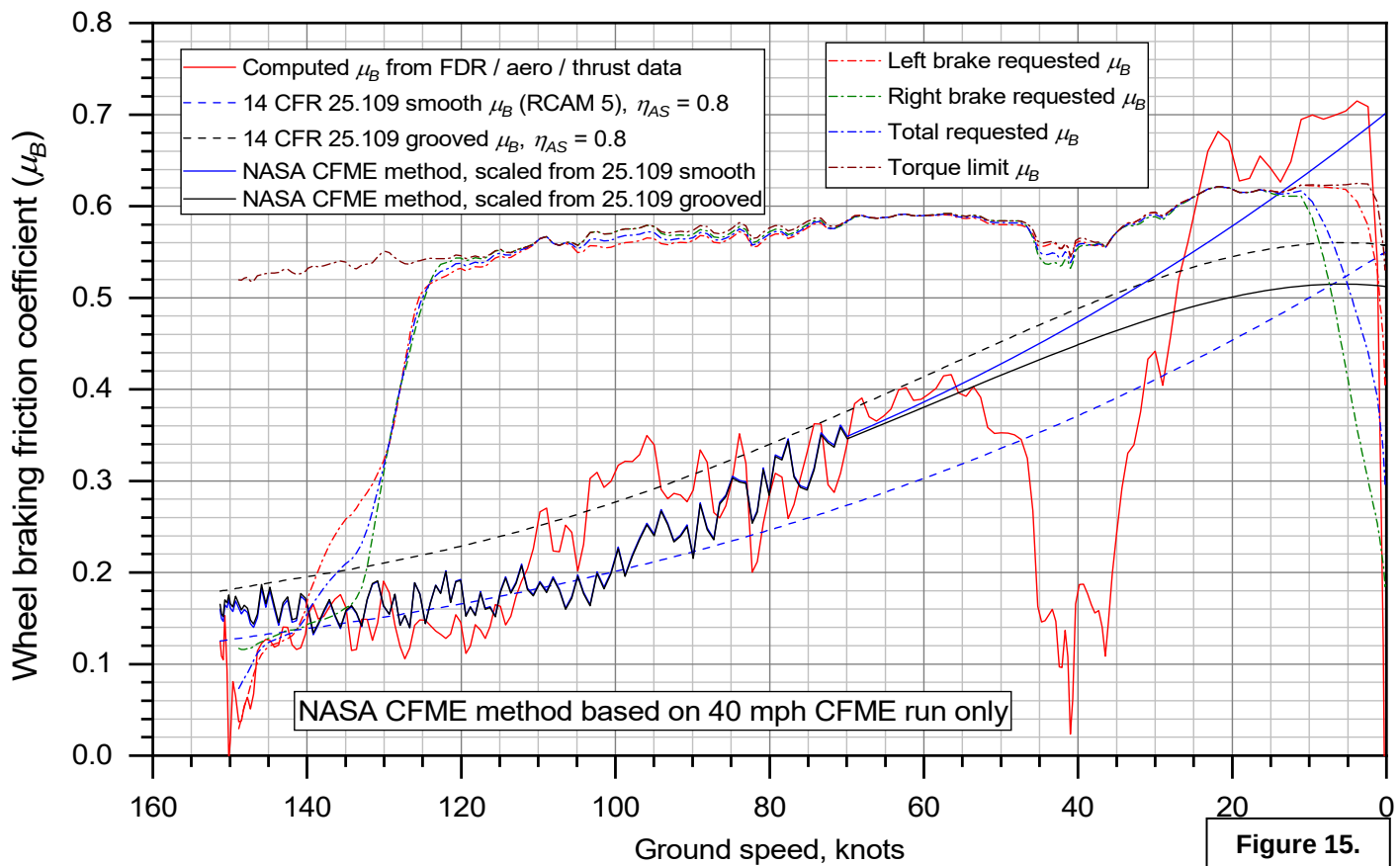
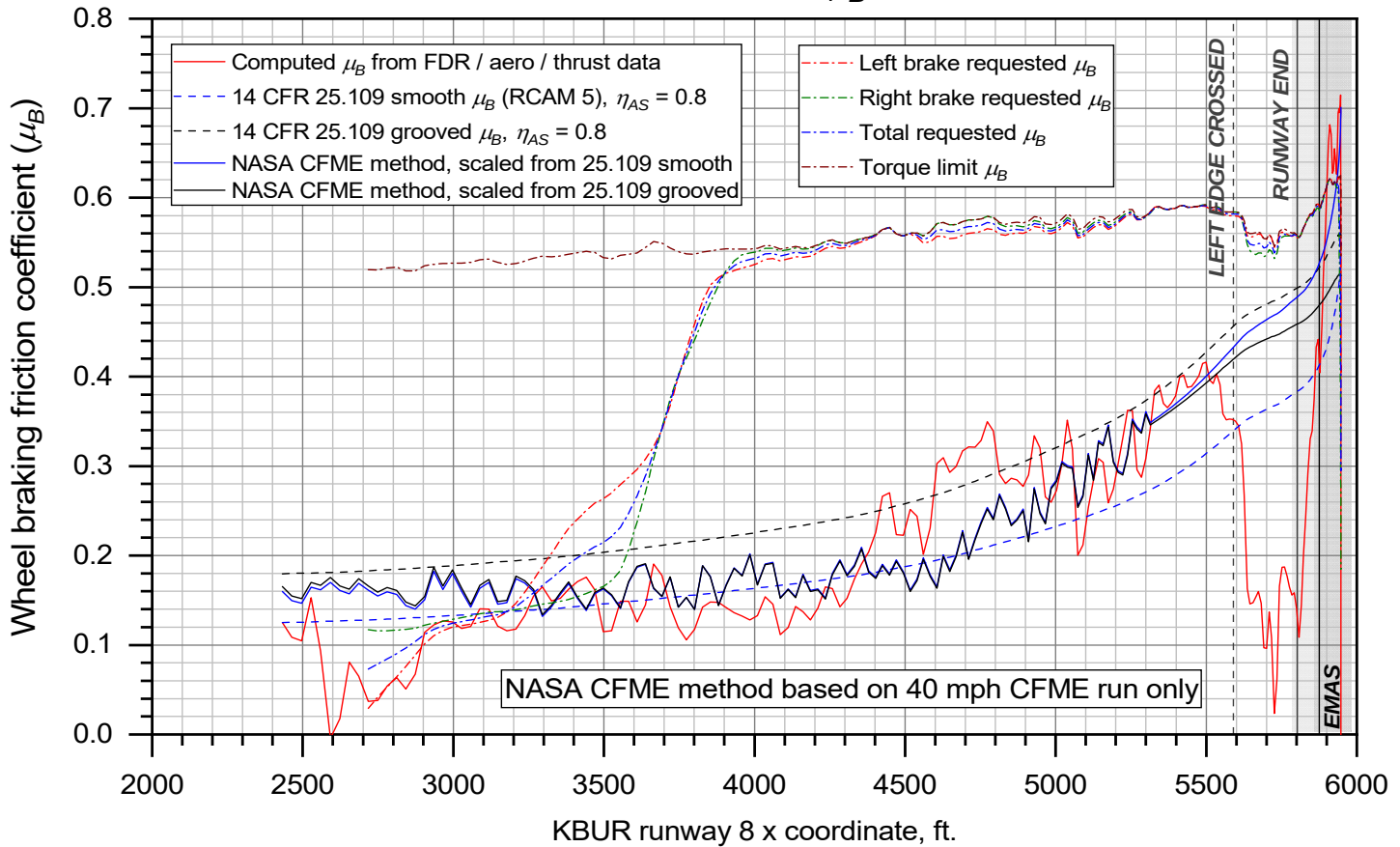


Figure 15.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Wheel braking friction coefficient (μ_B) & ground speed during ground roll simulations

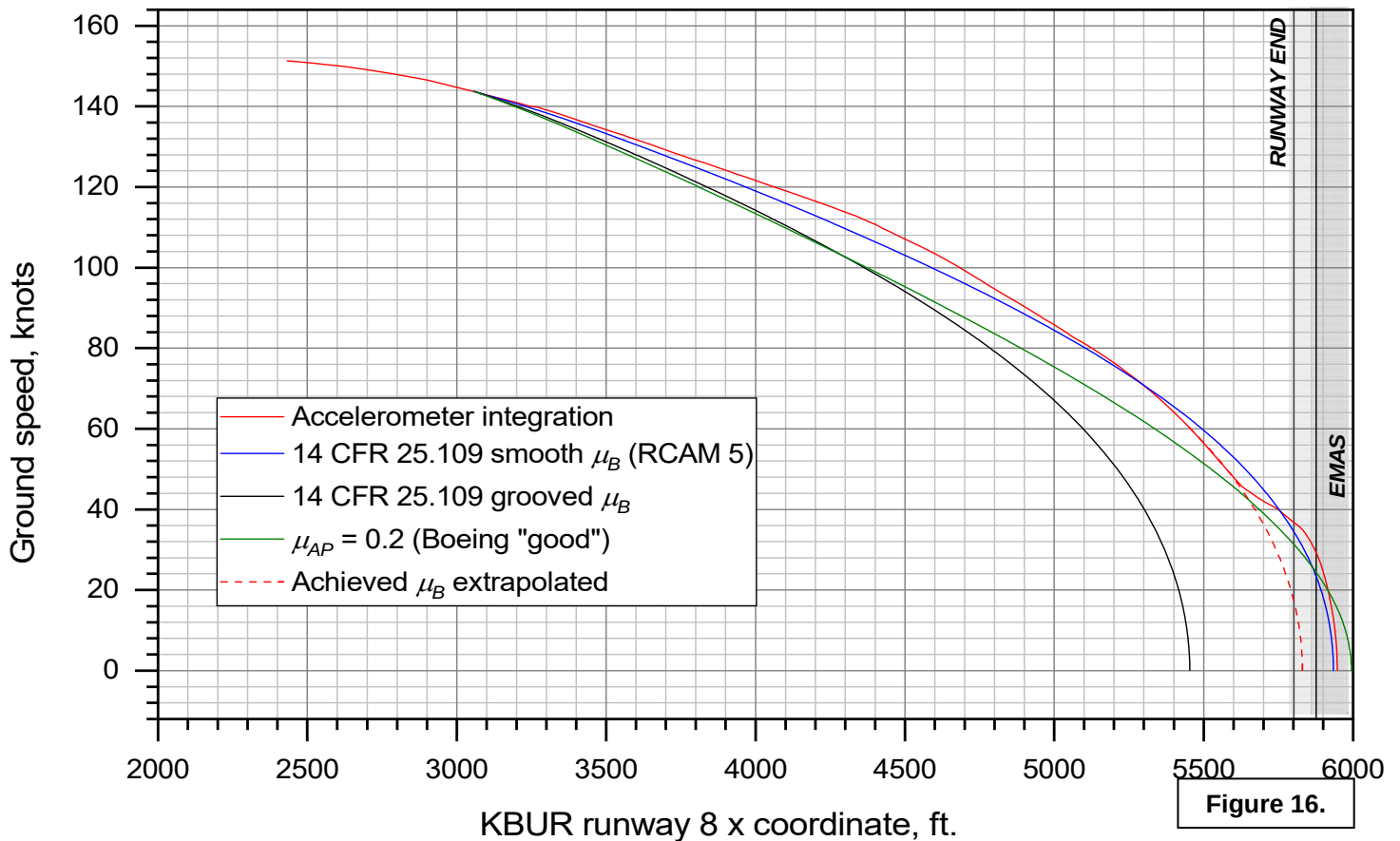
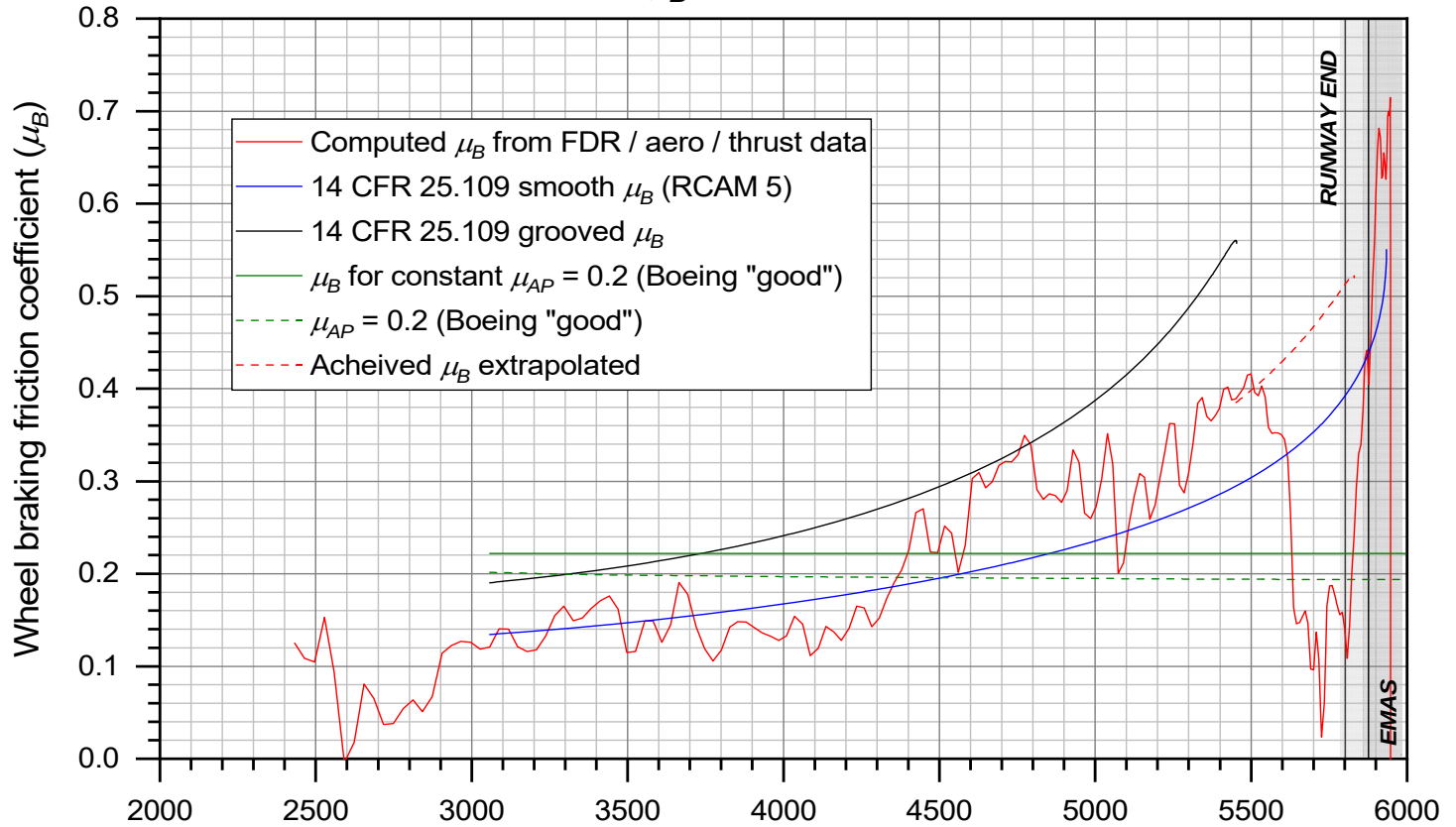


Figure 16.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

KBUR runway 8 CFME measurements, 12/05/2018

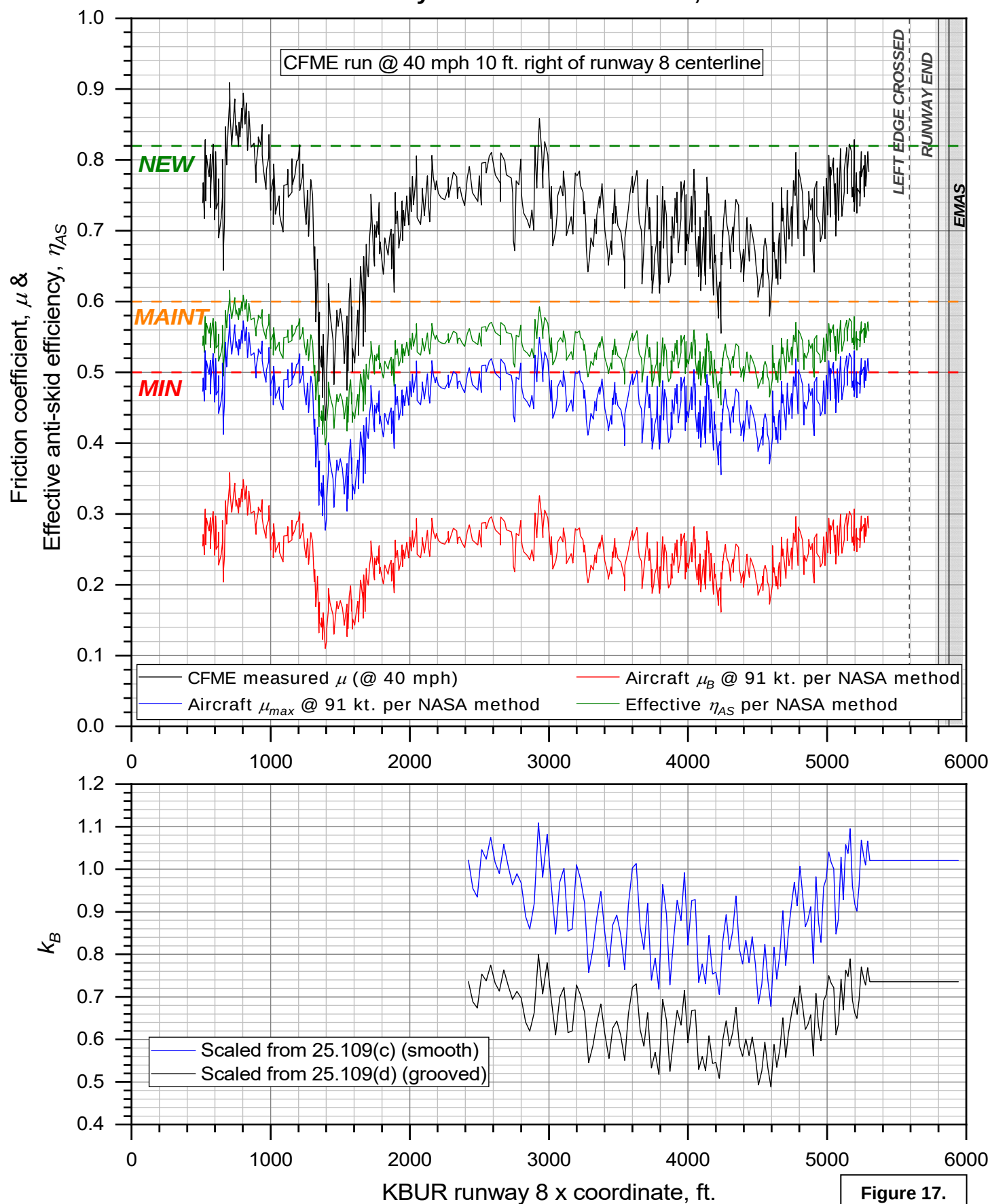


Figure 17.

Figure 18: Runway Surface Condition–Pilot Reported Braking Action—Wheel Braking Coefficient Correlation Matrix, from AC 25-32

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" may 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.

DCA19IA036: SWA flight 278, Boeing 737-700 N752SW, Burbank, CA, December 6, 2018

Landing flare comparisons

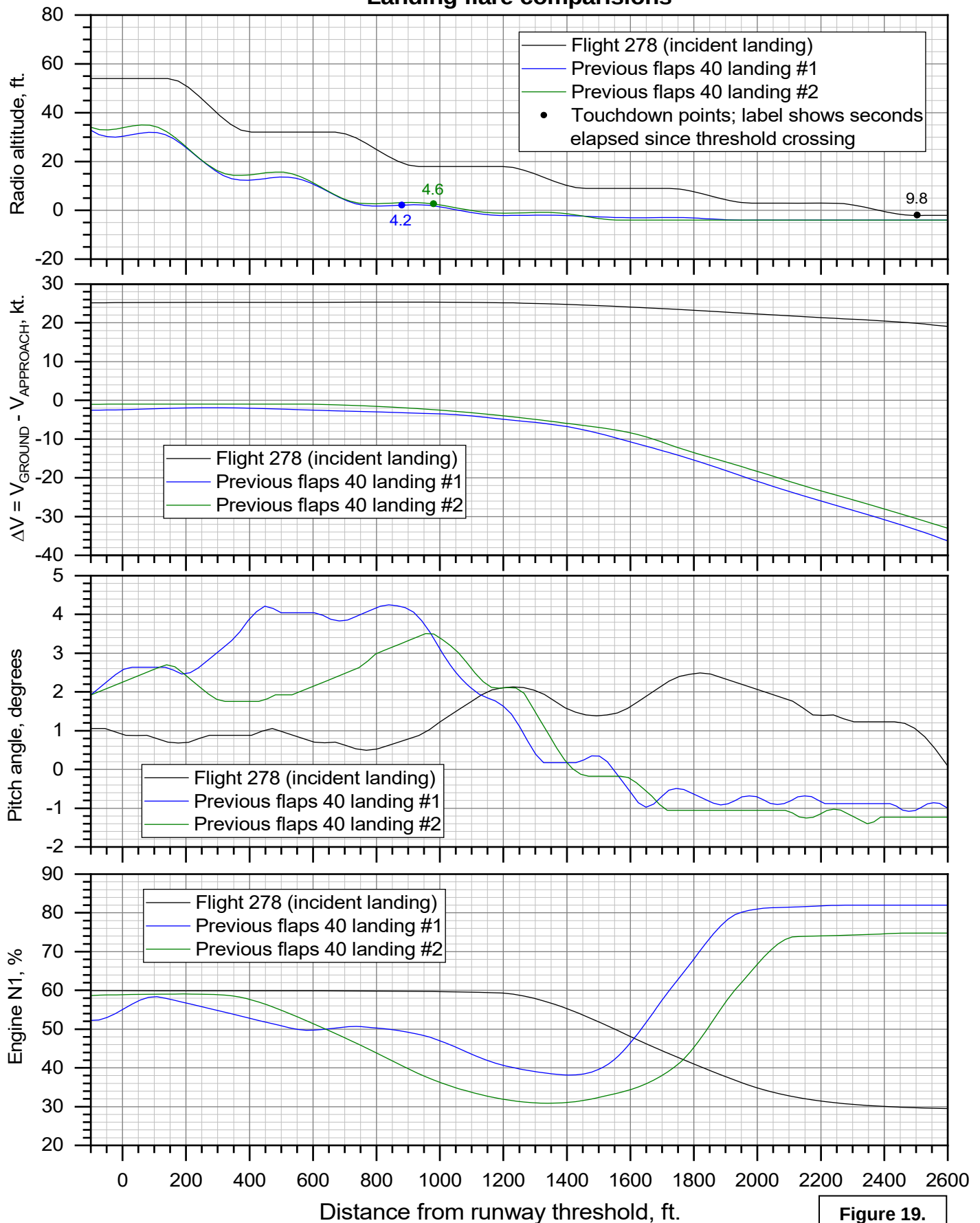


Figure 19.



Figure 20. Boeing RAAS optimized runway exiting: Predicted (green bars) and actual (green oval) stopping performance displayed on an Airport Moving Map (from Reference 25).

THIS PAGE DELIBERATELY LEFT BLANK

APPENDIX A:

KBUR airport diagram and other information



SIGN UP HERE



Airports

Nav aids

Airspace Fixes

Aviation Fuel

Hotels

AIRBOSS

iPhone App

My AirNav

1564 users online [LOGIN](#)

KBUR Bob Hope Airport

Burbank, California, USA



GOING TO BURBANK?



AVIS

Hertz

Reserve Online Reserve Online

[Reserve a Hotel Room](#)

FAA INFORMATION EFFECTIVE 06 DECEMBER 2018

[Loc](#) | [Ops](#) | [Rwys](#) | [IFR](#) | [FBO](#) | [Links](#)
[Com](#) | [Nav](#) | [Svcs](#) | [Stats](#) | [Notes](#)

Location

FAA Identifier: BUR

Lat/Long: 34-12-02.5000N / 118-21-31.2000W

34-12.041667N / 118-21.520000W

34.2006944 / -118.3586667

(estimated)

Elevation: 778 ft. / 237.1 m (surveyed)

Variation: 12E (2020)

From city: 3 miles NW of BURBANK, CA

Time zone: UTC -8 (UTC -7 during Daylight Saving Time)

Zip code: 91505

Airport Operations

Airport use: Open to the public

Activation date: 12/1942

Control tower: yes

ARTCC: LOS ANGELES CENTER

FSS: HAWTHORNE FLIGHT SERVICE STATION

NOTAMs facility: BUR (NOTAM-D service available)

Attendance: CONTINUOUS

Wind indicator: lighted

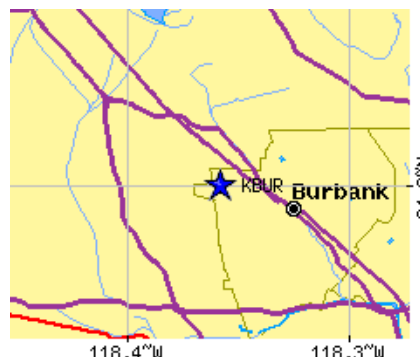
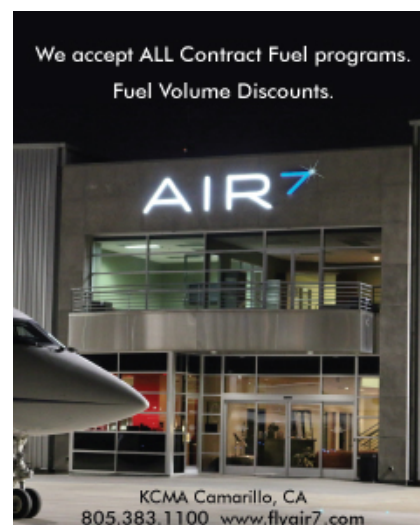
Segmented circle: no

Beacon: white-green (lighted land airport)

Operates sunset to sunrise.

Fire and rescue: ARFF index C

International operations: customs landing rights airport



Road maps at: [MapQuest](#) [Bing](#) [Google](#)

Aerial photo

Airport Communications

UNICOM: 122.95

WX ASOS: PHONE 818-841-1384

BURBANK GROUND: 123.9 348.6

BURBANK TOWER: 118.7 132.325(HELICOPTERS) 254.3

SOCAL APPROACH:

A3

120.4(VNY 280 - BUR 050) NORTH
 124.6(S BTN BUR 150-VNY 160)
 134.2(VNY 160 - VNY 280) WEST
 135.05(BUR 050-BUR 150)
 SOCAL DEPARTURE: 120.4(VNY 280 - BUR 050) NORTH
 124.6(S BTN BUR 150-VNY 160)
 134.2(VNY 160 - VNY 280) WEST
 135.05(BUR 050-BUR 150)
 CLEARANCE DELIVERY: 118.0 348.6
 CLASS C: 120.4(VNY 280-BUR 050) 124.6(S
 BTN BUR 150-VNY 160) 134.2(VNY
 160-VNY 280) 135.05(BUR 050-BUR
 150)
 D-ATIS: 134.5 135.125(ARR VIA FIM/PMD
 VORTAC ONLY)
 EMERG: 121.5 243.0
 IC: 120.4(VNY 280 - BUR 050) NORTH
 134.2(VNY 160 - VNY 280) WEST
 JANNY STAR: 120.4
 OROSZ DP: 124.6
 ROKKR STAR: 128.75
 SLAPP DP: 124.6
 THRNE STAR: 126.7
 VVERA DP: 124.6
 WEESL STAR: 120.4
 WX AWOS-3PT at WHP (4 nm NW): 132.1 (818-899-9820)
 WX ASOS at VNY (7 nm W): PHONE 818-904-9213
 WX ASOS at SMO (12 nm SW): PHONE 310-392-6453
 WX ASOS at LAX (16 nm S): PHONE 310-568-1486
 WX ASOS at HHR (17 nm S): PHONE 310-973-8930
 WX AWOS-3PT at EMT (17 nm SE): 118.75 ((626) 444-1107)
 WX AWOS-3PT at CPM (20 nm S): 127.150 (310-631-4958)

- ELEV 741.9

Nearby radio navigation aids

VOR radial/distance	VOR name	Freq	Var
VNY r087/6.7	VAN NUYS VOR/DME	113.10	15E
SMO r008/12.4	SANTA MONICA VOR/DME	110.80	15E
LAX r358/16.5	LOS ANGELES VORTAC	113.60	15E
FIM r095/27.5	FILLMORE VORTAC	112.50	15E
SLI r314/29.3	SEAL BEACH VORTAC	115.70	15E
POM r269/29.3	POMONA VORTAC	110.40	15E
PMD r194/29.7	PALMDALE VORTAC	114.50	15E
LHS r145/30.9	LAKE HUGHES VORTAC	108.40	15E
VTU r066/34.7	VENTURA VOR/DME	108.20	15E
CMA r076/36.5	CAMARILLO VOR/DME	115.80	15E

NDB name **Hdg/Dist** **Freq** **Var** **ID**
[EL MONTE](#) 278/17.6 359 15E EMT . - - -

Airport Services

Fuel available: 100LL JET-A MOGAS

WARNING: Photo may not be current or correct



Photo by David Newcomer
 Taken in October 2017
 from 12,000' MSL looking northwest.

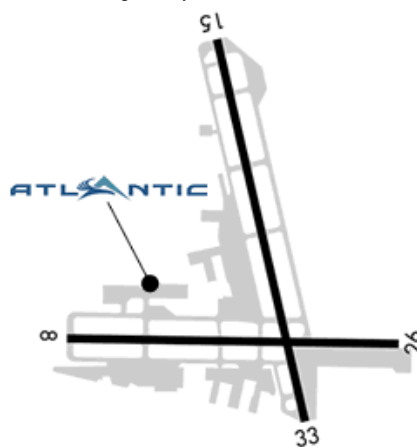
Do you have a better or more recent aerial photo of Bob Hope Airport that you would like to share? If so, please [send us your photo](#).

Sectional chart



Airport diagram

CAUTION: Diagram may not be current



[Download PDF](#)
 of official airport diagram from the FAA

Airport distance calculator

Flying to Bob Hope Airport? Find the distance to fly.

From to KBUR
[CALCULATE DISTANCE](#)

A4

Parking: hangars and tie-downs
 Airframe service: MAJOR
 Powerplant service: MAJOR
 Bottled oxygen: HIGH
 Bulk oxygen: HIGH

Runway Information

Runway 15/33

Dimensions: 6886 x 150 ft. / 2099 x 46 m
 Surface: asphalt/grooved, in excellent condition
 Weight bearing capacity: PCN 42 /F/A/X/T
 Single wheel: 30.0
 Double wheel: 180.0
 Double tandem: 300.0

Runway edge lights: medium intensity

RUNWAY 15

Latitude: 34-12.740680N
 Longitude: 118-21.627643W
 Elevation: 778.0 ft.
 Gradient: 1.2%

Traffic pattern: right

Runway heading: 155 magnetic, 167 true

Displaced threshold: 909 ft.

Declared distances: TORA:6885 TODA:6885
 ASDA:6885 LDA:5976

Markings: nonprecision, in good condition

Visual slope indicator: 4-box VASI on left (3.25 degrees glide path)
 VASI UNUSBL BYD 5 DEGREES OF CNTRLN.

Runway end identifier lights: yes

Touchdown point: yes, no lights

Obstructions: 30 ft. rr, 200 ft. from runway, 250 ft. left of centerline
 +15 FT ROAD 100-200 FT FROM RY END; +14 FT BLAST FENCE;
 MULTIPLE LIGHT STANDARDS 15 FT FROM END OF RY.

RUNWAY 33

34-11.634312N
 118-21.322208W
 694.5 ft.
 1.2%

left

335 magnetic, 347 true

350 ft.

TORA:6885
 TODA:6885
 ASDA:6885
 LDA:6535

nonprecision, in good condition
 4-light PAPI on left (3.20 degrees glide path)
 PAPI UNUSBL BYD 2 DEG RIGHT OF CNTRLN.

yes

yes, no lights

31 ft. pole, 201 ft. from runway, 240 ft. right of centerline
 +20 FT POLE 198 FT FROM RY THR; +14 FT BLAST FENCE AT THR.

Sunrise and sunset

Times for 11-Dec-2018

	Local (UTC-8)	Zulu (UTC)
Morning civil twilight	06:23	14:23
Sunrise	06:50	14:50
Sunset	16:43	00:43
Evening civil twilight	17:11	01:11

Current date and time

Zulu (UTC)	11-Dec-2018 16:56:57
Local (UTC-8)	11-Dec-2018 08:56:57

METAR

KBUR 111553Z 0000KT 10SM CLR 11/04
 A3002 RMK AO2 SLP159 T01060044
KWHP 111600Z 0000KT 10SM SCT050
 4nm NW 12/01 A3006
KVNY 111551Z 0000KT 10SM SCT200
 6nm W 11/06 A3002 RMK AO2 SLP162
 T01110061
KCQT 111547Z AUTO 0000KT 10SM CLR
 11nm SE 12/06 A3002 RMK AO2 SLP166
 T01220061
KSMO 111551Z 0000KT 10SM CLR 13/07
 12nm S A3003 RMK AO2 SLP168 T01330072
KLAX 111553Z 0000KT 10SM FEW018
 16nm S SCT140 BKN180 13/08 A3003 RMK
 AO2 SLP168 T01280078
KHHR 111553Z 0900KT 10SM CLR 13/08
 17nm S A3003 RMK AO2 SLP169 T01280078
KEMT 111545Z 0000KT 10SM CLR 08/07
 19nm SE A3005

TAF

KBUR 111153Z 1112/1212 VRB03KT P6SM
 SCT250 FM112200 14006KT P6SM
 SKC FM120300 VRB03KT P6SM
 SCT250
KVNY 111153Z 1112/1212 VRB03KT P6SM
 6nm W SCT250 FM120100 36006KT P6SM
 SCT250
KSMO 111355Z 1114/1212 VRB03KT P6SM
 12nm S SCT010 FM112000 26008KT P6SM
 SKC FM120100 VRB03KT P6SM SKC
 FM120900 03003KT P6SM SCT008
 SCT250
KLAX 111354Z 1114/1218 09005KT P6SM
 16nm S SCT007 BKN250 FM111700 VRB03KT
 P6SM SCT010 FM112100 26008KT
 P6SM SKC FM120400 VRB03KT P6SM
 SKC FM120700 06005KT P6SM
 SCT010 SCT250 FM121300 VRB03KT
 P6SM BKN010

NOTAMs

🔗 [Click for the latest NOTAMs](#)

NOTAMs are issued by the DoD/FAA and will open in a separate window not controlled by AirNav.

Runway 8/26

Dimensions: 5802 x 150 ft. / 1768 x 46 m
 Surface: asphalt/grooved, in excellent condition

Weight bearing capacity: PCN 46 /F/A/X/T

Single wheel: 30.0

Double wheel: 180.0

Double tandem: 300.0

Runway edge lights: high intensity

RUNWAY 8

Latitude: 34-11.874657N

Longitude: 118-22.148575W

Elevation: 727.4 ft.

Gradient: 0.5%

Traffic pattern: right

Runway heading: 079 magnetic, 091 true

Declared distances: TORA:5801 TODA:5801

ASDA:5801 LDA:5801

Markings: precision, in good condition

Visual slope indicator: 4-light PAPI on left (3.00 degrees glide path)

RVR equipment: touchdown

Approach lights: MALSR: 1,400 foot medium intensity approach lighting system with runway alignment indicator lights

Runway end identifier lights: no

Touchdown point: yes, no lights

Instrument approach: ILS

Obstructions: 14 ft. road, 300 ft. from runway, 7:1 slope to clear

RUNWAY 26

34-11.859023N

118-20.997595W

697.3 ft.

0.5%

left

259 magnetic, 271 true

TORA:5801

TODA:5801

ASDA:5801

LDA:5801

nonprecision, in good condition

rollout

yes

yes, no lights

40 ft. pole, 245 ft. from runway, 410 ft. right of centerline, 1:1 slope to clear
+28' SIGN 90 FT FM RY THLD, +14 FT BLAST FENCE AT THLD.

Airport Ownership and Management from official FAA records

Ownership: Publicly-owned

Owner: BURBANK-GLENDALE-PASADENA APT
2627 HOLLYWOOD WAY
BURBANK, CA 91505
Phone 818-840-8840

Manager: TOM JANOWITZ

2627 HOLLYWOOD WAY
BURBANK, CA 91505
Phone 818-840-9536

TOM JANOWITZ- MANAGER, OPERATIONS (818) 840-9536

Airport Operational Statistics

Aircraft based on the field: 106

Aircraft operations: avg 354/day *

Single engine airplanes: 32 38% commercial
 Multi engine airplanes: 14 29% transient general aviation
 Jet airplanes: 50 17% local general aviation
 Helicopters: 10 15% air taxi
 <1% military
 * for 12-month period ending 30 September 2017

Additional Remarks

E60- ENGINEERED MATERIAL ARRESTING SYSTEM (EMAS) 170 FT LENGTH BY 350 FT WIDTH LCTD AT THE DER 08.

- ACFT IN TFC PAT (1225 FT AGL) AT WHITEMAN AIRPARK 5 MI NW.
- HANG GLIDER ACTIVITY BTN 5 & 10 NM NORTH OF ARPT 6000 FT AGL SR-SS.
- TWY G RSTRD TO ACFT WITH WINGSPAN OF 95 FT OR LESS.
- POWER ENGINE RUNUPS AT TWY ALPHA HOLD AREA PROHIBITED.
- 14 FT BLAST FENCE 35 FT FM DEP END RY 15.
- 14 FT BLAST FENCE 93 FT FM DEP END RY 33.
- 8 FT BLAST FENCE 260 FT FM DEP END OF RY 26.
- 14 FT BLAST FENCE 256 FT FROM DEP END RY 08.
- TWY A RESTRICTED TO ACFT WITH WINGSPAN OF 171 FT OR LESS.
- PILOTS SHOULD CALL AHEAD FOR ARPT NOISE RULES (818) 840-8840.
- RESTRICTIONS AND FINES EFFECTIVE 2200-0700 FOR STAGE 2 JETS, CERTAIN PROPS, RUN-UPS AND FLIGHT TRAINING ACTIVITIES, CALL (818) 840-8840 BEFORE OPERATING.
- HELICOPTER ARRIVALS RESTRICTED TO RY 08/26 AND 15/33.
- NONSTANDARD BLUE TWY CENTERLINE ALONG THE WEST END OF TWY DELTA USED TO BYPASS THE ILS CRITICAL AREA WHEN DIRECTED BY ATCT.
- TWY B RESTRICTED TO ACFT WITH WINGSPAN OF 79 FT OR LESS BEGINNING 300 FT NORTH OF TWY D AND CONTINUING NORTH.
- NO GA ACFT PARKING AT TERMINAL RAMP.
- TURBULENT CONDS NEAR ARPT AT TIMES OF HIGH WINDS FM N & E. DOWNDRAFTS/WIND SHEAR MAY OCCUR AT LIFT OFF OR FINAL.
- ACFT WILL USE EASY PWR WHEN LVG ASGND GATE. CTN MUST BE USED WHEN TAXIING FM TRML AREA DUE TO CLOSE PROXIMITY TO THE TRML. PSNL AND GND EQUIP IN AREA.
- ACFT WITH WINGSPAN GTR THAN 95 FT RQR TAXI INSTRNS FM ATC FOR A RWY 33 DEP.
- ACFT RSTRD FM TAXIING SB PAST GATE B1 ON TERM RAMP.
- ACFT WITH WINGSPAN GTR THAN 79 FT RSTRD FROM USING TWY C W OF TWY C8.
- RWY 26 CLSD TO TKOF/JET ACFT WITH FOUR OR MORE ENGS.
- X BLEED STARTS PROHIBITED IN ALL NON-MOVMT AREAS INCLG THE AIRLINE TRML RAMP. ATC MAY APV X BLEED STARTS ON TWY A NORT OF TWY D, ALL OTHER REQS MUST BE COORDD AND APVD BY OPS.
- BIRD ACTIVITY NORTH END RY 15/33 AND WEST END RY 08/26.
- RY 08 CLSD TKOF MULTI ENG 12,500 LBS OR GREATER.

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 from 6 December 2018 at 0901Z to 3 January 2019 at 0900Z.

STARs - Standard Terminal Arrivals

FERNANDO SEVEN

JANNY FIVE (RNAV)

LYNXX EIGHT

ROKKR TWO (RNAV)

THRNE THREE (RNAV)

2 pages: [\[1\]](#) [\[2\]](#) (355KB)

[download](#) (279KB)

[download](#) (272KB)

2 pages: [\[1\]](#) [\[2\]](#) (309KB)

2 pages: [\[1\]](#) [\[2\]](#) (336KB)

WEESL ONE (RNAV)

[download](#) (143KB)**IAPs - Instrument Approach Procedures**

ILS Y OR LOC Y RWY 08

[download](#) (447KB)

ILS Z OR LOC Z RWY 08

[download](#) (463KB)

RNAV (RNP) Y RWY 08

[download](#) (369KB)

RNAV (GPS) Z RWY 08

[download](#) (324KB)

RNAV (GPS)-A

[download](#) (343KB)

VOR RWY 08

[download](#) (400KB)

FOUR STACKS VISUAL RWY 15

[download](#) (142KB)

NOTE: Special Alternate Minimums apply

[download](#) (34KB)**Departure Procedures**

ELMOO EIGHT

[download](#) (159KB)

OROSZ TWO (RNAV)

[download](#) (225KB)

SLAPP ONE (RNAV)

2 pages: [\[1\]](#) [\[2\]](#) (293KB)

VAN NUYS THREE

2 pages: [\[1\]](#) [\[2\]](#) (424KB)

VVERA TWO (RNAV)

[download](#) (241KB)

NOTE: Special Take-Off Minimums/Departure

Procedures apply

[download](#) (132KB)

Other nearby airports with instrument procedures:

[KWHP](#) - Whiteman Airport (4 nm NW)[KVNY](#) - Van Nuys Airport (7 nm W)[KSMO](#) - Santa Monica Municipal Airport (12 nm SW)[KLAX](#) - Los Angeles International Airport (16 nm S)[KHHH](#) - Jack Northrop Field/Hawthorne Municipal Airport (17 nm S)[KEMT](#) - San Gabriel Valley Airport (17 nm SE)**FBO, Fuel Providers, and Aircraft Ground Support**

Business Name	Contact	Services / Description	Fuel Prices	Comments
	ASRI 131.60 818-841-2966 [web site] [email]	Aviation fuel, Aircraft parking (ramp or tiedown), Hangars, Hangar leasing / sales, Passenger terminal and lounge, Catering, Courtesy transportation, ... More info and photos of Atlantic Aviation	independent 100LL Jet A FS \$7.38 \$5.43 Updated 10-Dec-2018	not yet rated 3 read write
 Million Air Burbank	ASRI 129.625 818-843-8311 [web site] [email]	 Aviation fuel, Aircraft parking (ramp or tiedown), Hangars, Passenger terminal and lounge, Catering, Rental cars, Courtesy transportation, ...  100LL Jet A FS \$7.50 \$5.09 Updated 03-Dec-2018 More info about Million Air Burbank	not yet rated 1 read write	
			FS= Full service 	

Aviation Businesses, Services, and Facilities

Business Name	Contact	Services / Description	Distance	Comments
 LEADING EDGE AVIONICS EXCELLENCE HAS NO EQUAL	toll-free 1-855-955-6151 [web site] [email]   	Leading Edge Avionics is a FAA Certified Part 145 Repair Station (137R236D) that provides outstanding avionics repair and installation services for all General Aviation aircraft from business jets to helicopters to single engine airplanes. We are committed to delivering our customers with services that ensure uncompromised safety and the highest quality of workmanship and reliability, while exceeding our clients' expectations on all levels. 24/7 AOG Service is also available at all Southern California airports, so call us at (855) 955-6151 and let us exceed all your service expectations! More info and photos of Leading Edge Avionics	located at KSNA	not yet rated write

Would you like to see your business listed on this page?

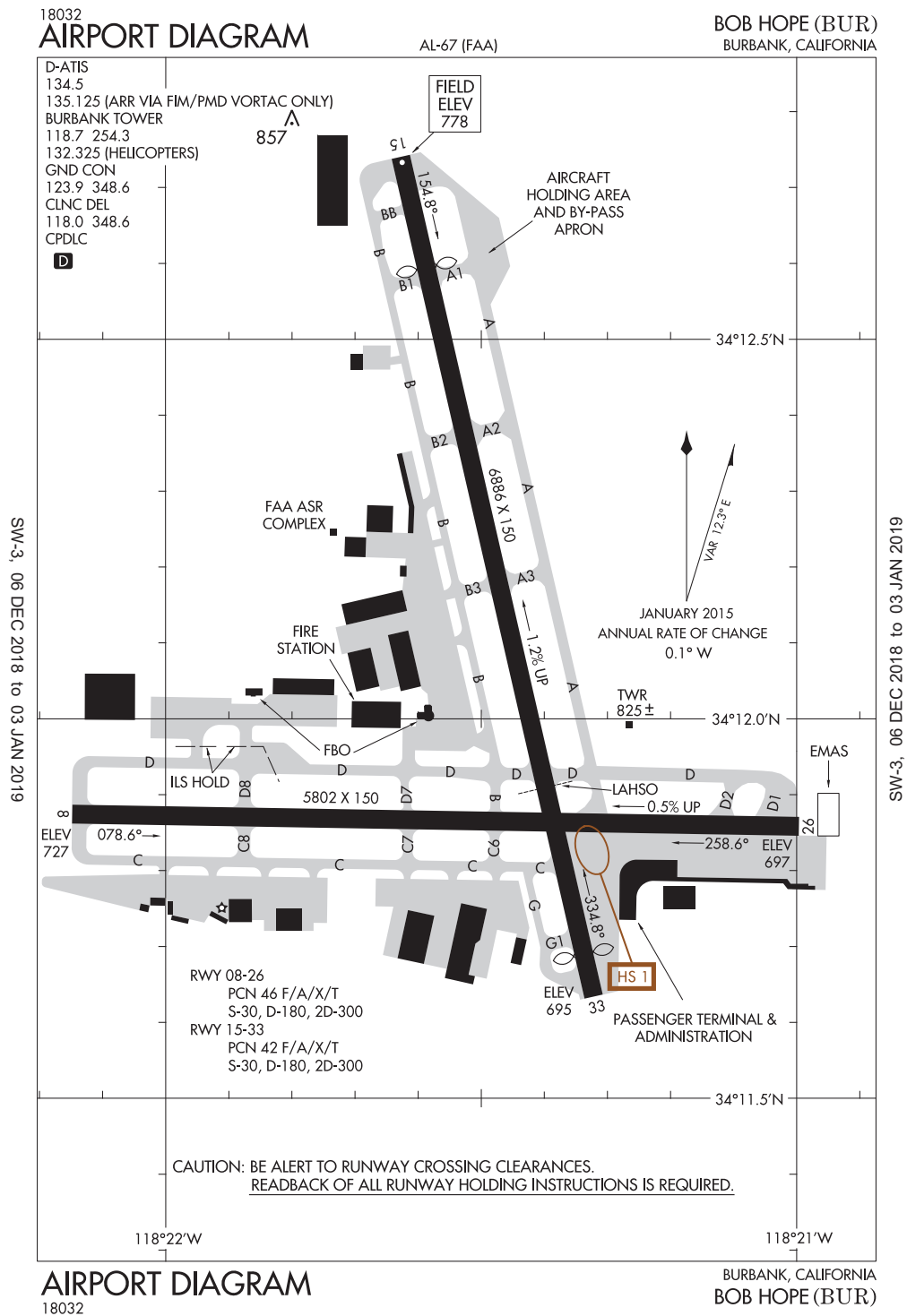
If your business provides an interesting product or service to pilots, flight crews, aircraft, or users of the Bob Hope Airport, you should consider listing it here. To start the listing process, click on the button below

[ADD YOUR BUSINESS OR SERVICE](#)

Other Pages about Bob Hope Airport

[www.burbankairport.com](#)

[UPDATE, REMOVE OR ADD A LINK](#)



Airport Details for KBUR - ACTIVE
Chart Date: 07/19/2018
BOB HOPE
BURBANK
AL #: 67

A10

State:	CALIFORNIA	Magnetic Variation/Year:	E 12/2020	Weather Station:	YES
Country:	United States	Site Nbr:	01353	Control Tower:	YES
Category:	AERODROME ONLY	Data Source:	THIRD_PARTY 08/06/2017	THIRD_PARTY	
FAR Part 139:	YES	Owner:	STATE	Use:	CIVIL
Reimbursable Agreement:				Military Type:	
Coordinates		Office		Local Auto Weather	
Latitude:	N 34° 12' 02.5000"	Flight Inspection:	SAC	Weather Source:	ASOS
Longitude:	W 118° 21' 31.2000"	Procedure Development:	130	Type:	OTHER
Field Elevation:	778.0	Region Code:	WP	Frequency:	134.500
Ellipsoid Elevation:	665.8 S	Service Area:	WEST	Service A:	Y
Horizontal Datum:	NAD83	OCC Code:	POCC	Phone number	(818)841-1384
Vertical Datum:	NAVD88	International:	NO		

CONTACTS

Contact Role	Last Name	First Name	Phone Number	E-mail	Remark
OWNER			(818)940-9536		

ALTIMETERS

Type	Primary	Airport ID	Field Alt Source	Latitude	Longitude	Operational Timing
L	YES	KBUR	ASOS	N 34° 12' 02.5000"	W 118° 21' 31.2000"	FULL-TIME

ALTIMETER COMMENTS

RUNWAYS

08 (A) 26 (A) 15 (A) 33 (A)

RUNWAY DETAIL

A11

Landing Strip		
Chart Date: 07/19/2018	Publication Status: A	Pseudo Rwy: NO
Surface: ASPH EXCELLENT	Width: 150	Physical Length: 5802

Rwy Number: 08

Use Category: RUNWAY ONLY
Chart Date: 07/19/2018 Pub. Status: A
Data Source: THIRD_PARTY 08/06/2017
Markings: PIR-G

Threshold	
Latitude:	N 34° 11' 52.4794"
Longitude:	W 118° 22' 08.9145"
Elevation:	727.4
Ellipsoid Elev:	614.7 S
Ellipsoid Elev Meters:	187.4 M
Ellipsoid Elev Model:	NAVD88
Horz. Datum:	NAD83
Vert. Datum:	NAVD88

Displaced Threshold	
Latitude:	
Longitude:	
Elevation:	
Ellipsoid Elev:	
Ellipsoid Elev Meters:	
Ellipsoid Elev Model:	
Horz. Datum:	UNKNOWN
Vert. Datum:	UNKNOWN

Landing Length: 5802
FI RWY Length: 5802
FI RWY Height: 697.3
Tdz Elevation: 727.4
True Bearing: 90.931
Ft Disp Th:
Gradient: -0.5%
RVRTouchdown: YES
MidPoint:
Rollout:
Rail: YES
OIS Data Source: VG 08/06/2017 THIRD_PARTY
Assoc. Fac.: BUR ILS (A)

KBUR08

VGSi Lights					
VGSi Lights Type:		PAPI-4L			
Owner:		STATE			
Pilot Cntl Freq:					
Th Cross Ht:		72.0			
High Angle:					
Com. Date:		08/31/2016			
Com. Angle:		3.00			
DWB Elev:					
DWB Thres:					
Ref Pt Lat:		N 34° 11' 52.2330"			
Ref Pt Long:		W 118° 21' 50.6790"			
Ref Pt Elev:		722.0			
Ref Pt Thres:		1532			
Height Group:		3			
Lights					
Config	Len	Owner	Mil Type	Com Dt	Pilot Cntrl
MALSR		NTL		07/10/1984	
HIRL		NTL			

Rwy Number: 26

Use Category: RUNWAY ONLY
Chart Date: 07/19/2018 Pub. Status: A
Data Source: THIRD_PARTY 08/06/2017
Markings: NPI-G

Threshold	
Latitude:	N 34° 11' 51.5414"
Longitude:	W 118° 20' 59.8557"
Elevation:	697.3
Ellipsoid Elev:	584.9 S
Ellipsoid Elev Meters:	178.3 M
Ellipsoid Elev Model:	NAVD88
Horz. Datum:	NAD83
Vert. Datum:	NAVD88

Displaced Threshold	
Latitude:	
Longitude:	
Elevation:	
Ellipsoid Elev:	
Ellipsoid Elev Meters:	
Ellipsoid Elev Model:	
Horz. Datum:	UNKNOWN
Vert. Datum:	UNKNOWN

Landing Length: 5802
FI RWY Length: 5802
FI RWY Height: 727.4
Tdz Elevation: 716.3
True Bearing: 270.942
Ft Disp Th:
Gradient: 0.5%
RVRTouchdown:
MidPoint:
Rollout: YES
Rail: NO
OIS Data Source: VG 08/06/2017 THIRD_PARTY
Assoc. Fac.:

KBUR26

Lights					
Config	Len	Owner	Mil Type	Com Dt	Pilot Cntrl
HIRL		NTL			
REIL		STATE			

RUNWAY LANDING STRIP COMMENTS

RUNWAY 08 COMMENTS

RUNWAY 26 COMMENTS

A12

Landing Length:	5977	Landing Length:	6536
FI RWY Length:	5627	FI RWY Length:	5627
FI RWY Height:	698.4	FI RWY Height:	767.9
Tdz Elevation:	767.9	Tdz Elevation:	735.8
True Bearing:	167.078	True Bearing:	347.082
Ft Disp Th:	909	Ft Disp Th:	350
Gradient:	-1.2%	Gradient:	1.2%
RVRTouchdown:		RVRTouchdown:	
MidPoint:		MidPoint:	
Rollout:		Rollout:	
Rail:	NO	Rail:	NO
OIS Data Source:	VG 08/06/2017 THIRD_PARTY	OIS Data Source:	VG 08/06/2017 THIRD_PARTY
Assoc. Fac.:		Assoc. Fac.:	

RUNWAY 15 COMMENTS

RUNWAY 33 COMMENTS

Topic	Priority	Date	Remark
LIGHTS		11/03/2015	REIL Owner: Burbank Airport Authority
LIGHTS		05/20/2016	PAPI Owner: BGPAA (Airport Sponsor)
RESTRICTION		04/26/2017	BUR RWY 33 PRECISION PATH INDICATOR BYD 2 DEG RIGHT OF CENTERLINE UNUSABLE.

COMMENTS				A13
Topic	Priority	Date	Remark	
SIAP	1	11/05/1999	CVFP: FOUR STACKS VISUAL RWY 15.	
CHANGE	2	09/02/2015	ECD 03/31/2016: MagVar change from 15E/1975 to 12E/2020	
CHANGE	3	03/07/2018	Third party survey dated 8/6/2017 updating airport and runways.	

SIAPS						
Nav Ident	Nav Type	Description	FAS	Amendment	Type	Magnetic Variance/Year
		FOUR STACKS VISUAL RWY 15		ORG		E15/1975
BUR	ILS	ILS Y OR LOC Y RWY 8	901 / TREE / N34°12'33.59" / W118°27'49.82"	6	CIVIL	E12/2020
BUR	ILS	ILS Z OR LOC Z RWY 8	901 / TREE / N34°12'33.59" / W118°27'49.82"	39	CIVIL	E12/2020
		RNAV (GPS) Z RWY 8	894 / T-L TWR / N34°12'07.95" / W118°23'22.83"	2	CIVIL	E12/2020
			901 / TREE / N34°12'33.59" / W118°27'49.82"			
		RNAV (GPS)-A	1183 / STACK / N34°14'40.00" / W118°23'34.00"	ORG	CIVIL	E12/2020
		RNAV (RNP) Y RWY 8		2	CIVIL	E12/2020
VNY	VOR_DME	VOR RWY 8	986 / BLDG / N34°13'10.30" / W118°26'57.59"	12	CIVIL	E15/1975

ASSOCIATED MONITORS

ASSOCIATED DGPS

ILS INQUIRY - ACTIVE

Chart Date: 07/19/2018

Temp Mobile : NO

A14
Pseudo Navaid :

AIRPORT: BOB HOPE	Service Area: WEST		OCC: POCC	DATUMS	Horz: NAD83	Vert: NAVD88	CTRY: US
	ARPT-ID: KBUR	RWY: 08	LCTN: BURBANK	ST: CA	REG: WP	FIFO: SAC	USE: CIVIL
	AL#: 67	Reimbursable Agreement:		OWN: NTL	MIL TYPE:	INTL: NO	

AFIS DATA						AIRPORT DATA			
ILS-ID	BUR	GS-ALN	3.00	OM-DIS	28996	FC-ALN	1.5 - 0.5	CHART DATE	07/19/2018
APT-ID	KBUR	GS-WID	0.70	RW-BRG	90.93	BC-ALN		PUBLICATION STATUS	A
TH-HGT	727	TH-DIS	1226	RW-LEN	5802	UPDATE-DIST	5802	ARP-LAT	N34-12-02.50
RE-HGT	697	TH-LAT	N34-11-52.48	COUNTRY-CODE	US	UPDATE ELV MSL	697.3	ARP-LON	W118-21-31.20
RWY-ID	08	TH-LON	W118-22-08.91	PUB.STATUS	A	TH-ELLIP-HGT	614.7	S FIELD-ELEV	778.0
CAT		I DME-DIS		LC-OFF	R0	GEOID-SEP	112.7	FLD-ELIP-ELEV	665.8 S
GS-LAT	N34-11-52.28	DME-OFF		LC-DIS	-2234			RWY CHART DATE	07/19/2018
GS-LON	W118-21-54.32	DME-HGT		LC-FCB	90.931			RWY PUBLICATION STATUS	A
GS-HGT	723	FREQ	109.500	LC-BCB	270.942			TH-LAT	N34-11-52.48
GS-OFF	L1	MVAR	E12/2020	LC-WID	5.00			TH-LON	W118-22-08.91

LOCALIZER		(DFL CODE - ILS/L)							
CHART DATE	07/19/2018	PUBLICATION STATUS	A						
ANT LAT	N34-11-52.64	XMTR		DUAL LOC-RE	-6809/ -1.121	LCW-TAIL		N RE-LON	W118-20-59.86
ANT LON	W118-22-20.91	EQUIP-TYPE	MK20A	LOC-TH	-1007/ -0.166	LCW-FT-TH		88 RE-ELEV	697.3
ELEV	728.2	STBY-POWER		B LOC-IM	0.0 /	DATE-COMM	11/22/1983	RE-ELIP-ELEV	584.9 S
ANT-TYPE	LOG-PER	ESV		YES LOC-MM	0.0 /	DATE-RECON		RWY-LGTH/WIDTH	5802/150
DUAL-FREQ		YES RESTRICTED		YES LOC-OM	37889/ 6.236	VOICE	NONE	DSPLCD-TH-DIST	
US-DIST:FC	14000/25.0	BC		LOC-FAF	37889/ 6.236	REC TYPE		DSPLCD-TH-LAT	
CLRNC-CVG:FC	90/35 150/35	BC		MON-AL-WID	W5.85	N4.15 ROLLOUT		NR DSPLCD-TH-LON	
LOC-WIDTH-MX-ALERT	5.51 / 4.49			LOC-AL-MX-ALERT	12uA			DSPLCD-TH-ELEV	
LOC-WIDTH-INITIAL	5.70 / 4.30			DATA SOURCE	THIRD_PARTY	08/06/2017		DISP-TH-ELIP-ELEV	
					THIRD_PARTY			RWY-LDG-LGTH	5802
								TDZ-ELEV	727.4
								FAR PART 139	YES

GLIDESLOPE		(DFL CODE - ILS/G)							
CHART DATE	07/19/2018	PUBLICATION STATUS	A						
ELEV	725.2	XMTR		DUAL DIST-TH-PT-C	765.8/ 0.126	GS-ANT-OFF	L302		
ANT-TYPE	CAP-EFF	EQUIP-TYPE	MK20A	GS-TH	1226/ 0.202	MON-AL-ANG	H3.30/L2.78		
CL-ELEV-ABM	723.0	FREQ	332.600	GS-IM	0.0 /	DATE-COMM	07/25/1990		
RDH	60 (60.25)	ESV		NO GS-MM	0.0 /	DATE-RECON	10/03/2017		
ELEV-FOR-CALC	CROWN	RESTRICTED		NO GS-OM	38107/ 6.272	STBY-POWER	B		
AFIS-CORDS	AIMING POINT	GPI-TH	1142.3	GS-FAF	38108/ 6.272	CBP-TH	N		
ANT: LAT	N34-11-55.27	RPI-TH	1226.2	AIM-PT: LAT	N34-11-52.28				
LON	W118-21-54.26			LON	W118-21-54.32				
GS-WID-MX-ALERT	.82 / .58	GS-ANG-MX-ALERT	3.18 / 2.87	DATA SOURCE	THIRD_PARTY	08/06/2017			
					THIRD_PARTY				

FAF	OUTER MARKER	MIDDLE MARKER	INNER MARKER
CHART DATE	07/19/2018		
PUBLICATION STATUS	A		
LAT	N34-11-58.59		
LON	W118-29-27.93		
ELEV	750.4		
DIST-TH	36882/ 6.070	36883/ 6.070	
DIST-DIR-CL		L40	
DATE-COMM	05/18/1982		
DATE-RECON			
NAME/USE	BUDDE		
DATA SOURCE	THIRD_PARTY		
TAPELINE	1997.2	1997.1	
MSL-ALTITUDE	2753.0	2752.9	
DFL CODE	ILS/MO		

DECISION-HEIGHTS			
<u>DH</u>	<u>DIST/RALT</u>		
(100)	0		0
(150)	0		0
(200)	0		0
PERFORMANCE-CLASS I / A			

GENERAL DATA	
YR/MVAR	E12/2020
BC-STATUS	
MON-CAT	1
REM-MON	ATCT
FULL-TIME	YES
FULL-TIME	
NFPO-PROCEDURES	130

ASSOC-FACS

LIGHTING	HIRL MALSR PAPI-4L
----------	--------------------

PROCEDURES DATA	
PSEUDO-GS-LAT	N00-00-00.00
PSEUDO-GS-LON	W000-00-00.00
PSEUDO-TH-LAT	N00-00-00.00
PSEUDO-TH-LON	W000-00-00.00
PSDO-GS-TO-PSDO-TH	0.0
LOC-CROSSES-C/L	0

RESTRICTIONS		
09/28/2017	LOC	FRONT Unusable byd 030° right of course (150Hz side)
12/02/2018	LOC	FRONT Unusable within 0.9NM

RESTRICTIONS ASSOC-FACS

ESVS		
Cmpnt	Svc Date	Remark
LOC	08/04/2011	259/000/D21/30/140
LOC	08/15/2012	259/000/D25/30/140

CONTACTS

COMMENTS

COMMENTS				A15
Topic	Priority	Date	Remark	
FLIGHT_INSPECTION		04/13/2000	LOC LCTD ON CNTRLN EXTENDED 1008.647 FT PRIOR TO THR.	
FLIGHT_INSPECTION	2	08/14/2009	LOC MOD EXCEEDS 60 PERCENT BYND 25 DEGS R OF CRS.	
FLIGHT_INSPECTION	3	08/09/2017	FAF to MAP Distance value set to 5.41NM from SIAP: ILS Z OR LOC Z RWY 8 (11/10/2016).	
FLIGHT_INSPECTION	4	08/09/2017	FAF Distance to Threshold value set to 6.07NM from SIAP: ILS Z OR LOC Z RWY 8 (11/10/2016).	
FLIGHT_INSPECTION	5	09/28/2017	COMPARABILITY UNSAT LSA 3000'.	
SURVEY	6	03/08/2018	UPDATED PER THIRD PARTY SURVEY DTD 8/6/2017. NFDD#18-110 & 112.	
GENERATED	1	04/23/2018	COMM IAW 8240.47 ARDH = 59FT, REF ELEV = 723.2FT	
FLIGHT_INSPECTION	9	11/20/2018	All ILS-2s maneuvers will be flown at 3,000' (T). Due to airspace per FISST (SD). Use 44,266' for OM-DIST.	
FLIGHT_INSPECTION	7	11/20/2018	There is an LDA-C SIAP to KVNy predicated on the BUR LOC. Due to lower altitudes, fly a separate approach to KVNy for each xmtr. Determine alignment as "SAT" or "UNSAT". Report the worst case structure by graphical average in the FAS.	
FLIGHT_INSPECTION	8	11/20/2018	The BUR MB/O is the MAP (Point C) for the LDA-C and is located 6.1NM from the KBUR threshold. Reference structure	
FLIGHT_INSPECTION	10	12/02/2018	distance from the MAP. Report data in the remarks section of the BUR ILS report. Localizer restriction (0.9NM) due to 400' width requirement IAW 8200.1, Section 2, para 4f.	

SAFETY ALERTS	
Date	Remark
01/13/2003	ILS-1 CAUTION: HIGH TERRAIN BYD 20 DEG EITHER SIDE OF LOC CRS.

SIAPS							
AirId	AirportName	State	Description	FAS	Amdt	Type	Magnetic Variance/Year
KBUR	BOB HOPE	CA	ILS Y OR LOC Y RWY 8	901 / TREE / N34°12'33.59" / W118°27'49.82"	6	CIVIL	E12/2020
KBUR	BOB HOPE	CA	ILS Z OR LOC Z RWY 8	901 / TREE / N34°12'33.59" / W118°27'49.82"	39	CIVIL	E12/2020
KVNy	VAN NUYS	CA	LDA-C		3A	CIVIL	E12/2020

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 (retired)
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 SKIDDMETER
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:

$$(V_p) \text{ spin-down} = 3.43 \sqrt{p}$$

$$(V_p) \text{ spin-down} = 9 \sqrt{p}$$

for SI Units

for U.S. Customary Units

$$\mu_{cd} = 0.93 - 1.6 \times 10^{-4} p$$

$$\mu_{cd} = 0.93 - 1.1 \times 10^{-3} p$$

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; Track wetted; Water depth 0.5mm (0.02 in.)

GROUND TEST VEHICLE	FAIRED μ	SPEED, V_0		V_0/V_p	TIRE HYDROPLANING PARAMETERS		ESTIMATED 8-737 AIRCRAFT BRAKING			ACTUAL 8-737 A/C μ_{EFF}
		KNOTS	MPH		$\bar{Y}_L$	$\bar{Y}_R$	μ_{MAX}	μ_{EFF}	V_0 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 (DBV)	.47	30	34	.680	.392	.642	.488	.268	76.2	.290
	.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	—
Skidometer	.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	—
Alu-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 ($\bar{V}_R$) and nonrotating ($\bar{V}_L$) tire hydroplaning parameters.

$\bar{V}_R$	$\bar{V}_L$	$\bar{V}_R$	$\bar{V}_L$	$\bar{V}_R$	$\bar{V}_L$	$\bar{V}_R$	$\bar{V}_L$	$\bar{V}_R$	$\bar{V}_L$
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

NASA

PRELIMINARY

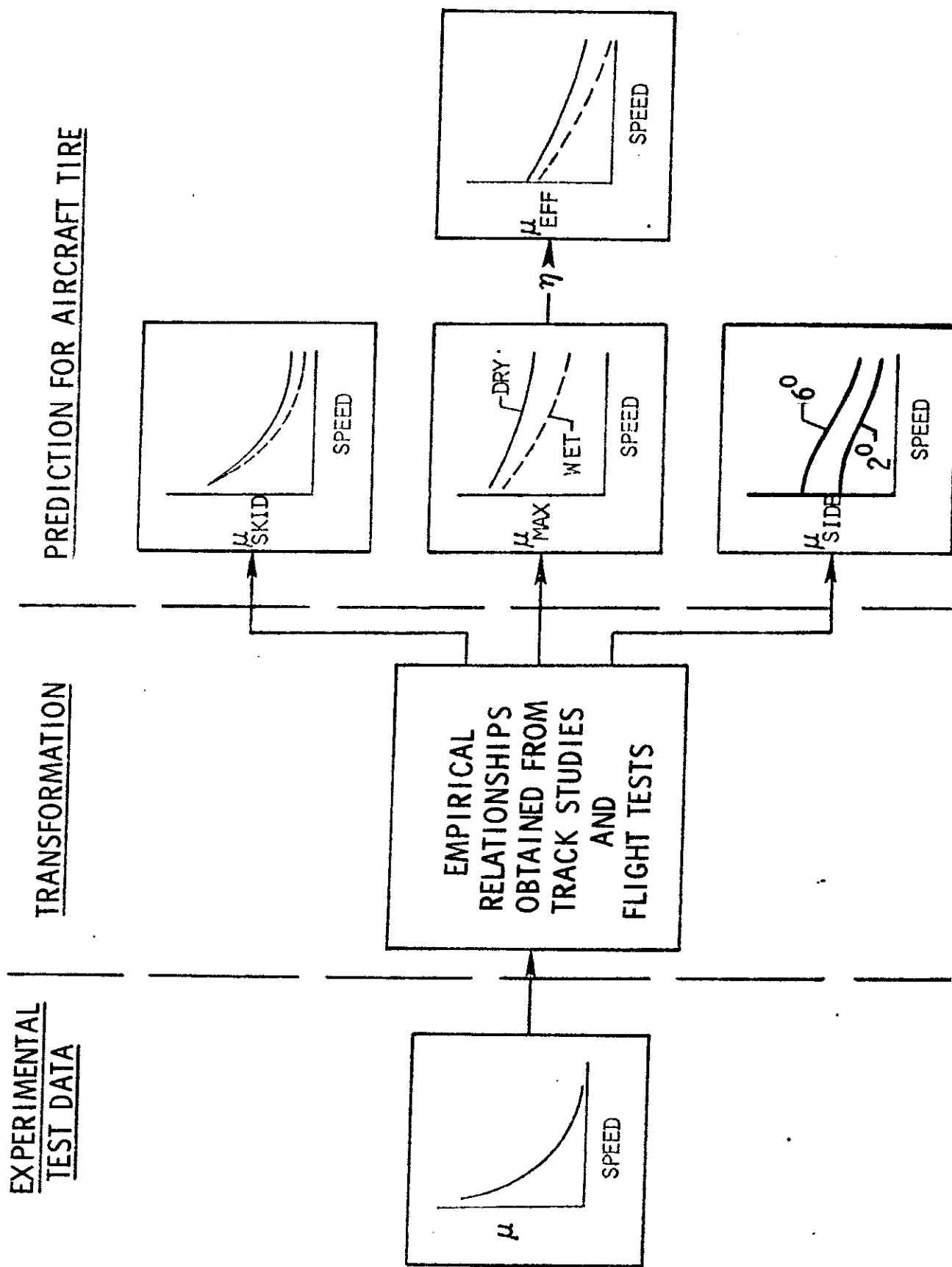


Figure 1. - Methodology used to estimate aircraft tire friction performance.

Figure 2 - RANGE OF AIRCRAFT AND GROUND VEHICLE PARTICULI MEASUREMENTS

STUNNY SEEL ASPHALT SURFACE
THICK WETTED WATER DEPTH 0.5 INCH (0.02 IN)

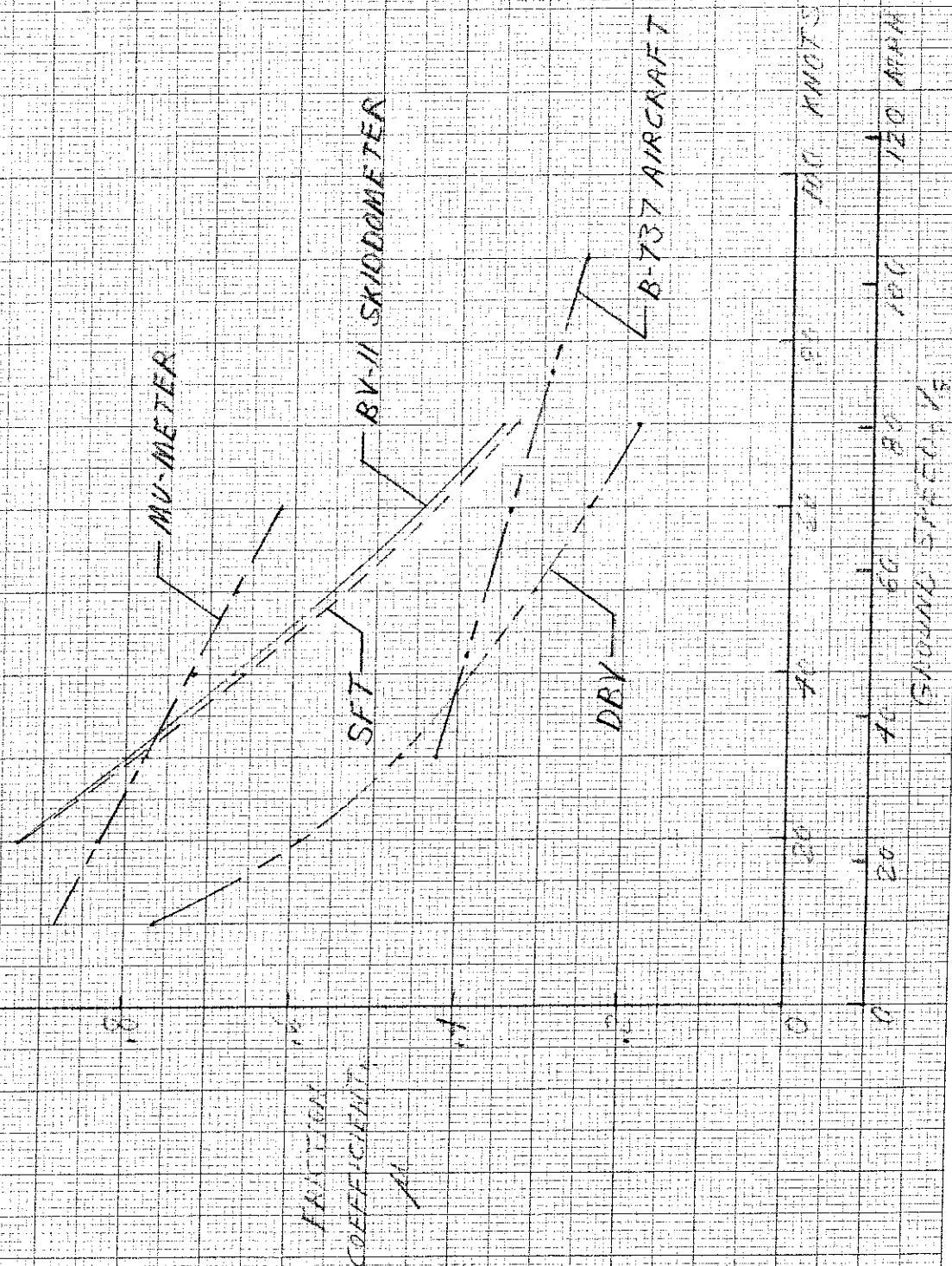
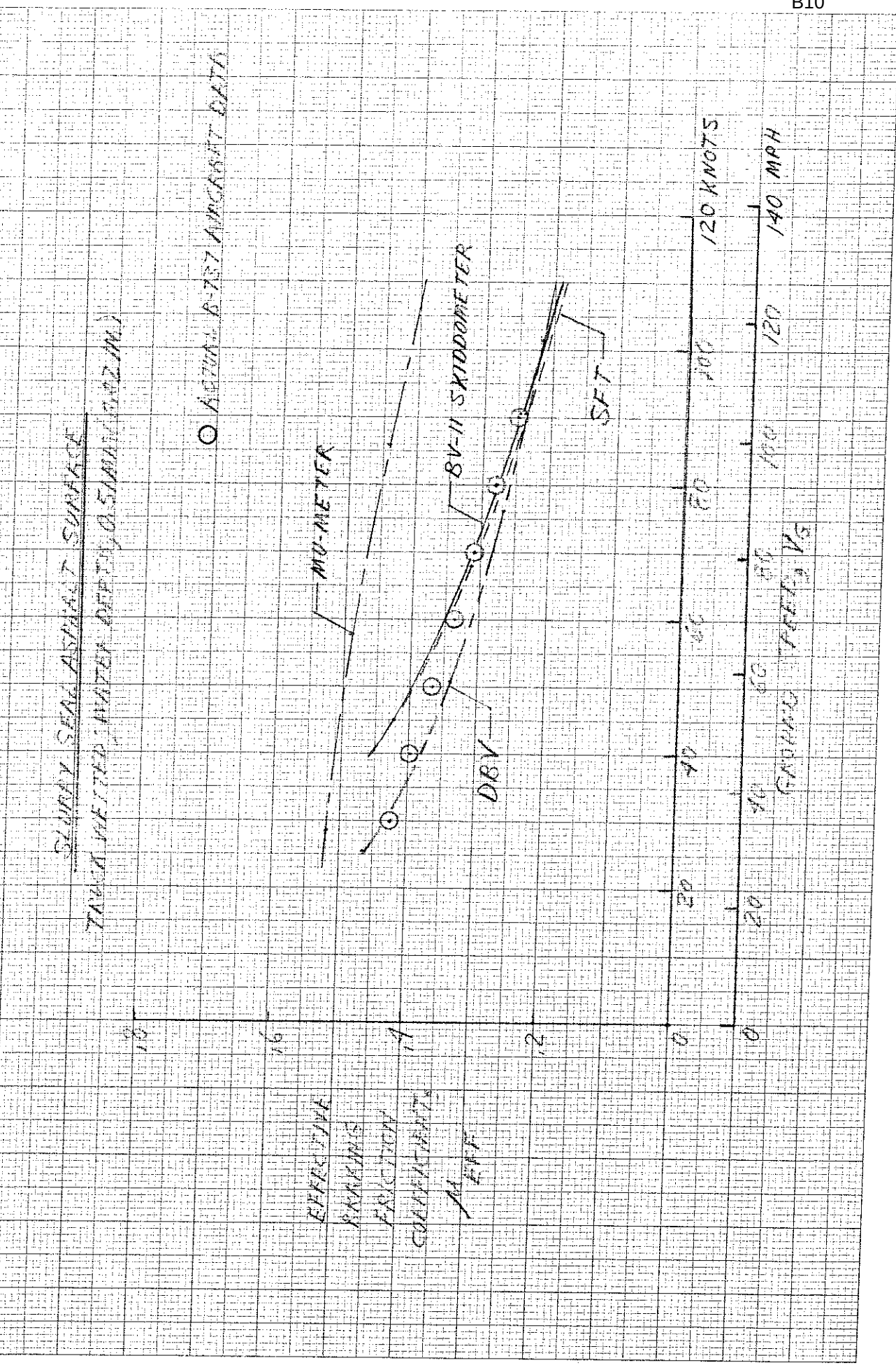


Figure 3. - ESTIMATED AIRCRAFT BRAKING PERFORMANCE FROM SPEED AND WHEEL FRICTION DATA



SET $M_{GRY} = 1.10$; $V_p = 500$ mph

10-11-60

[illegible]

DCA08MA085: BAe125-800A, N818MV, Owatonna, MN, 07/31/2008
CAPS runway friction braking coefficients

