

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



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AIRCRAFT PERFORMANCE GROUP STUDY

December 13, 2022

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A. ACCIDENT

Location: Honolulu, Hawaii
Date: July 2, 2021
Time: 0145 Hawaii Standard Time (HST)
1145 Coordinated Universal Time (UTC)
Airplane: Boeing 737-200C, N810TA, Rhodes Aviation Inc., dba Transair flight 810

B. AIRCRAFT PERFORMANCE GROUP

Chairman: Kevin J. Renze
National Transportation Safety Board
Washington, DC

Members: Dan Ahner
Boeing Commercial Airplanes
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Pratt & Whitney
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Wallace Horibata
Transair
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Lawrence Ward
Federal Aviation Administration
Washington, DC

C. SUMMARY

On July 2, 2021, at about 0145 local, Rhoades Aviation, Inc. dba Transair, flight 810, a B737-200C, N810TA, reported engine anomalies in both engines and subsequently ditched into Mamala Bay shortly after takeoff from Daniel K. Inouye International Airport (HNL), Honolulu, Hawaii. The two flight crew members were rescued, and the airplane was substantially damaged. The flight was operating under Title 14 *Code of Federal Regulations* Part 121 as a cargo flight from HNL to Kahului International Airport (OGG), Kahului, Hawaii.

1. Introduction

The Federal Aviation Administration (FAA) Air Traffic Control (ATC) communications and FAA Automatic Dependent Surveillance-Broadcast (ADS-B) data for Transair flight 810 were available to the National Transportation Safety Board (NTSB) investigation in July 2021. Other NTSB groups or specialists collected additional data including crew and operator interviews, flight dispatch paperwork, fuel and cargo records, crew operating manuals, airplane performance data, and airframe and engine maintenance records. In October 2021, the airplane Flight Data Recorder (FDR), Cockpit Voice Recorder (CVR), Enhanced Ground Proximity Warning System (EGPWS) unit, airframe, and engines were recovered from the Pacific Ocean sea floor off the coast of Honolulu.

An NTSB aircraft performance group was convened in February 2022 and staffed by subject matter experts from Transair (operations), the Federal Aviation Administration (operations), Pratt & Whitney (powerplants), Boeing Commercial Airplanes (aerodynamics), and NTSB (vehicle performance). A biweekly, virtual meeting schedule was used to discuss issues, assign tasks, and review progress. Documents were exchanged via email or through an NTSB document server.

The group's activities were concentrated in several areas, including 1) collection and distribution of factual evidence related to aircraft performance, 2) time alignment and visualization of recorded aural and parametric data, 3) calculated airplane performance capability, 4) preparation of data required to support engine model and integrated airplane model simulation, 5) development, validation, and simulation of accident-specific thrust increments to the baseline P&W JT8D-9

engine model, and 6) integrated B737-200 ADV airplane, engine, and flight controls modeling, validation, and simulation of selected segments of the accident flight.¹

2. Objective and Scope of the *Aircraft Performance Group Study*

The objectives of the study were to 1) quantify the expected airplane climb performance capability with one engine inoperative, 2) evaluate the accident airplane actual climb performance after the rapid right engine pressure ratio (EPR) reduction, and 3) determine if the accident aircraft motion, in response to engine EPR changes, configuration changes, and flight control inputs, was consistent with the behavior of the nominal B737-200 ADV integrated airplane/engine/flight controls simulation model. The group did not consider and the study did not evaluate any items related to the performance capability of the system defined by the crew, aircraft, engines, atmosphere, and ocean for altitudes less than one wing span above the ocean surface.

3. Summary of Results

Based on performance data consistent with data used to develop the Airplane Flight Manual (AFM), the B737-200 ADV has adequate performance capability with one engine inoperative (OEI) to climb or maintain altitude for the accident airplane loading and flight conditions. In addition, subsequent to the right engine rapid EPR reduction, with no change to the left engine EPR, the accident airplane demonstrated the ability to climb to 1,000 feet, accelerate, climb to 2,000 feet, and maintain altitude. When left engine EPR reduced and remained below 1.2, the total airplane engine thrust was less than the thrust required for the airplane to maintain altitude over the recorded range of flight conditions, flight control inputs, left and right engine EPR values, and flap configurations encountered. Finally, the accident aircraft motion, in response to gear/flap configuration changes, flight control inputs, and engine EPR changes, was generally consistent with the behavior of the nominal B737-200 ADV integrated airplane/engine/flight controls simulation model.

D. DETAILS OF THE INVESTIGATION

1. Accident Aircraft

Transair Boeing 737-200C, N810TA, was a twin-engine, narrow-body, transport category, convertible (passenger/freighter) aircraft powered by two Pratt & Whitney JT8D-9A low bypass ratio, turbofan engines. The NTSB Structures Group Chairman's Factual Report provides an overview of the aircraft configuration, dimensions, and construction. The NTSB Maintenance/ Human Performance Group Chairman's Factual Report includes the history of N810TA airframe and engine operations, maintenance, and modifications.

The Boeing 737-200 ADV passenger airplane configuration is documented in the three-view drawing included in Attachment 1. The drawing does not reflect all details of the N810TA convertible aircraft configuration.

2. Aircraft Engine Modification

The two JT8D-9A engines installed on N810TA were modified in May 2004 to add an Av Aero hush kit for noise abatement according to Supplemental Type Certificate (STC) ST223CH, "Installation of a Stage 3 hush kit when powered by P&W JT8D-9 series engines (AV Aero Systems)," amended 5/30/95. A records search conducted by Federal Aviation Administration (FAA) and Pratt & Whitney (P&W) staff located ST223CH documentation that enabled P&W engineering staff to model the engine thrust increments due to the Av Aero hush kit.

¹ The B737-200 ADV has improved (or advanced) aerodynamics, engines, payload, and range relative to the B737-200.

3. Departure Airport and Runway

Daniel K. Inouye International Airport (HNL) is located 3 miles northwest of Honolulu, Hawaii. Transair flight 810 departed on HNL runway 8R. The runway 8R surface is 12,000 feet long, 200 feet wide, elevated about 10 feet above sea level, constructed of asphalt, and grooved. An HNL airport diagram is included in Attachment 2.

4. Aircraft Weight & Balance

The accident flight weight and balance is documented by maintenance records for the N810TA empty weight and flight 810 operational records for the crew, cargo, and fuel loading. The aircraft basic empty weight as of April 19, 2021 was 59,720 pounds. The accident flight was loaded with 19,897 pounds of cargo and 14,000 pounds of fuel. The resulting flight 810 weight and balance reconstruction based on the load manifest is shown in Table 1.

Table 1: N810TA Weight and Balance Reconstruction

	Weight	Arm	Moment	Flight 810	Struct. Limit
	lb	inches or %m.a.c.	inch-lb	lb	lb
Basic Empty Weight	59,720	654.63	39,094,013		
Crew 1	220	250	55,000		
Crew 2	220	250	55,000		
Cargo	19,897	698	13,888,106		
Zero Fuel Weight	80,057			95,000	95,000
Fuel	14,000	579.8	8,117,200		
Ramp Weight	94,057			105,830	120,000
Taxi Fuel Burn	500	550	275,000		
Takeoff weight	93,557	651.31	60,934,319	105,330	119,500
Takeoff c.g. (%m.a.c.)		19.1			
Enroute fuel	2,786	550	1,532,300		
Landing weight at planned destination	90,771	654.42	59,402,019	105,000	105,000
Landing c.g. at planned destination (%m.a.c.)		21.4			

For ease of reference, Attachment 3 contains N810TA jacking point and empty weight records extracted from the NTSB Maintenance/Human Performance Group Chairman's Factual Report as well as flight 810 load manifest and cargo records documented in the NTSB Operational Factors/Human Performance Group Chairman's Factual Report, Attachment 9. The aforementioned Operational Factors/Human Performance report also contains the accident flight paperwork (Attachment 7), N810TA fueling records (Attachment 8), and HNL runway analysis data (Attachment 15). The load manifest maximum takeoff weight of 105,330 lb indicates the flaps 5, climb-limited weight for N810TA departing HNL runway 08R at 26°C outside air temperature. Enroute fuel and landing weight and c.g. are for the planned flight, not the accident flight.

5. Aircraft Takeoff & Ditching Configuration

The flight 810 load manifest indicates the takeoff weight was 93,557 pounds, the airplane longitudinal center of gravity was located at 19.1 percent mean aerodynamic chord, the horizontal stabilizer trim was 5.2 units, flaps 5 were planned, 08R was the departure runway, and the runway surface was not wet. Additional aircraft performance parameters included temperature 26°C, runway headwind component 8 knots, antiskid wheel brakes and engine bleeds on, and maximum engine thrust obtained at an engine EPR of 2.01. Engine EPR for a derated takeoff was 1.89.

Based on crew interviews, CVR data, and the post-recovery airframe inspection, N810TA was configured with flaps 1 and gear retracted when the water ditching occurred.

6. Meteorological Conditions

The following hourly and 5-minute HNL Automated Surface Observing System (ASOS) data that bound the accident time were extracted from the NTSB Meteorology Specialist's Factual Report:

[0053 HST] METAR PHNL 021053Z 07013KT 10SM FEW025 SCT045 26/18 A3004 RMK AO2 SLP170 T02560183=

[0153 HST] METAR PHNL 021153Z 06010G21KT 10SM FEW025 SCT050 26/17 A3003 RMK AO2 SLP169 60000 T02560172 10267 20256 56008=

[0253 HST] METAR PHNL 021253Z 07010KT 10SM FEW024 FEW046 26/17 A3002 RMK AO2 SLP166 T02560167=

At 0153 HST, the HNL ASOS reported a wind from 060° at 10 knots with gusts to 21 knots, visibility of 10 statute miles or greater, few clouds at 2,500 feet above ground level (agl), scattered clouds at 5,000 feet agl, temperature of 26° Celsius (C) and dew point temperature of 17°C, altimeter setting of 30.03 inches of mercury; Remarks included: automated station with a precipitation discriminator, sea level pressure of 1016.9 hectopascals (hPa).

The five-minute HNL ASOS data near the accident time were:

[0140 HST] 5-MIN PHNL 021140Z 05011KT 10SM SCT050 26/18 A3003 -80 61 1200 040/11 RMK AO2 T02560178

[0145 HST] 5-MIN PHNL 021145Z 06014KT 10SM SCT050 26/18 A3003 -80 61 1200 050/14 RMK AO2 T02560178

[0150 HST] 5-MIN PHNL 021150Z 07015G21KT 10SM FEW025 SCT050 26/17 A3003 -80 59 1200 060/15G21 RMK AO2 SLP169 60000 T02560172 10267 20256 50008

At 0145 HST, the HNL ASOS five-minute report indicated a wind from 060° at 14 knots, visibility of 10 statute miles or greater, scattered clouds at 5,000 feet agl, temperature of 26°C and dew point temperature of 18°C, altimeter setting of 30.03 inches of mercury, pressure altitude of -80 feet, relative humidity of 61 percent, density altitude of 1,200 feet, magnetic wind direction of 050° with a wind magnitude of 14 knots; Remarks included: automated station with a precipitation discriminator, temperature of 25.6°C and dew point temperature of 17.8°C.

The NTSB Air Traffic Control Group Chairman's Factual Report states that Automated Terminal Information Systems (ATIS) information Kilo (K) was current as of 1053 UTC, which reported the weather as:

wind 060 degrees at 10 knots, visibility of 10 statute miles or greater, few clouds at 2,500 feet agl, scattered clouds at 4,500 feet agl, temperature 26°C, dew point temperature 18°, altimeter 30.04, runways 4 and 8 ILS or visual approaches in use, LAHSO [Land and Hold Short Operations] in effect.

The paraphrased CVR events included the following weather and supplemental information:

ATIS K was heard including: 1053Z 06013KT 10SM FEW025 SCT045 26/18 3004, with notes for landing and departing runways, LAHSO operations in effect, taxiway closures, birdstrike hazard, and cranes in the vicinity.

7. Flight 810 Aural Communications

7.1. Air Traffic Control Communications Transcript

The FAA Air Traffic Control (ATC) communications for the accident flight are documented in the NTSB Air Traffic Control Group Chairman's Factual report, Attachment 2. The ATC communication events were overlaid on time history and flight path plots containing FDR and CVR time history data to align the data and corroborate these independent records of factual evidence.

7.2. Paraphrased Cockpit Voice Recorder (CVR) Events

Each aircraft performance group member was authorized by NTSB senior management to possess, assess, and discuss a paraphrased subset of CVR events to support group tasks. The paraphrased CVR events incorporated in this study are documented in Attachment 4.

8. Flight 810 Parametric Data

8.1. Flight Data Recorder (FDR) Data

The available FDR data are documented in the NTSB Flight Data Recorder Specialist's Factual Report. The available FDR parameters included normal (vertical), longitudinal, and lateral acceleration, pressure altitude, indicated (computed) airspeed, left and right engine EPR, pitch attitude, bank angle, magnetic heading, control column and elevator surface deflection, control wheel and aileron surface deflection, rudder pedal and rudder surface deflection, VHF radio keyed, and autopilot engaged status. Time history plots of FDR parameters available to the group with annotated CVR and ATC events overlaid are provided in Attachment 5. Methods used to validate FDR flight control input and flight control surface parameters and correct improperly scaled FDR parameters or replace invalid FDR parameters are documented in Section 10.

8.2. Enhanced Ground Proximity Warning System (EGPWS) Data

The Enhanced Ground Proximity Warning System (EGPWS) data are documented in the NTSB Systems Group Chairman's Factual report. Available EGPWS time history parameters for the last 3 minutes 37 seconds of the flight (when the aircraft is generally descending between 575 feet radio altitude and the ocean surface and decelerating from about 160 to 122 knots calibrated airspeed) include:

Line No, Rec ID, Flt Leg, Oper Time, Lat, Long, Pos Uncert, CAS, TAS, Gspd, VFOM, GPS Alt, Uncorr Alt, TACAIt, Rad Alt, Terr Elv, Alt Rte, Mag Trk, Tru Trk, Tru Hd, Pitch, Roll, BAOA, L. Accl, N. Accl, I.V.Accl, Glides, Loc, Pos Src, SAT, Rng1, Rng2, TotShear, Gr Dn, Flp Sel, InAir, Apprch, WSAprch, TADlnh, Disp1 En, Disp2 En, Tact Sel, Audiolnh, EnvMod, NISF1, NISF2, Sel Mode

The following EGPWS parameters were overlaid on FDR data (see time history plots in Attachment 6) to understand the recorded event sequence and validate calculated aircraft parameters: time (Oper Time), latitude (Lat), longitude (Long), calibrated airspeed (CAS), true airspeed (TAS), groundspeed (Gspd), GPS altitude (GPS Alt), uncorrected altitude (Uncorr Alt), TACAIt, radio altitude (Rad Alt), magnetic ground track angle (Mag Trk), true ground track angle (Tru Trk), true heading (Tru Hd), pitch attitude (Pitch), bank angle (Roll), airplane body angle of attack (BAOA), longitudinal acceleration (L. Accl), and normal acceleration (N. Accl). The EGPWS gear down (Gr Dn) and flap selected (Flp Sel) parameters were not able to be validated.

8.3. Automatic Dependent Surveillance-Broadcast (ADS-B) Data

FAA Automatic Dependent Surveillance-Broadcast data are documented in the NTSB Air Traffic Control Group Chairman's Factual report. The entire accident flight including the ground taxi segment was recorded. The ADS-B data were recorded at about 1 sample per second, began at 11:22:23.267 and ended at 11:45:17.902 UTC, and include the following parameters, among others: date, time, latitude, longitude, pressure altitude, geometric altitude, groundspeed, vertical rate, and ground track heading.

According to the NTSB Air Traffic Control Group Chairman's Factual report:

The RDS810 assigned Mode S transponder address was AB0B06 and the accident airplane was assigned an ATC transponder beacon code of 2107.

An overhead view of the N810TA flight path documented by ADS-B data is shown in Figure 1. The HNL runway 8R and 26L thresholds are annotated with yellow arrows and due north is toward the top of the page. The ADS-B data show the airplane ground taxi path to runway 8R followed by the takeoff, initial climb, and multiple altitude hold, course change, and descent segments. The aircraft direction of travel during the approximately 12-minute in-air segment is in the clockwise direction.

The ADS-B flight path data were overlaid with selected engine EPR, altitude, and airspeed events identified by P&W engineering staff (events tabulated in Attachment 7) to construct Figure 2. Similarly, FAA ATC communication events and paraphrased CVR events were overlaid on the ADS-B flight path to create Figures 3 and 4, respectively. Subsets of the ATC communication events plotted in Figure 3 and the paraphrased CVR events plotted in Figure 4 may be obscured by adjacent or other foreground events due to text display format and zoom scale limitations.

9. Time Alignment

The CVR crew-initiated radio communication events and the FDR VHF radio keyed parameter were used to time align recorded flight 810 aural and parametric data for this study. The initial time alignment attempt was unsuccessful due to an unexpected FDR subframe recording rate that differed from the expected 768 bits per second (64 words/sec x 12 bits/word = 768 bits/sec), as discussed in the NTSB Flight Data Recorder Specialist's Factual Report. A joint CVR and FDR recorder specialist effort determined that the FDR time parameter needed to be scaled by a factor of 1.0069659 to properly align the CVR and FDR radio communication events.

The time alignment between ATC communication events, paraphrased CVR events, and FDR, ADS-B, and EGPWS parametric data is summarized in Table 2.

Table 2: Time Alignment

	ATC, CVR	FDR Elapsed Time (seconds)			ADS-B	EGPWS
		NTSB	Boeing	P&W		
Right Engine Initial EPR Reduction	01:33:56.53 HST	41,636.53	9481.15 = NTSB FDR - 32,155.38	+1.03	Boeing FDR + 8,787.90	01:33:56.53 HST

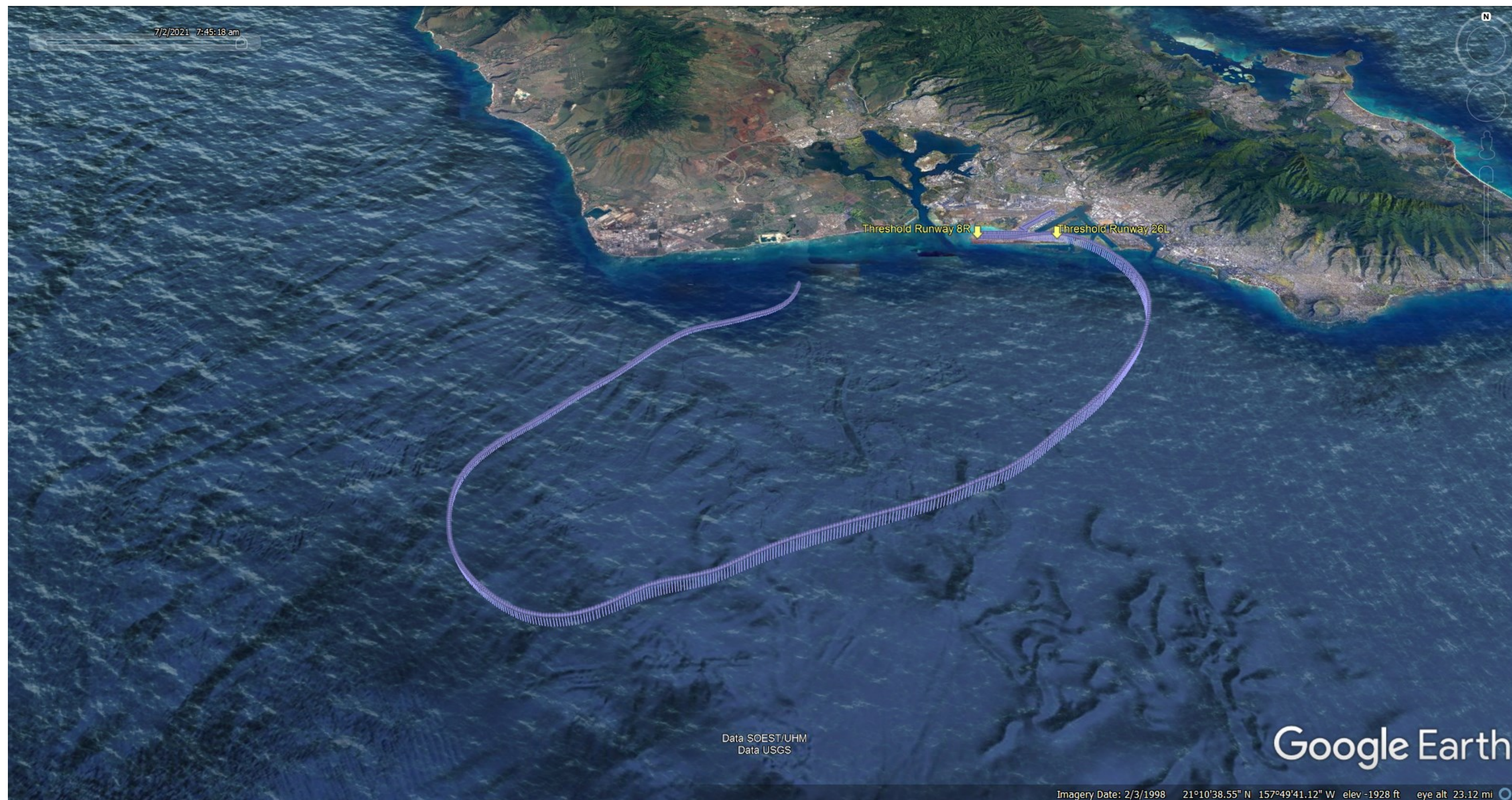


Figure 1: FAA ADS-B data depicting N810TA accident flight sequence from ground taxi to runway 8R through the takeoff, initial climb, and multiple altitude hold, course change, and descent segments to the ocean surface. Aircraft direction of travel during the approximately 12-minute flight is in the clockwise direction. Due north is toward the top of the page.

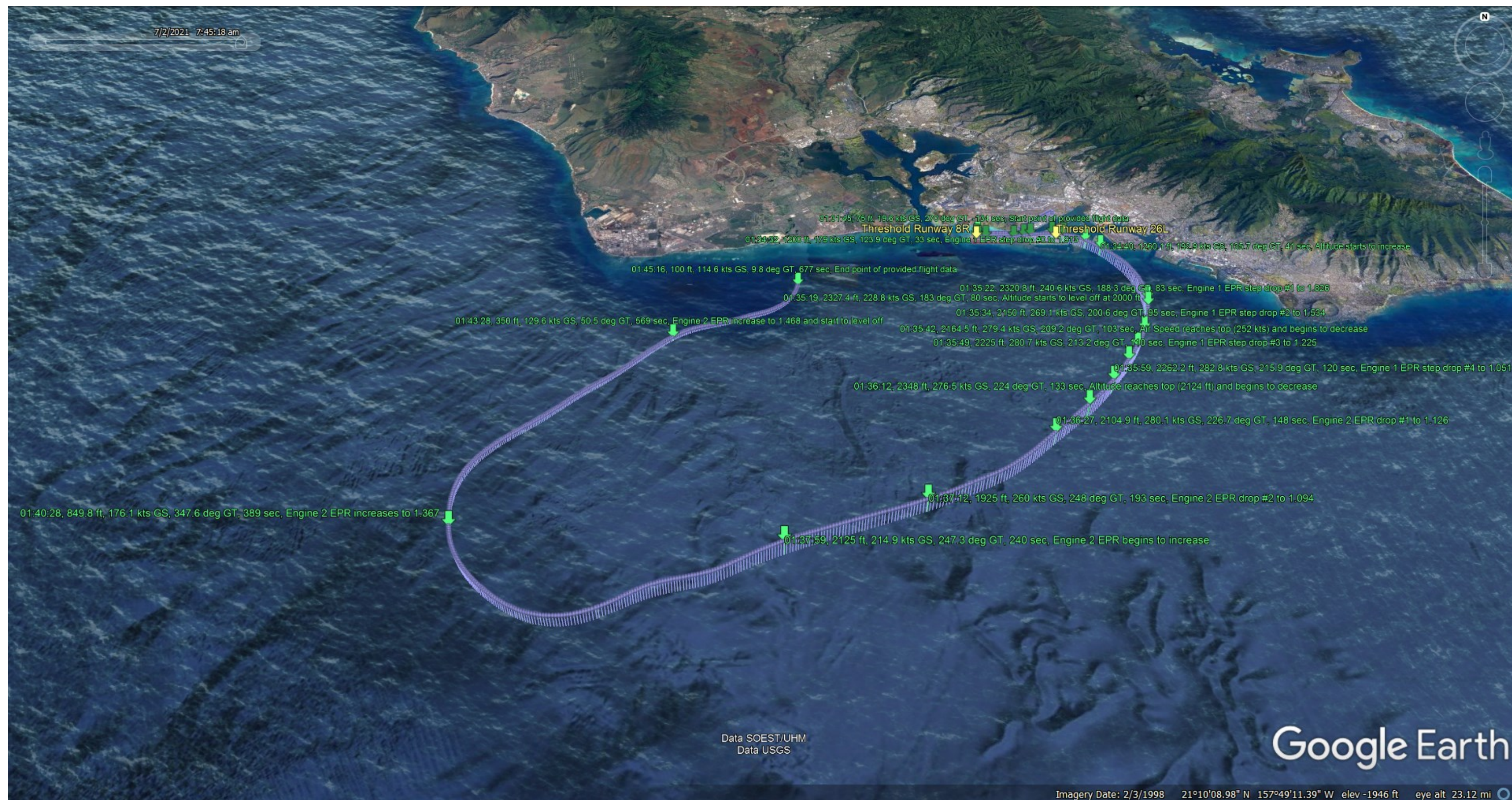


Figure 2: Addition of Pratt & Whitney engine events to FAA ADS-B data depicting N810TA accident flight sequence from ground taxi to runway 8R through the takeoff, initial climb, and multiple altitude hold, course change, and descent segments to the ocean surface. Aircraft direction of travel during the approximately 12-minute flight is in the clockwise direction. Due north is toward the top of the page. Parametric data indicate time (HST hh:mm:ss), altitude, groundspeed, ground track heading, and P&W elapsed time in seconds.

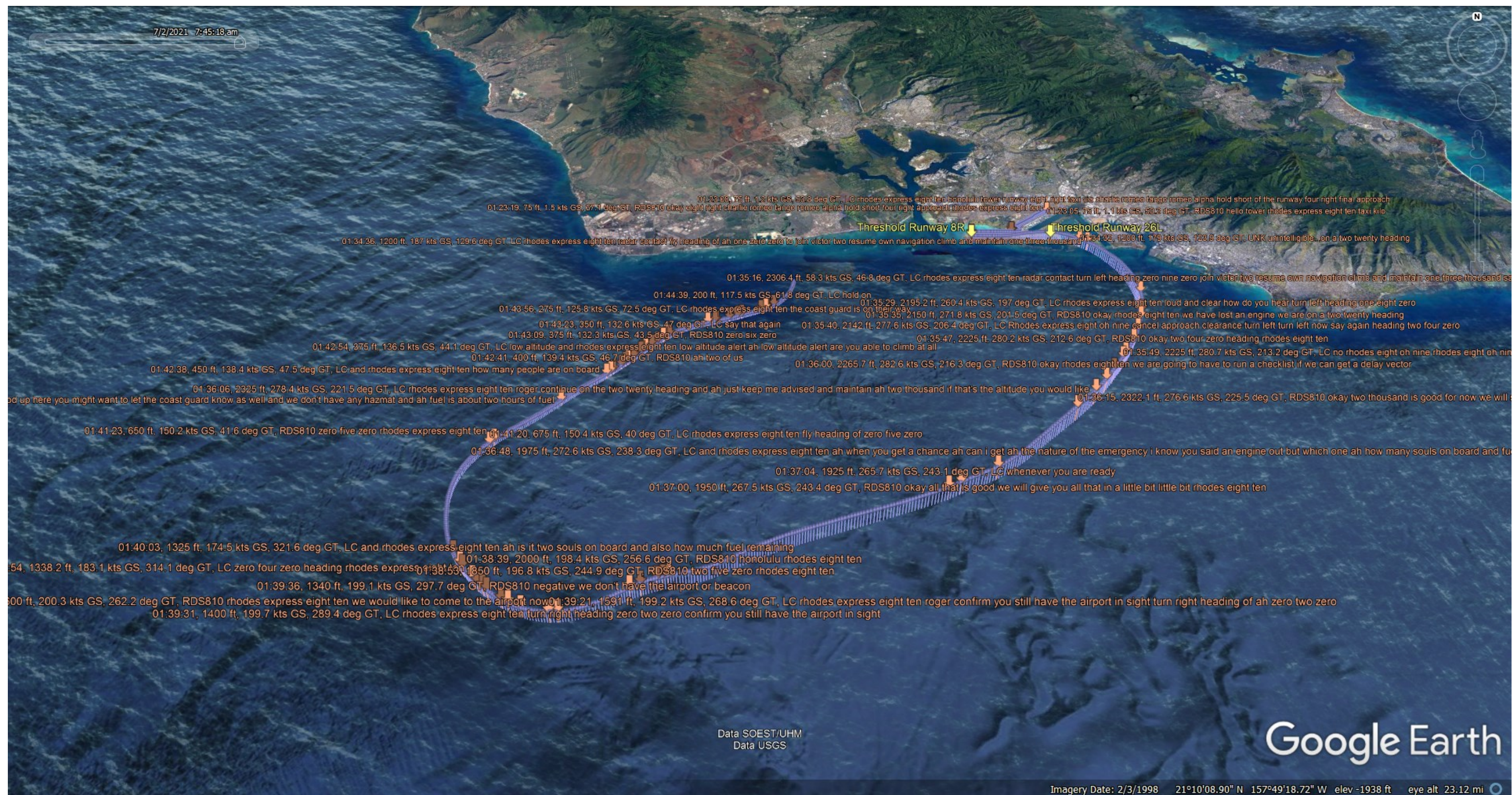


Figure 3: Addition of FAA ATC communication events to FAA ADS-B data depicting N810TA accident flight sequence from ground taxi to runway 8R through the takeoff, initial climb, and multiple altitude hold, course change, and descent segments to the ocean surface. Aircraft direction of travel during the approximately 12-minute flight is in the clockwise direction. Due north is toward the top of the page. Parametric data indicate time (HST hh:mm:ss), altitude, groundspeed, and ground track heading.



Figure 4: Addition of paraphrased CVR events to FAA ADS-B data depicting N810TA accident flight sequence from ground taxi to runway 8R through the takeoff, initial climb, and multiple altitude hold, course change, and descent segments to the ocean surface. Aircraft direction of travel during the approximately 12-minute flight is in the clockwise direction. Due north is toward the top of the page. Parametric data indicate time (HST hh:mm:ss), altitude, groundspeed, and ground track heading.

10. FDR Parameter Validation & Adjustments

The FDR equipment and dataframe on N810TA and N809TA were provided by supplemental type certificate (STC) holder AACO.² Boeing engineering staff reviewed the FDR dataframe conversion from binary to engineering units and found that the N810TA accident flight FDR contained three parameters—control wheel deflection, rudder pedal deflection, and rudder surface deflection—with recorded values that exceeded their expected full travel range. An independent FDR STC installation check using N809TA FDR data also indicated full travel range exceedance behavior for these parameters. However, no operational reports of N810TA accident flight or preceding N810TA or N809TA flight control input or flight control surface deflection anomalies were found. Therefore, the aircraft performance group assumed that 1) the N810TA flight controls were properly rigged and operated near nominal and 2) the AACO dataframe document content for control wheel deflection, rudder pedal deflection, and rudder surface deflection was incomplete or incorrect.

Data from N810TA and N809TA were subsequently used to calculate linear scaling factors to apply to recorded FDR control wheel and rudder pedal deflection. These linear factors yield improved estimates of the respective flight control input and flight control surface parameters during the accident flight (relative to the recorded FDR data and AACO dataframe) under no load (zero dynamic pressure) conditions. However, these simplified adjustments cannot fully model the actual N810TA system behavior, including nonlinear effects. The Boeing 737-200 ADV integrated airplane/engine/flight controls model discussed in Section 13 accounts for dynamic pressure, nonlinear behavior, and assumptions that the airplane flight controls were appropriately rigged and operating within the nominal travel range.

10.1. Control Wheel Deflection (Expected vs. Recorded)

The expected and recorded control wheel deflection ranges are summarized below.

Boeing, expected control wheel deflection

No-load, full aileron system travel:	±87.5°
Travel due to mechanical factors (cable stretch, system friction, lost motion) ³ :	±90°
At mechanical stops:	±107.5°

AACO dataframe, expected control wheel deflection:	±107.5°
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Recorded FDR values (N810TA, N809TA, on-ground control sweeps and in flight):	±125°
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A scaling factor of **(90/125) = 0.72** was initially applied to the FDR recorded control wheel to yield a full scale control wheel deflection of 90°. However, the linear relationship that exists for recorded control wheel deflections between ±100° becomes nonlinear for recorded deflections beyond ±100°. As a result, the FDR control wheel data were deemed erroneous.

Access to a validated airplane flight controls model is an alternate path to estimate control wheel deflection. This approach adds the benefit of enforcing nominal relationships between control wheel deflection, left and right aileron deflection, and roll spoiler deflection. The B737-200 ADV integrated airplane simulation flight controls model was used to construct surrogate control wheel deflection values based on FDR aileron deflection. The quality of follow-on simulation match results, including calculated values of control wheel and aileron deflection, can be assessed against both the surrogate control wheel and the FDR aileron values.

² AACO document GCD-0001-001 defines the FDR parameter layout and conversions from binary to engineering units.

³ Mechanical factors like cable stretch, system friction, and lost motion between the control wheel and the position sensor may contribute to momentary recorded wheel deflections of up to 90° if the control wheel is moved quickly.

10.2. Aileron Surface Deflection (Expected vs. Recorded)

The expected and recorded aileron surface deflection ranges are summarized below.

Expected left and right aileron full surface deflection:	Boeing	$20.0 \pm 1.0^\circ$
Expected aileron full surface deflection:	AACO	$\pm 21.0^\circ$
Recorded (left) aileron from accident flight:	N810TA	about $\pm 21^\circ$
Recorded (left) aileron from another ship:	N809TA	about $\pm 21^\circ$

The recorded FDR aileron values were generally consistent with the AACO dataframe document and the values expected by Boeing engineering staff. Therefore, recorded FDR aileron data were deemed to be representative of actual aileron surface deflection.

Data presented in Figure 5 show control wheel deflection vs. aileron surface deflection for the N810TA event flight FDR data (red circles and yellow shaded region), the Boeing simulation expected nominal relationship (blue, dashed line), and calculated wheel deflection based on FDR aileron deflection (dark blue squares). The relationship between FDR recorded control wheel deflection and recorded aileron surface deflection is nonlinear throughout the range of recorded wheel travel, due in part to mechanical factors like cable stretch, system friction, and lost motion.

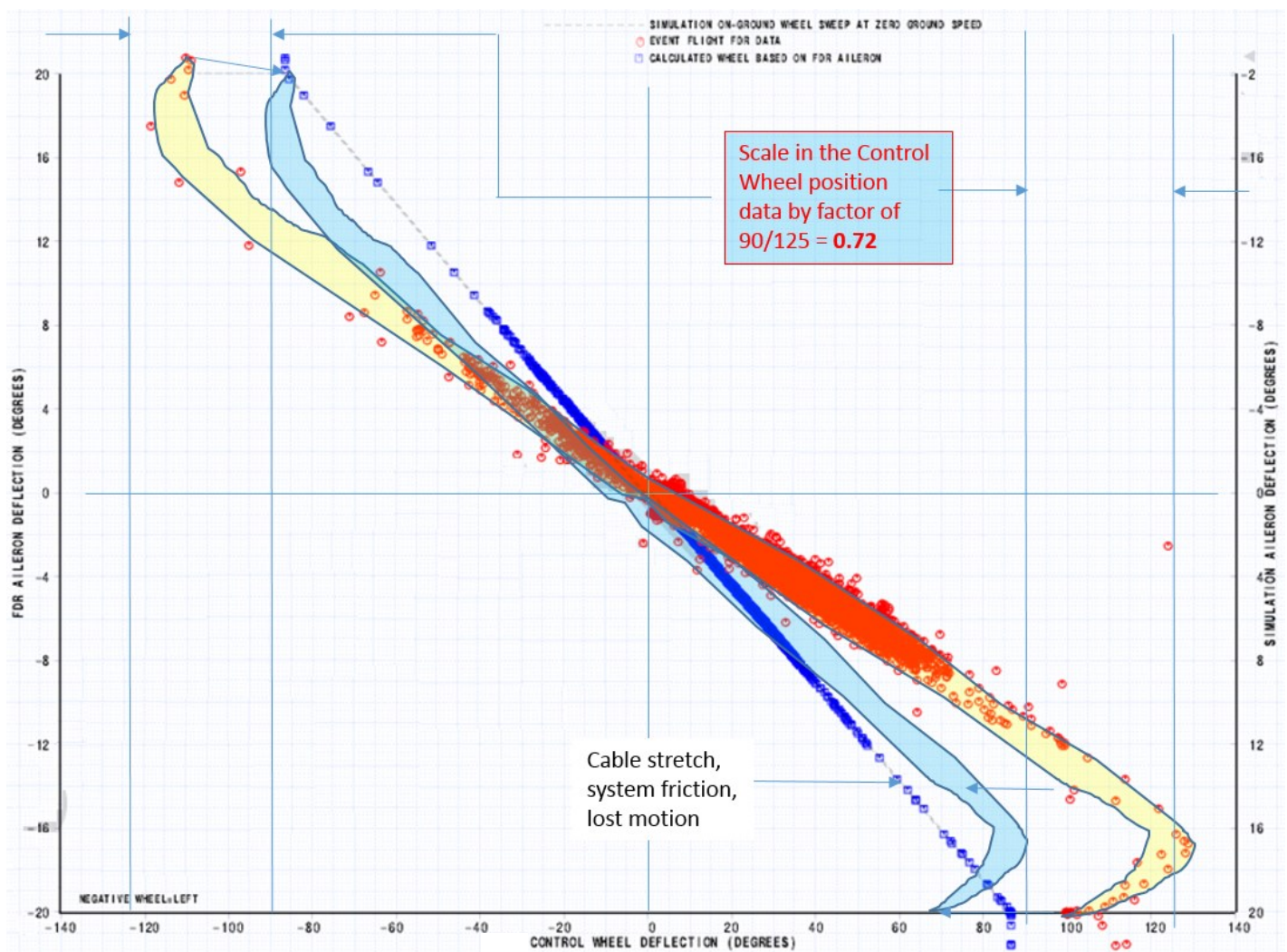


Figure 5: FDR recorded and corrected roll axis parameters (control wheel vs. aileron surface)

10.3. Rudder Pedal Deflection (Expected vs. Recorded)

The expected and recorded rudder pedal deflection ranges are summarized below.

Expected rudder pedal full deflection:	Boeing	$\pm 12.6^\circ$
Expected rudder pedal full deflection:	AACO	$\pm 15^\circ$
Recorded (captain's) pedal from accident flight:	N810TA	$\pm 14.7^\circ$
Recorded (captain's) pedal from another ship:	N809TA	$\pm 14.7^\circ$

Boeing engineering staff applied an adjustment factor of $(12.6/14.7) = 0.86$ to the recorded rudder pedal deflection values to model rudder pedal deflection.

10.4. Rudder Surface Deflection (Expected vs. Recorded)

The expected and recorded rudder surface deflection ranges are summarized below.

Expected rudder full surface deflection:	Boeing	$\pm 26^\circ$
Expected rudder full surface deflection:	AACO	$\pm 15^\circ$
Recorded rudder surface deflection from accident flight:	N810TA	0 to $+100^\circ$
Recorded rudder surface deflection from another ship:	N809TA	0 to $+100^\circ$

Boeing engineering staff reviewed rudder surface deflection during the on-ground portion of the N810TA accident flight and the in-flight segment. Given the expected versus recorded parameter differences, the sign of the recorded rudder surface deflection values was flipped from positive to negative for negative values of recorded rudder pedal deflection. A scaling factor of $(26/97) = 0.27$ was subsequently applied to the intermediate (sign-adjusted) rudder surface deflection to provide a more accurate estimate of rudder surface deflection. Figure 6 illustrates rudder pedal deflection vs. rudder surface deflection for the N810TA event flight on-ground pedal sweep FDR data, the Boeing simulation expected nominal relationship, and the calculated rudder pedal and rudder surface deflection based on FDR pedal.

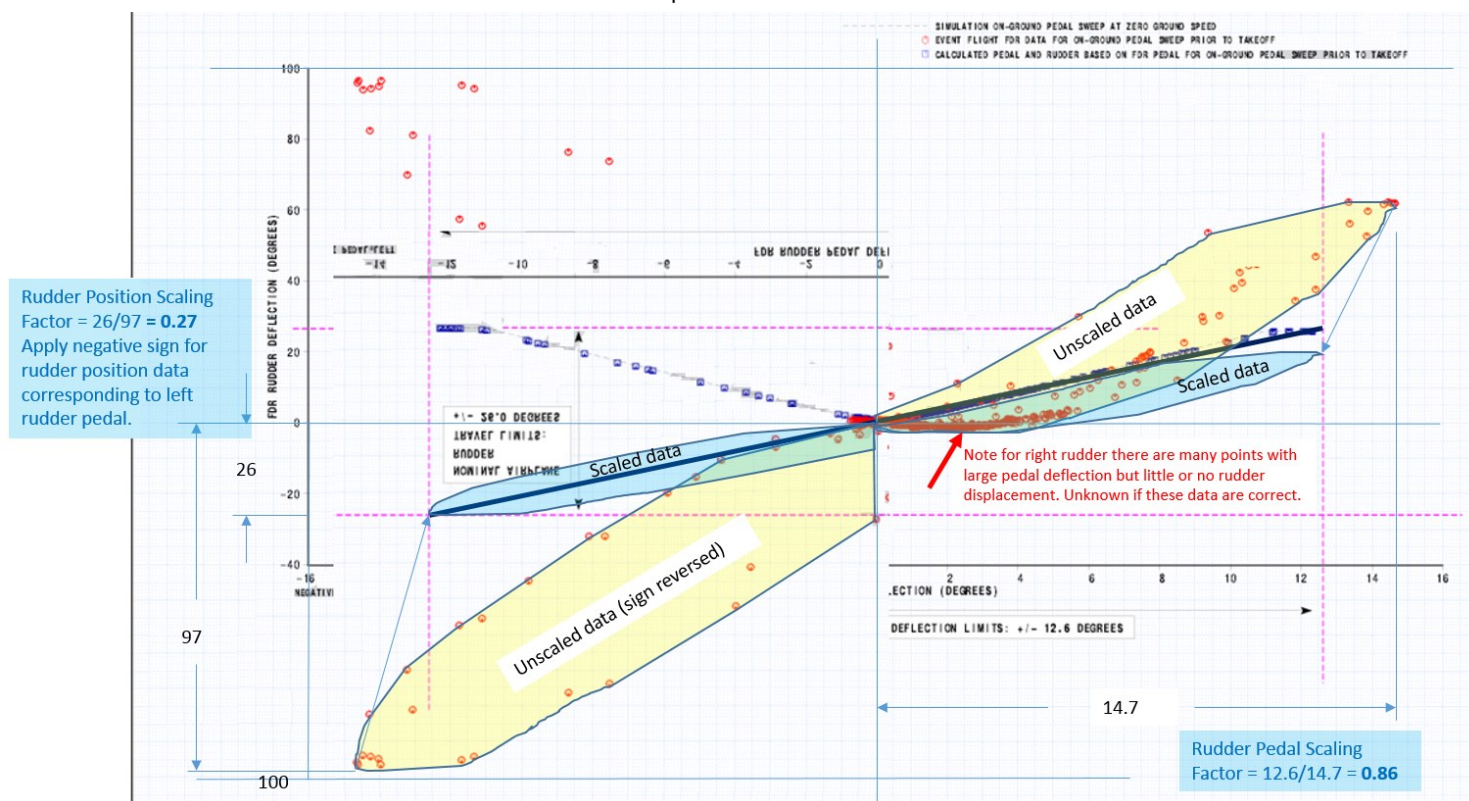


Figure 6: FDR recorded and corrected yaw axis parameters (rudder pedal vs. rudder surface)

The relationship between rudder surface deflection and rudder pedal deflection is proportional to the dynamic pressure on the rudder surface (which is a function of airspeed and pressure altitude). This nonlinear relationship cannot be reasonably estimated by making direct adjustments to the FDR dataframe. Because the linear scaling factors for FDR rudder pedal and rudder surface deflection do not account for dynamic pressure or yaw damper effects, the B737-200 ADV airplane flight controls model was used to construct surrogate rudder surface deflection values based on adjusted FDR pedal deflection data and the recorded flight conditions. Rudder yaw damper effects were accounted for in the integrated airplane simulation model work discussed in Section 13.

11. Pratt & Whitney JT8D-9A Engines

During flight 810, the FDR recorded a right engine rapid EPR reduction event and the CVR recorded related crew recognition events, actions, and communications to ATC. Engine issues were also discussed during post-accident crew interviews. The Aircraft Performance Group engaged the Powerplants Group to understand the available engine factual evidence and P&W engineering staff to explore options to model and simulate the accident flight total engine thrust as a function of time. Fuel samples from N809TA, which was serviced by the same truck as N810TA, complied with the ASTM D1655 specification.

11.1. Engine Hardware Evidence

Based on recovered engine, nacelle, thrust reverser, and accessory components documented by the NTSB Powerplants Group Chairman's Factual Report, the left engine had no evidence of soft body impact, thrust reverser actuation, fire, uncontainment, case rupture, ovalized case(s), or missing case(s). Metal deterioration and coral deposits typical of salt water immersion were present. No issues were found with the fuel pump, fuel control unit, recovered accessories, bearings (cages, rollers, spacing, diameter, discoloration, blistering, seizure), combustor (burn through, metallization, or thermal distress), or inlet guide vanes. Clashing damage was evident in the low pressure compressor (LPC) on stage 1 blade TEs and on stages 4 and 5 stator TEs. Two stage 5 blades were fractured off. The stage 6 blades (as viewed in the arrested/seized position, from the rear of the engine) were full length and straight between 8 and 11 o'clock, full length and bent opposite the direction of rotation between 11 and 12 o'clock, and fractured at the platform between 12 and 8 o'clock. The intermediate case front skirt was deformed and dented over LPC stages 5 and 6. Four high pressure compressor (HPC) stage 7 blades were fractured and the stage 9 blades were either fractured at the platform or missing from their slots. LPC and HPC blade bending/deformation was present in the direction opposite of rotation. No issues were found with the high pressure turbine (HPT), high turbine shaft, or low pressure turbine (LPT) vanes or blades. The low turbine shaft was bent but intact.

All casings aft of the right engine fan case were intact with no indications of fire, uncontainment, or case rupture. Metal deterioration and coral deposits typical of salt water immersion were present. Two HPT (T1) blades were found fractured outboard of mid-span. All right engine LPT stages (T2, T3, and T4) exhibited damage.⁴ The fan, LPC, and HPC exhibited evidence of blade bending/deformation in the direction opposite of rotation.

11.2. Engine Models and Simulation

Pratt & Whitney engineering staff provided baseline JT8D-9 engine model data for each engine for the duration of flight 810 based on METAR and FDR indicated (computed) airspeed, pressure altitude, left engine

⁴ The Powerplants Group Factual states that three T2 vanes at 5 o'clock exhibited leading edge (LE) damage, all T2 vanes exhibited trailing edge (TE) breakout damage, and all T2 blades exhibited outer span fractures. The T3 exhibited outer span blade fractures and TE stator breakout damage similar to the T2 damage. Up to three inches of outer span material was missing from all T4 blades and T4 vane airfoil breakout damage was most pronounced between the mid-span and tip.

EPR, and right engine EPR data.⁵ The following engine output parameters were calculated on a per engine basis: engine N1 (speed of low pressure spool), engine N2 (speed of high pressure spool), net thrust (gross thrust - ram drag of the airflow streamtube), exhaust gas temperature, fuel flow, and engine PLA (power lever angle).

Three additional engine simulation modeling and validation tasks were identified by the group to quantify engine performance increments applicable to N810TA flight 810. P&W staff accepted tasks to develop, validate, and exercise engineering models to incrementally account for:

1. The AvAero hush kit STC installation on each engine
2. N810TA serialized engine performance (in-service/on-wing engine deterioration on a per engine basis) documented by engine health monitoring data collected by crews for each engine during the cruise segment of preceding flights
3. Right engine thrust increments for flight conditions and engine EPR values recorded after the right engine rapid EPR reduction at about 400 feet above ground level (agl), based on photos, field notes, engine hardware evidence, and P&W engine thrust degradation models

P&W left and right engine simulation model results for each configuration described above (namely, baseline JT8D-9, plus AvAero hush kit, plus serialized engine deterioration, and plus right engine HPT and LPT turbine damage) are presented in Attachment 7. Detailed time history plots of engine model inputs and calculated engine parameters for the three left engine and four right engine configurations follow the tabulated results.

11.3. Uncertainty in Estimated Engine Thrust

P&W engineering indicated that the JT8D-9 engine modeled thrust uncertainty for percent delta net thrust at a constant EPR value of 2.0 is ± 0.9 percent (2 standard deviation confidence level, or 2s). This estimate accounts for system model calibration fidelity, engine-to-engine variation (i.e., hardware variation), and engine installation tolerance (i.e., jet nozzle and inlet recovery).

A ± 0.9 percent delta net thrust at a constant engine EPR of 2.0 would apply to both N810TA engines (prior to the right engine rapid EPR reduction) and to the left engine prior to the first step in the recorded EPR step-reduction sequence. Further, incremental in-service deterioration delta net thrust effects would be small/negligible for the low bypass ratio JT8D-9 engine running at constant EPR (the P&W JT8D engine control strategy is based on engine EPR as opposed to engine N1).

The group requested P&W engineering to quantify the left engine net thrust uncertainty at low engine EPR settings. The P&W response stated that the engine thrust uncertainty increases to ± 5 percent at idle (2s) which equates to about 50 pounds of net thrust for the event conditions. This idle net thrust uncertainty was estimated from JT8D production data minimum idle variation, which dominated relative to engineering model fidelity and installation tolerance factors.

The group made a similar request for P&W engineering to quantify the right engine net thrust uncertainty with the addition of model increments to account for the observed right engine HPT and LPT airfoil damage. P&W engineering staff indicated that the observed LPT damage introduced a net thrust uncertainty of ± 120 pounds or ± 2.4 percent (2s). When the damage estimate is root-sum-square (RSS) combined with the base uncertainty factors, the right engine total net thrust uncertainty (after the rapid EPR reduction event) is ± 2.6 percent (2s) at engine EPR settings near 1.4.

⁵ The P&W JT8D-9A engine model was unavailable so Pratt & Whitney and Boeing engineering staff used the JT8D-9 engine (closest available model) to support engine and integrated airplane modeling, validation, and simulation tasks.

11.4. Estimated Left and Right Engine Thrust Lever Angle

In response to an NTSB request, Boeing engineering staff estimated N810TA engine thrust lever angle (TLA) position during the accident flight based on the METAR outside air temperature (78.8°F) and FDR time-varying values of calibrated airspeed, pressure altitude, left engine pressure ratio, and right engine pressure ratio. These data and a standard atmosphere model were used to calculate Mach number (from pressure altitude and calibrated airspeed), total air temperature (TAT) from Mach number and METAR-reported surface temperature at HNL, and engine TLA (position estimated from engine EPR, atmospheric conditions, and engine control rigging data). Estimated engine TLA values for flight 810 were not incorporated in this study for the following reasons:

- 1) Calculated engine TLA values may vary somewhat over time (due to the TAT calculation method) when the actual flight 810 engine TLA likely remained constant (e.g., at the takeoff setting) prior to the right engine rapid EPR reduction.
- 2) The flight 810 calculated right engine TLA values become invalid after the rapid reduction in right engine EPR shortly after takeoff.
- 3) Calculated engine TLA values are unreliable near engine idle (i.e., TLA displacements below about 10°) due to a shallow slope in the TLA-EPR relationship at low power settings.

12. Estimated B737-200 ADV Low Speed Performance

The total engine thrust required to maintain level flight at the accident flight condition with gear up is indicated by the solid black lines in Figure 7. Total engine thrust is plotted as a function of airspeed for flaps Up (top half of the figure) and flaps 1 (bottom half of the figure). Total thrust required accounts for full engine inoperative drag, meaning windmill and yaw drag are calculated assuming one engine has failed. Airplane Flight Manual (AFM) one engine inoperative (OEI) maximum takeoff thrust and maximum continuous thrust are indicated by the respective regions bounded by solid blue lines. The airplane stick shaker, enroute climb, and recommended maneuver speeds in knots calibrated airspeed (KCAS) are summarized in Table 3 as a function of flap position (Up, 1, and 5) and annotated in Figure 7.

Table 3: B737-200 ADV Speed Schedules (KCAS), 93,000 lb, Gear Up

	Flaps Up	Flaps 1	Flaps 5
Recommended Maneuver Speed	210	190	170
Enroute Climb Speed	198	----	----
Stick Shaker Speed	159	129	122

The calculated total engine thrust during the latter portion of flight 810 based on FDR engine EPR, altitude, and airspeed is depicted by the red square symbols in Figure 7. The N810TA “direction” of travel is clockwise along the numbered red square sequence, from higher to lower engine thrust values (points 5 to 8), followed by a progressive airspeed decrease as total engine thrust increases (points 8 to 11).

The data in Figure 7 indicate that N810TA had adequate total engine thrust to maintain altitude or climb for the initial portion of the flight depicted, though total engine thrust decreased below OEI maximum continuous thrust. However, as total engine thrust progressively decreased, N810TA transitioned to and remained at a low energy state (i.e., low total engine thrust, low airspeed, and low altitude) that was inadequate for the aircraft to climb or maintain altitude without additional engine thrust. Calculated rate of climb data in Figure 8 illustrate the aircraft transition from positive climb capability to inability to maintain altitude (see points 6 and 7 in each subplot). The points annotated 5 to 11 correspond to the P&W engine events tabulated in Attachments 7 and 8.

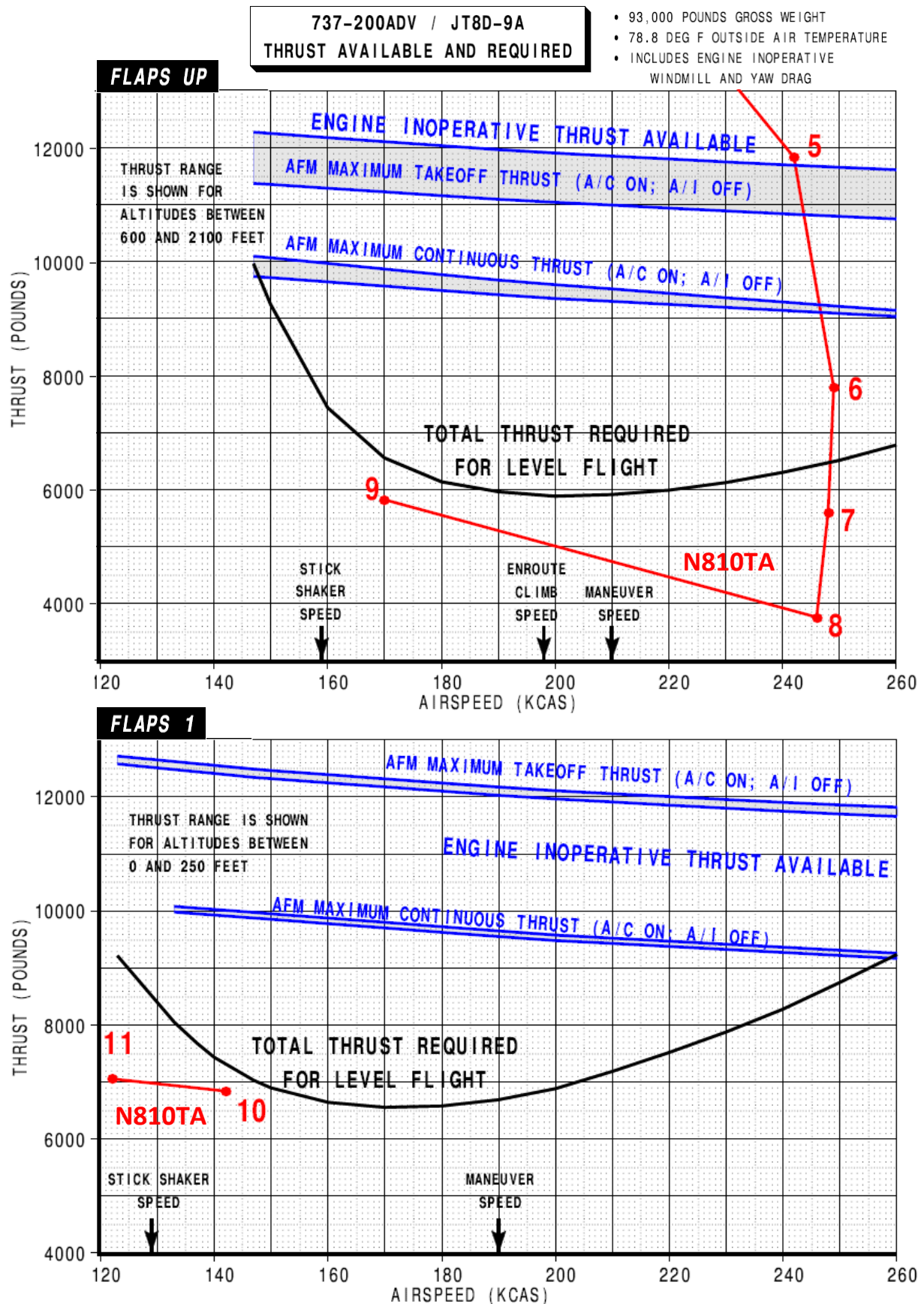


Figure 7: B737-200 ADV thrust as a function of airspeed, 93,000 lb, gear up, pressure alt. as noted, 78.8°F. N810TA points 5-9 are flaps Up; points 10-11 are flaps 1. A/C ON means air conditioning on, A/I OFF means anti-ice off.

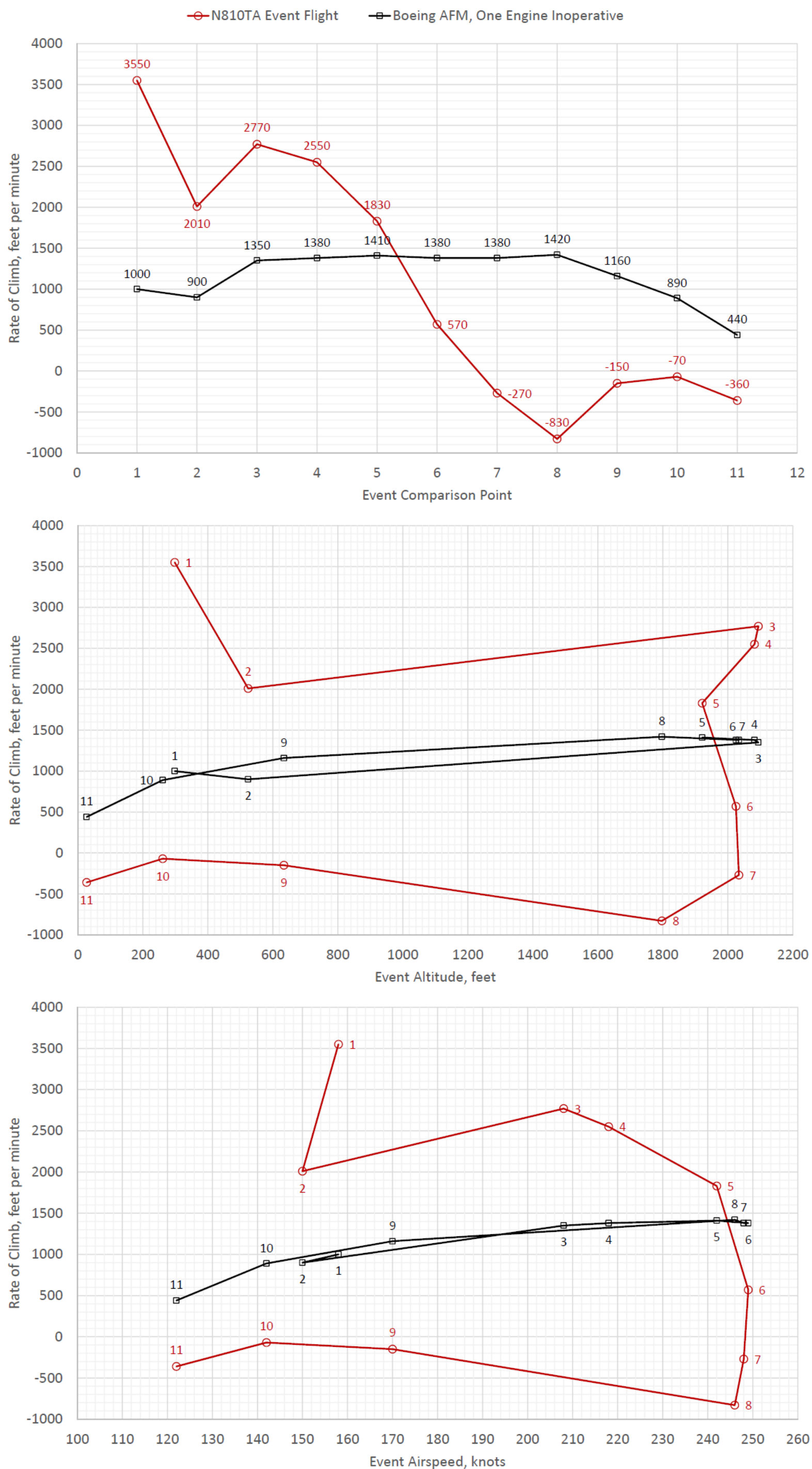


Figure 8: B737-200 ADV with JT8D-9 engines, AFM-based rate of climb for OEI (black line) and Transair flight 810 event (red line) as a function of P&W engine event items 1-11 (top), pressure altitude (middle), and airspeed (bottom).

Boeing engineering staff calculated baseline AFM takeoff and climb performance for the 737-200 ADV with JT8D-9 engines and tabulated expected one engine inoperative (OEI) and N810TA demonstrated climb/descent gradients in percent grade and rate of climb in feet per minute. The expected OEI and demonstrated flight 810 results are tabulated in Attachment 8. These data assume landing gear retracted, unaccelerated flight, neutral control wheel, and that the engine inoperative thrust asymmetry is trimmed with rudder.

NTSB and Boeing engineering staff performed independent consistency checks of recorded FDR longitudinal acceleration, indicated (computed) airspeed, engine EPR, and flap configuration parameters during the takeoff ground roll. NTSB staff used aircraft takeoff weight and FDR longitudinal acceleration (corrected for pitch attitude) with Boeing Low Speed Performance System (LSPS) parameters (engine thrust, aerodynamic lift, and aerodynamic drag, all as a function of airspeed) to calculate the equivalent airplane friction coefficient at the wheel/runway interface.

Boeing engineering staff modeled the N810TA ground roll acceleration during the accident flight takeoff assuming an unmodified 737-200 ADV with JT8D-9 engines and all engines operating. Boeing provided tabular data for calculated total engine thrust and an aggregated term to account for rolling friction coefficient, aerodynamic lift, and aerodynamic drag. The calculated performance was plotted and compared to the recorded takeoff data from the accident flight. Boeing and NTSB staff concurred that a +0.036 g bias to the FDR longitudinal acceleration was needed to match the expected, free rolling friction coefficient value of 0.0165 during the takeoff ground roll.

13. B737-200 ADV Integrated Airplane Simulation Model

During commercial airplane development and certification programs, The Boeing Company routinely collects airplane flight test data to build and validate engineering models that are used to support stability and control, handling qualities, performance, loads, systems, autoflight, flight crew training, and incident/accident investigation applications. Flight crew training simulator data packages are typically based on airplane engineering models validated by airplane flight test data, wind tunnel test data, and various analytical methods.

A key milestone in engineering simulator model validation is the development of the Proof-of-Match (POM) document, which compares calculated simulation results to available flight test data for specific flight test maneuvers at defined test conditions. For each maneuver type and condition selected to support the B737-200 ADV POM document, calculated engineering simulation tool results were quantitatively compared to corresponding flight test parameters using time history plots. In addition, tabulated data were used to record the initial conditions, trim setup, and (applicable) math pilot setup for each test condition. For certain parameters, the difference between the calculated simulation results and the flight test data at each time (or trim snapshot) must not exceed a specified numeric tolerance.

13.1. Boeing Kinematic Consistency and Wind Calculations

A kinematic consistency (KinCon) evaluation was conducted on the FDR and ADS-B data to correct potential inconsistencies in recorded data from different sensors due to instrumentation biases, misalignment in inertial measurements, contamination of static/total pressure measurements (e.g., induced by flow separation, blockage, icing), and sample rate differences. Integrated acceleration data are used to ensure basic inertial parameters such as altitude, ground speed, and drift angle are mathematically and physically compatible and comparable. The output is a kinematically consistent set of data that properly accounts for acceleration biases and enables calculations of angle of attack (AOA), sideslip angle, wind data, ground track information and other parameters.

Winds are calculated by taking the difference between body-axis inertial speeds and body-axis airspeeds and then rotating these components to the earth axis. This is a multi-step process that begins by using KinCon acceleration data and the Euler angles (bank angle, pitch attitude, and heading angle) to calculate the body-axis inertial speed components. The body-axis airspeed components are then calculated based on true airspeed, AOA, and sideslip angle, which are estimated using recorded aircraft data, meteorological data, and subsets of the airplane aerodynamics and flight controls models.

True airspeed is calculated from recorded airspeed, recorded pressure altitude, and static outside air temperature (11°C above standard day temperature for this event based on METAR weather reporting). Airplane body AOA for N810TA was calculated using an aerodynamics lift model extracted from the simulation (because vane AOA was not recorded). The sideslip angle was calculated based on recorded lateral acceleration, estimated rudder surface deflection (derived from adjusted rudder pedal deflection and the nominal simulation pedal deflection/rudder deflection relationship), calculated control wheel deflection (derived from recorded left aileron and the simulation nominal control wheel deflection/left aileron deflection relationship), and airplane configuration information (load manifest, flap, gear). Body-axis wind speed components are then determined by differencing the body-axis inertial speeds and the body-axis airspeeds. The earth-axis horizontal and vertical winds are calculated from the derived body-axis wind components and the Euler angles. The calculated winds are invalid while the airplane is on ground due to the lack of ground interaction modeling.

The calculated horizontal wind speed and direction for the time segments evaluated varied between 10 and 30 knots and from 40 to 80 degrees, respectively. The calculated horizontal wind speeds in-air are higher than the METAR-reported wind speed, which is common because reported winds near the runway are typically lower than winds aloft. The calculated wind direction for this event is generally consistent with the METAR-reported wind direction.

13.2. Accident Flight Simulation

Transair flight 810 airplane simulation work was accomplished on an engineering workstation using the Boeing 737-200 ADV Parallel SIMulation (PSIM) engineering tool with a specified Integrated Airplane Configuration (IAC) and Pratt & Whitney JT8D-9 engines.⁶ In response to related group discussions, Boeing engineering staff reconstructed the following segments of the accident flight:

1. Takeoff ground roll and initial climb
2. Right engine rapid EPR reduction, climb and level off
3. Left engine EPR step-reduction sequence
4. In-air turn
5. Deceleration, flaps Up
6. Deceleration, flaps 1

Based on the paraphrased CVR transcript content, the nose gear retraction complete event occurred shortly after takeoff at a time value equated to Boeing FDR time 9,477.65 seconds. Boeing flight test data indicated that the normal nose gear retraction time is 1.0 seconds from the start of gear handle movement to the start of gear movement, 4.5 seconds of actual nose gear retraction time, and 1.0 seconds for uplock and flight deck indication.

⁶ The Boeing PSIM engineering tool supports both workstation simulation and pilot in-the-loop simulator needs for Boeing Commercial Airplane products. The PSIM integrated airplane simulation models consist of a six degree-of-freedom, nonlinear simulation with mathematical models for the airplane aerodynamics, propulsion, flight controls, autoflight systems, landing gear, hydraulic systems, mass properties, and the environment. The simulation models are updated and validated with flight test data and used to develop flight crew training simulator data packages.

The start time of the flap retraction event shortly after takeoff was equated to Boeing FDR time 9,506.65 seconds, based on the paraphrased CVR transcript. Flaps 5 was assumed for takeoff per the load manifest. The flaps were assumed retracted from flaps 5 to flaps Up based on the paraphrased CVR transcript content. Boeing flight test data indicate that the normal flap retraction time from flaps 5 to flaps Up is 21.7 seconds.

A summary of the accident flight event sequence is presented in Table 4. Complementary Boeing 737-200 ADV simulation match results are provided in Table 5. Supporting Boeing engineering staff discussion and plots are included in Attachment 9. The NTSB accepted the Boeing PSIM simulation results documented herein as the basis for Transair flight 810 desktop simulation work, pending completion of requested simulation model validation work.

13.3. Boeing 737-200 ADV Simulation Model Limitations

In general, airplane simulation limitations are defined by an angle of attack and sideslip angle envelope based on data gathered from flight tests, wind tunnel tests, analytical methods, and extrapolation. Engineering confidence in the simulation envelope varies by data source from high (for flight validated data for a variety of test and flight conditions) to medium (for wind tunnel or analytical methods) to low (for extrapolated data). The 737-200 ADV simulation envelopes for flaps up and flaps down flight in free air are intended to model the normal operating envelope (takeoff, climb, maneuvering, cruise, descent, landing, limited approach to stall, and limited unusual attitude recovery) as opposed to wing stall, tail stall, stall recovery, and/or other unusual angle of attack, sideslip angle, engine power, control input, ground effect, or ground contact/interaction conditions.

13.4. Model Validation

The NTSB has requested Boeing engineering staff to demonstrate that the current Boeing 737-200 ADV integrated airplane, engine, and flight controls simulation models used to support the N810TA investigation are capable of reconstructing previously documented simulation checkout cases that reflect relevant airplane configurations, engine configurations, and/or flight conditions. Boeing staff have accepted the task and ongoing work is planned to be documented as an addendum to the NTSB Aircraft Performance Group Study. The following airplane and/or engine configurations and flight conditions have been selected for this task:

1. Normal takeoff
2. Gear retraction
3. Flap retraction
4. Flap deployment
5. Engine power reduction
6. Engine power increase
7. One engine inoperative (straight, level, thrust asymmetry/rudder balance)
8. One engine inoperative turn
9. Decelerated flight (in-air, approach to stick shaker)

Maneuvers relevant to the investigation of Transair flight 810 will be modeled using the PSIM B737-200 ADV airplane simulation model with a specified IAC and Pratt & Whitney JT8D-9 engines. The maneuvers listed above reflect airplane operations within the normal operating envelope. Maneuvers that require approach to stall, full stall, very high sideslip angles, or very low speed, high angle of attack flight in ground effect or free air are beyond the scope of this task.

Table 4: Data-Driven Summary of Transair Flight 810 Events (based on FDR and ADS-B data)

Boeing Time	NTSB Time	Description	Comp. Airspeed	Press. Altitude	L. Engine EPR	R. Engine EPR	Bank Angle	Pitch Attitude	Magnetic Heading	Control Column	Calculated Wheel	Adjusted Pedal	GrndSpd ADS-B	GrndTrk ADS-B	Climb Rate ADS-B	Latitude ADS-B	Longitude ADS-B
seconds	seconds		knots	feet	nondim	nondim	degrees	degrees	degrees	degrees	degrees	degrees	knots	degrees	fpm	degrees	degrees
9433	41588.33	Initial thrust application for takeoff	---	-71	1.05	1.07	0.4	-1.3	80.6	-0.6	5.8	5.8	---	---	---	21.3068	-157.94525
9446	41601.33	Takeoff thrust	---	-70	1.99	1.95	0.4	-1.3	79.7	-0.5	5.3	0.9	---	---	---	21.30678	-157.94394
9461	41616.33	Takeoff rotation	122	-68	2.01	1.95	0.0	-0.9	80.0	-0.5	4.0	-0.4	---	---	---	21.30682	-157.93834
9467	41622.33	Estimated liftoff	143	-82	2.00	1.94	0.9	6.7	79.7	2.8	-8.3	-0.8	---	---	423.2	21.30678	-157.93473
9481.2	41636.53	Right engine rapid EPR reduction, positive climb rate	155	390	1.97	1.45	-0.9	18.6	78.0	-0.3	-28.7	-1.2	142.2	92.8	2801.3	21.3064	-157.92398
9482.2	41637.53	Assumed left rudder pedal deflection, positive climb rate	154	449	1.97	1.43	2.7	17.4	79.3	-0.3	-33.8	-3.6	141.2	92.8	2952.8	21.30637	-157.92323
9497	41652.33	Airplane begins to level off near 1,000 feet	141	978	1.97	1.44	-1.3	9.3	81.7	-1.0	0.0	-3.9	133.5	95.2	976.9	21.30564	-157.91394
9515	41670.33	Airplane accelerating, banks right	174	1012	1.91	1.43	14.5	4.9	109.7	0.4	8.3	-3.7	172.5	120.3	253.7	21.30206	-157.90104
9520	41675.33	Airspeed and pitch angle increase	187	1002	1.90	1.42	13.6	9.3	115.1	0.2	2.7	-3.6	184.8	127.3	247.1	21.29959	-157.89733
9555	41710.33	Airspeed increasing, airplane climbing toward 2,000 feet	208	1921	1.92	1.42	14.5	11.5	155.8	0.1	18.3	-3.5	218.4	173.4	1822.0	21.27028	-157.88162
9558	41713.33	Altitude 2,000 feet, less left rudder pedal	208	2017	1.92	1.42	16.9	10.6	159.7	-0.6	15.7	-2.6	220.4	176.6	1396.6	21.26728	-157.88143
9576	41731.33	Increased airspeed, left engine EPR reduction, pitch decrease	242	1944	1.53	1.40	11.1	4.5	185.8	-0.7	-7.1	-2.8	264.4	199.0	-571.0	21.24724	-157.88512
9580	41735.33	245+ knots, 1,900 feet, less left rudder pedal	249	1893	1.53	1.40	14.5	6.2	189.1	-1.1	20.0	-1.1	272.0	201.6	-159.2	21.24234	-157.88712
9610	41765.33	Left & right engine EPR reductions, pitch decrease	247	2082	1.05	1.35	16.1	6.7	209.6	-1.6	20.4	-1.6	279.5	220.4	240.9	21.20999	-157.9098
9614	41769.33	Peak altitude, left engine EPR 1.05 to end of flight	244	2124	1.05	1.35	13.6	4.9	212.6	-0.1	22.6	-1.7	277.4	222.7	82.2	21.20621	-157.91351
9615	41770.33	Maintained 245 knots, 1900 to 2100 feet over last 40 seconds	244	2118	1.05	1.34	13.2	4.9	213.7	-0.3	14.8	-1.5	276.6	223.1	82.1	21.20518	-157.91454
9634	41789.33	Right engine EPR reduction, end right bank, return to wings level	245	1847	1.05	1.18	0.0	4.5	217.1	-1.0	23.0	-1.5	280.8	226.6	-661.5	21.18812	-157.9336
9635	41790.33	Begin airspeed & altitude decrease	245	1843	1.05	1.18	0.4	4.5	216.5	-1.0	19.2	-1.4	280.1	226.4	-823.6	21.18718	-157.93456
9679	41834.33	Right engine EPR reduction, left control wheel, neutral pedal	224	1684	1.05	1.10	2.7	4.5	241.7	-0.4	-6.6	-0.5	258.3	248.9	0.0	21.15864	-157.98458
9680	41835.33	220+ knots, 1,680 feet, aft control column	222	1679	1.05	1.10	0.4	4.5	241.8	0.6	-5.3	-0.3	258.3	248.9	82.2	21.15823	-157.98574
9700	41855.33	Pitch angle increase, climb 200 feet, 20+ knot decrease	198	1870	1.05	1.11	1.3	7.1	242.5	-0.1	-2.7	-0.3	234.4	249.8	395.9	21.15042	-158.00792
9710	41865.33	Airspeed decrease, slow right engine EPR increase trend	191	1878	1.05	1.12	-1.3	8.0	242.0	-0.1	1.4	-0.4	227.8	250.0	82.0	21.14664	-158.01915
9720	41875.33	Small left bank angle and left heading change	183	1916	1.05	1.12	-2.2	7.6	239.1	0.3	3.2	0.5	217.6	248.1	-82.8	21.14306	-158.02904
9725	41880.33	180+ knots, 1,900 feet, aft column 1 to 3 deg. to end of flight	182	1896	1.05	1.13	-1.8	6.2	237.0	1.6	2.3	-0.3	215.1	247.0	-332.9	21.141	-158.03425
9727	41882.33	Slow right engine EPR increase trend	182	1872	1.05	1.14	-2.7	6.7	236.4	1.3	1.9	-0.4	215.0	246.4	-412.2	21.14012	-158.03629
9751	41906.33	Right engine EPR increase, right control wheel, pedal, & bank angle	175	1723	1.05	1.20	15.7	11.1	241.0	1.3	20.4	0.6	209.3	247.2	164.0	21.12961	-158.05841
9752	41907.33	Reduced right control wheel deflection	174	1732	1.05	1.20	16.1	10.2	242.0	0.9	7.9	0.6	208.4	248.6	81.5	21.12926	-158.05929
9753	41908.33	Reduced right control wheel deflection	173	1742	1.05	1.20	16.1	9.3	243.3	1.6	1.9	0.6	207.5	250.0	243.8	21.12894	-158.06035
9754	41909.33	170+ knots, 1,750 feet, heading 244 deg.	172	1751	1.05	1.20	14.0	9.3	244.3	1.8	1.9	0.6	205.9	251.3	327.7	21.12862	-158.06131
9758	41913.33	Left control wheel deflection, reduced right bank angle	168	1771	1.05	1.21	5.4	9.8	248.3	2.2	-12.2	0.6	203.0	254.9	330.7	21.12763	-158.0653
9760	41915.33	Slow airspeed decrease, neutral control wheel deflection	167	1781	1.05	1.21	1.8	10.2	248.3	2.0	0.0	-0.4	201.8	256.2	327.8	21.12716	-158.06723
9768	41923.33	160+ knots, 1,750+ feet, left bank angle, left heading change	161	1795	1.05	1.21	-10.2	8.9	241.2	1.7	4.5	-0.4	194.8	254.8	-411.1	21.12534	-158.07498
9770	41925.33	Right control wheel deflection 20 to 30 deg.	161	1781	1.05	1.21	-12.8	6.7	238.4	1.2	21.3	0.6	194.5	253.0	-501.9	21.12473	-158.07678
9795	41950.33	Airspeed increase, altitude decrease, 20+ deg. right bank angle	172	1423	1.05	1.24	19.8	9.3	242.7	1.7	22.2	0.6	204.3	248.5	-162.6	21.11504	-158.09875
9797	41952.33	170+ knots, 1,400+ feet, progressive right turn	171	1424	1.05	1.21	21.7	7.6	247.5	3.3	31.7	0.6	203.4	249.9	-80.7	21.11446	-158.10058
9805	41960.33	Near constant speed and altitude right turn, passing through 267 deg.	168	1395	1.05	1.21	23.3	6.2	267.0	1.9	11.4	-0.5	199.3	267.1	-488.4	21.1133	-158.1085
9825	41980.33	Bank angle decrease to 10+ deg., aft column, altitude decrease	174	1119	1.05	1.22	11.5	8.4	299.4	1.7	5.3	0.6	197.8	302.4	-242.7	21.11896	-158.12712
9845	42000.33	1,100+ feet, right turn through 317 deg., airspeed decrease to 157 knots	158	1165	1.05	1.19	10.2	8.4	317.1	2.4	20.0	-0.3	177.2	319.1	-253.4	21.13081	-158.14113
9846	42001.33	Maintain 10+ deg. right turn	157	1159	1.06	1.19	11.1	8.0	318.2	2.3	22.6	0.7	176.1	320.1	-341.7	21.13145	-158.14169
9870	42025.33	Right engine EPR & airspeed increase, altitude decreased to 700 ft	171	719	1.05	1.35	10.2	7.1	343.2	2.1	24.3	0.5	174.9	345.1	-1074.4	21.14823	-158.1503
9930	42085.33	165 knots, 450+ feet, continuing shallow right turn through 35 deg.	165	487	1.05	1.36	9.3	9.3	34.7	2.0	22.2	0.5	150.7	43.1	-246.6	21.18964	-158.13884
9950	42105.33	160 knots, wings level	160	469	1.05	1.36	0.0	9.3	40.0	2.8	22.6	0.5	144.7	49.5	-82.4	21.19836	-158.1283
10060	42215.33	Airspeed and altitude decrease, right engine EPR increase to 1.47	137	252	1.05	1.47	8.4	10.6	46.9	1.7	20.4	1.0	125.1	55.4	0.0	21.24674	-158.07363
10080	42235.33	140 knots, 140+ feet, continuing right turn to 60 deg.	140	147	1.05	1.46	3.1	11.5	60.2	2.1	13.5	1.1	126.2	72.0	-158.2	21.25144	-158.06234
10090	42245.33	Right pedal deflection near 1 deg. since right engine EPR increase to 1.47	137	144	1.05	1.46	1.8	12.3	60.3	2.3	14.4	1.1	124.9	72.3	-79.6	21.25309	-158.05665
10099	42254.33	Near wings level, 14+ deg. pitch attitude, near constant heading	136	147	1.05	1.46	-1.8	14.9	57.9	2.0	27.4	1.2	123.6	71.1	163.7	21.25479	-158.05127
10100	42255.33	135+ knots, 140+ feet, right control wheel, right pedal	136	147	1.05	1.46	0.4	14.5	56.9	2.5	24.3	1.0	122.7	71.0	162.1	21.25498	-158.05071
10009	42264.33	Airspeed decrease with altitude increase	128	191	1.05	1.46	4.9	11.9	57.3	2.7	14.8	1.1	114.8	67.5	82.9	21.25689	-158.04567
10110	42265.33	Right control wheel and right pedal deflections maintained	130	186	1.05	1.46	3.6	12.3	57.5	2.6	18.7	1.2	114.8	67.5	-82.7	21.25704	-158.04522
10145	42300.33	130+ knots, airplane descent near 0 pressure altitude,	132	-11	1.05	1.46	-8.0	15.7	23.2	3.2	28.7	1.7	120.1	34.5	79.4	21.26777	-158.02891
10161	42316.33	Estimated water impact	123	14	1.05	1.46	-14.9	12.3	6.1	2.0	87.0	5.2	114.6	9.5	-764.1	21.27616	-158.02565

+Column = airplane nose up, +Wheel = right wing down, +Pedal = airplane nose right, +Pitch = airplane nose up, +Bank = right wing down, Magnetic heading increase = airplane nose right or airplane turning right

Table 5: Summary of Boeing 737-200 ADV Simulation Setup and Quality of Match for 6 Event Flight Segments

Case	Description	Flaps	Landing Gear	Boeing Time (seconds)	Attachment 9, Figure, Parameters	Altitude	Airspeed	Longitudinal Acceleration	Normal Load Factor	Lateral Acceleration	Horizontal Stabilizer	Control Column	Control Wheel	Rudder Pedal	Engine EPR Bias Relative to FDR Engine EPR	Vertical Wind Speed	Horizontal Wind Speed	Horizontal Wind Direction
1	Takeoff ground roll & initial climb	5	Deployed, initiate retraction at 9,472.15	9,425 to 9,525	7A, Longitudinal 7B, Lateral/Directional 7C, Engine	Sim matches FDR	Sim matches FDR	Sim matches KinCon	Sim matches KinCon	Constant, no integration for lateral/directional	Load Manifest	Math pilot targets pitch attitude & rate, pressure alt., comp. airspeed	Calculated from FDR aileron & Sim model	Calculated from adjusted FDR pedal & Sim model	-0.02 L -0.02 R	Set to 0	Average of KinCon in-air horizontal wind speed	Average of KinCon in-air horizontal wind direction
Sim rotation and pitch attitude slightly lag FDR data. Sim control column and elevator magnitudes at rotation higher than corresponding FDR data. Sim assumes zero bank angle and constant (runway) heading. Left and right engine Sim thrust each about 500 pounds less than respective P&W engine model.																		
2	Right Engine EPR decrease	5 to Up	Retracted	9,470 to 9,570	8A, Longitudinal 8B, Lateral/Directional 8C, Engine	Sim matches FDR	Sim matches FDR	Sim matches KinCon	Sim matches KinCon	Sim matches KinCon & FDR	In-air trim, held constant to align Sim to FDR column	Math pilot targets pitch attitude & rate, pressure alt., comp. airspeed	Math pilot targets bank angle & roll rate	Constant, 0.85° right	0.00 L 0.00 R	KinCon in-air vertical wind speed	KinCon in-air horizontal wind speed	KinCon in-air horizontal wind direction
Airplane climbing through 300 feet on constant heading for 20+ seconds followed by in-air right turn. Right engine EPR step-reduction followed by left rudder step-input yielded constant airplane heading. Good match between Sim and FDR values for control column, elevator, and aileron, and between Sim and KinCon values for body angle of attack. Left engine Sim thrust is about 400 pounds lower and right engine Sim thrust is about 400 pounds higher than respective P&W engine model.																		
3	Left Engine EPR decrease	Up	Retracted	9,565 to 9,665	9A, Longitudinal 9B, Lateral/Directional 9C, Engine	Sim matches FDR	Sim matches FDR	Sim matches KinCon	Sim matches KinCon	More left lateral accel. in Sim than KinCon & FDR	In-air trim, held constant to align Sim to FDR column	Math pilot targets pitch attitude & rate, pressure alt., comp. airspeed	Math pilot targets bank angle & roll rate	Constant, 0.7° right	0.05 L 0.05 R	KinCon in-air vertical wind speed	KinCon in-air horizontal wind speed	KinCon in-air horizontal wind direction
Left engine EPR reduction in 4 sequential steps over about 30 seconds with 1 step-reduction in left pedal, as bank angle varied between wings level and 25° right wing down (RWD) and heading increased from 190 to 250°. Good match between Sim and FDR values for column and elevator and between Sim and KinCon body angle of attack. Sim control wheel generally aligns with wheel derived from FDR aileron. Left engine Sim thrust is about 200 to 400 pounds higher and right engine Sim thrust is about 800 pounds higher than respective P&W engine model.																		
4	In-air turn	Up	Retracted	9,700 to 9,800	10A, Longitudinal 10B, Lateral/Directional 10C, Engine	Sim matches FDR	Sim matches FDR	Sim matches KinCon	Sim matches KinCon	Sim match bounded by KinCon & FDR values	In-air trim, held constant to align Sim to FDR column	Math pilot targets pitch attitude & rate, pressure alt., comp. airspeed	Math pilot targets bank angle & roll rate	Constant, 0.5° right	-0.02 L -0.02 R	KinCon in-air vertical wind speed	KinCon in-air horizontal wind speed	KinCon in-air horizontal wind direction
In-air right turn from heading of 240 to 260° followed by left turn to 240° over a period of about 45 seconds as bank angle varied from wings level to 16° right wing down (RWD) to 13° left wing down and then back to wings level. Good match between Sim and FDR values for control column, elevator, and aileron and between Sim and KinCon body angle of attack. Sim control wheel matches wheel derived from FDR aileron. Left engine Sim thrust is about 250 pounds lower than the P&W engine model. Right engine Sim thrust is close to the P&W engine model.																		
5	Deceleration, flaps Up	Up	Retracted	9,800 to 9,900	11A, Longitudinal 11B, Lateral/Directional 11C, Engine	Sim matches FDR	Sim matches FDR	Sim matches KinCon	Sim matches KinCon	Sim matches KinCon	In-air trim, held constant to align Sim to FDR column	Math pilot targets pitch attitude & rate, pressure alt., comp. airspeed	Math pilot targets bank angle & roll rate	Constant, 0.6° right	0.03 L 0.03 R	KinCon in-air vertical wind speed	KinCon in-air horizontal wind speed	KinCon in-air horizontal wind direction
Airplane decelerates from 175 to 158 knots at altitude near 1,100 feet followed by ~0.02 increase in right engine EPR and altitude descent. Good match between Sim and FDR values for column and elevator. Sim body angle of attack is 0.5 to 1° higher than KinCon value. Sim body angle of attack exceeds flaps Up stick shaker threshold (11°) several times. Sim control wheel generally aligns with wheel derived from FDR aileron. Left engine Sim thrust is about 250 pounds higher and right engine Sim thrust is about 600 pounds higher than respective P&W engine model.																		
6	Deceleration, flaps 1	1	Retracted	10,070 to 10,170	12A, Longitudinal 12B, Lateral/Directional 12C, Engine	Sim matches FDR	Sim matches FDR	Sim matches KinCon	Sim matches KinCon	Sim matches KinCon	In-air trim, held constant to align Sim to FDR column	Math pilot targets pitch attitude & rate, pressure alt., comp. airspeed	Math pilot targets bank angle & roll rate	Constant, 1.0° right	-0.03 L -0.03 R	KinCon in-air vertical wind speed	KinCon in-air horizontal wind speed	KinCon in-air horizontal wind direction
Airplane decelerates from 135 to 127 knots at altitude near 150 feet followed by no increase in either engine EPR and altitude descent. Good match between Sim and FDR values for column and elevator. Sim body angle of attack is 1° higher than KinCon value. Sim body angle of attack exceeds flaps 1 stick shaker threshold (15.6°) several times. Sim control wheel generally aligns with wheel derived from FDR aileron. Left engine Sim thrust is about 500 pounds lower and right engine Sim thrust is 100 pounds higher than respective P&W engine model.																		

- Notes:
1. FDR control wheel and rudder surface position data determined to be unreliable. FDR pedal data rescaled to operational limits.

2. For all cases, calculated (simulation) pitch attitude, bank angle, and heading reasonably match the comparable time-varying FDR parameters.

3. For all cases, calculated (simulation) airplane groundspeed and rate of climb reasonably match the comparable time-varying ADS-B parameters.

4. For all cases, Sim control surface positions for elevator, aileron/roll spoiler, and rudder were determined from the respective longitudinal (column), lateral (wheel), and directional (pedal) flight control models.

E. CONCLUSIONS

Based on aerodynamic and engine performance data used to develop the Airplane Flight Manual (AFM), the B737-200 ADV with P&W JT8D-9 engines has adequate performance capability with one engine inoperative to climb or maintain altitude for the accident airplane loading and flight conditions.

Subsequent to the right engine rapid EPR reduction shortly after takeoff, with no change to the left engine EPR, the accident airplane demonstrated the ability to climb to 1,000 feet, accelerate, climb to 2,000 feet, and maintain altitude. When the left engine EPR was reduced and remained below 1.2, the total airplane engine thrust was less than the thrust required for the airplane to maintain altitude over the recorded range of flight conditions, flight control inputs, left and right engine EPR values, and flap configurations encountered.

Based on Boeing 737-200 ADV and P&W JT8D-9 engineering simulation models, the accident aircraft motion, in response to flight control inputs, configuration changes, and engine EPR changes, was generally consistent with the behavior of the nominal B737-200 ADV integrated airplane/engine/flight controls simulation model and the P&W calculated engine thrust profile for each engine. Pratt & Whitney engine models accounted for the installed AvAero hush kit and in-service deterioration for each engine, as well as the estimated engine thrust degradation due to the observed right engine HPT and LPT damage.

ATTACHMENTS

The study text is complemented by nine (9) attachments that are packaged together in a separate file on the NTSB public docket. The extensive P&W engine thrust modeling work is summarized in Attachment 7. Boeing engineering low speed performance work is tabulated in Attachment 8. The Boeing 737-200 ADV integrated airplane/engine/flight controls simulation study and low speed performance products are incorporated in full in Attachment 9.

Attachment 1: B737-200 ADV Three-View Drawing

Attachment 2: Airport Diagram (HNL)

Attachment 3: Weight and Balance Data (N810TA)

Attachment 4: Cockpit Voice Recorder (CVR) Events (Paraphrased)

Attachment 5: Flight Data Recorder (FDR) Data

Attachment 6: Enhanced Ground Proximity Warning System (EGPWS) Data

Attachment 7: Pratt & Whitney JT8D-9 Engine Model Data

Attachment 8: B737-200 ADV Climb Performance

Attachment 9: Boeing 737-200 ADV Simulation Study

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