

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



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AIRCRAFT PERFORMANCE GROUP STUDY

June 15, 2023

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A. ACCIDENT

Location: Farmington, Connecticut
Date: September 2, 2021
Time: 0951 Eastern Daylight Time (EDT)
1351 Coordinated Universal Time (UTC)
Airplane: Cessna Citation XLS+, N560AR, line number 560XL-6026

B. AIRCRAFT PERFORMANCE GROUP

Chairman: Kevin J. Renze
Vehicle Performance
National Transportation Safety Board (NTSB)
Washington, DC

Members: Dan Morris (now retired) Scott Griffin
Sr. Mgr. Flight Test/Chief Pilot Performance Sr. Engineering Specialist
Textron Inc. Textron Inc.
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Todd Gentry
Aviation Safety Investigator & Chief Pilot
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Washington, DC

C. SUMMARY

On September 2, 2021, at 0951 eastern daylight time, a Cessna Citation 560XLS+ airplane, N560AR, was destroyed when it was involved in an accident during takeoff from Robertson Field Airport (4B8), Plainville, Connecticut, runway 2. The two pilots and two passengers onboard were fatally injured. One person on the ground sustained serious injuries and three people sustained minor injuries. The airplane was operated as a Title 14 *Code of Federal Regulations* Part 91 personal flight from Plainville, Connecticut to Dare County Regional Airport (MQI), Manteo, North Carolina.

1. Introduction

The accident airplane was equipped with a Flight Data Recorder (FDR) and a Cockpit Voice Recorder (CVR) that were collected and processed by NTSB specialists. Witness marks on the departure runway and along portions of the flight path were documented by laser scanner and aerial drone survey. Video surveillance camera footage from four (4) sources that documented the accident flight was collected and processed. Other NTSB groups or specialists collected additional factual evidence including airplane impact evidence, wreckage location, structures, engines, systems, weather, flight dispatch paperwork, fuel and cargo records, crew operating manuals, airplane performance data, airframe and engine maintenance records, and witness statements.

An NTSB aircraft performance group was convened in February 2022 and staffed by subject matter experts from Textron (flight test engineering and operations), the Federal Aviation Administration (operations), and NTSB (vehicle performance). Textron Aviation (TXTAV) hosted the group in Wichita, Kansas on May 18-19, 2022. A periodic, 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, parametric, and video data, 3) calculated airplane performance capability, 4) preparation of data required to support engine model and airplane model simulation, and 5) calculation of the primary longitudinal forces and moments on the airplane during the takeoff ground roll.

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

The objectives of the study were to 1) quantify the expected airplane takeoff field length required, 2) calculate and compare the equivalent retarding force at the wheel/runway interface during the takeoff ground roll for the accident flight and several preceding flights, 3) estimate the required airplane nose up pitching moment increment required to rotate the airplane nose up during the accident flight, and 4) reconstruct the accident flight ground track.

3. Summary of Results

Based on Airplane Flight Manual (AFM) takeoff performance data and Textron Aviation takeoff performance models, N560AR had adequate performance capability to takeoff from Robertson Field Airport (4B8) for the documented airplane flaps configuration, engine thrust setting, loading, flight conditions, and field length. However, Cessna Citation 560XLS+ aerodynamics and engine thrust models indicate that during the takeoff roll the accident flight encountered an unexpected decrease in longitudinal acceleration and an unexpected increase in the equivalent retarding force at the wheel/runway interface. N560AR did not rotate airplane nose up as expected in response to elevator airplane nose up flight control inputs, at or beyond the target rotation speed, until after the airplane departed the improved runway surface and encountered a terrain elevation step-down. The unexpected equivalent retarding force at the wheel/runway interface during the takeoff roll reduced the airplane acceleration and introduced an unexpected airplane nose down pitching moment increment, which prevented the airplane from pitching airplane nose up, increasing the wing angle of attack, lifting off, and establishing the positive climb rate needed for obstacle clearance within the takeoff distance available.

D. DETAILS OF THE INVESTIGATION

1. Method

This aircraft performance study provides data-driven, quantified assessments of expected Cessna 560XLS+ takeoff performance capability and identifies factors that affected the observed N560AR takeoff performance. The study is based on available N560AR factual evidence and Cessna 560XLS+ aerodynamics and engine data that Cessna engineering and flight test/operations staff used to develop, test, and validate takeoff and stopping performance (and other engineering) models; construct the Aircraft Flight Manual (AFM); and certify the airplane. All of the Textron Aviation/Cessna foundational factual data and models used in this study predated the accident.

A review of the available FDR, CVR, and external surveillance camera factual evidence indicated that N560AR was able to accelerate to the rotation speed required for airplane liftoff. The airplane configuration and energy state during the takeoff ground roll are the focus of this study. The scope is primarily from airplane takeoff initiation to the position at which the airplane lifts off from and climbs to a height of 35 feet above runway 2 (accelerate-go scenario) or, in this case, departs from the improved pavement surface and the short, unpaved region at the departure end of runway 2.

2. Cessna Citation 560XLS+

The Cessna Citation 560XLS+ is a medium-size business jet powered by two Pratt & Whitney Canada PW545C medium bypass ratio, turbofan engines mounted on the aft fuselage. A three-view drawing of the Cessna 560XL is provided in Attachment 1.

3. Robertson Field (4B8) Runway 2/20

Robertson Field Airport (4B8) is located about 2 miles north of Plainville, Connecticut. Runway 2/20 was 3,665 feet long, 75 feet wide, constructed of ungrooved asphalt, and had non-precision markings. The runway 2 heading was 019° magnetic and 005° true, which equates to a magnetic variation of 14°W. The runway 2 approach end elevation was 188.6 feet and the departure end elevation was 201.6 feet, resulting in an average runway 2 upslope of 0.35 percent $[(201.6 - 188.6) / 3,665 = 0.0035]$. A 4B8 airport diagram and an aerial image are included in Attachment 2.

4. Meteorological Conditions

The hourly BDL Automated Surface Observing System (ASOS) data at the accident time were:

**[0951 EDT] METAR KBDL 021351Z 35012KT 10SM SCT027 SCT200 19/13 A2977
RMK AO2 SLP081 T01890128**

At 0951 EDT, the BDL ASOS reported a wind from 350° at 12 knots, visibility of 10 statute miles or greater, scattered clouds at 2,700 feet above ground level (agl) and 20,000 feet agl, temperature of 19° Celsius (C), dew point temperature of 13°C, and altimeter setting of 29.77 inches of mercury; Remarks included: automated station with a precipitation discriminator, sea level pressure of 1008.1 hectopascals (hPa), temperature of 18.9°C and dew point temperature of 12.8 °C.

Five-minute BDL ASOS data surrounding the accident time (highlighted in light gray color) [Source: https://mesonet.agron.iastate.edu/request/download.phtml?network=CT_ASOS]:

KBDL 021330Z AUTO 35010KT 10SM FEW018 BKN030 19/13 A2977 RMK T01900130
KBDL 021335Z AUTO 35014KT 10SM SCT022 19/13 A2977 RMK T01900130
KBDL 021340Z AUTO ///13KT 10SM SCT022 18/13 A2977 RMK T01800130
KBDL 021345Z AUTO 36011KT 10SM FEW024 19/13 A2977 RMK T01900130
KBDL 021350Z AUTO 35011KT 10SM SCT025 19/13 A2977 RMK T01900130
KBDL 021351Z 35012KT 10SM SCT027 SCT200 19/13 A2977 RMK AO2 SLP081 T01890128
KBDL 021355Z AUTO 36011G17KT 10SM FEW024 19/13 A2977 RMK T01900130
KBDL 021400Z AUTO ///13KT 10SM FEW024 19/13 A2977 RMK T01900130
KBDL 021405Z AUTO 35009KT 10SM FEW024 19/13 A2977 RMK T01900130
KBDL 021410Z AUTO 01011KT 10SM CLR 20/13 A2978 RMK T02000130
KBDL 021425Z AUTO ///11KT 10SM CLR 21/13 A2978 RMK T02100130
KBDL 021430Z AUTO ///11KT 10SM CLR 21/13 A2978 RMK T02100130

5. Video Surveillance Camera Evidence

Four (4) external video surveillance cameras recorded a portion of the accident flight. The video footage from each camera was separated into individual image frames and chronologically ordered. Image content pertinent to the investigation is documented in this study. The consecutive sequence of images was cropped, enlarged, and packaged in .pdf file format to simplify factual content reference and distribution. When image content was cropped or scaled, the original image aspect ratio was preserved. The resulting image sequence from each camera is provided in Attachments 3-8. Image content in the attachments is most easily viewed in full screen mode, using the arrow keys or mouse wheel to page forward or backward. A pictorial summary of the video camera evidence (camera view, aircraft position, time stamp) follows in Figures 1 through 7. Camera times shown have not been altered or aligned with FDR or CVR data.

Ground level visibility conditions appear to be clear on the video footage from all four cameras. The taxiway and runway pavement surface condition in the foreground of applicable images appears to be bare and dry.

"Airport" Camera (N560AR taxi segment), Attachment 3



Figure 1: Exemplar cropped and enlarged image sequence extracted from "Airport" surveillance camera recording. N560AR is taxiing toward the approach end of runway 2, moving left to right.

"Airport" Camera (N560AR takeoff ground roll segment), Attachment 4



Figure 2: Cropped and enlarged image sequence extracted from "Airport" surveillance camera recording. N560AR during takeoff roll toward the departure end of runway 2, moving right to left.

"Airport" Camera (N560AR near or beyond departure end of runway 2), Attachment 5



Figure 3: Cropped and enlarged image sequence extracted from "Airport" surveillance camera recording. N560AR (visible on left of each image) during takeoff near departure end of runway 2.

"Airport" Camera (N560AR near or beyond departure end of runway 2), Attachment 5



Figure 4: Cropped and enlarged image sequence extracted from "Airport" surveillance camera recording. N560AR (visible on left of each image) during takeoff beyond runway 2 departure end.

"Parking" Camera (N560AR in flight), Attachment 6



Figure 5: Cropped and enlarged image sequence extracted from "Parking" surveillance camera recording. N560AR is visible in the center of each image.

"Main Drive" Camera (N560AR in flight), Attachment 7



Figure 6: Cropped and enlarged image sequence extracted from "Main Drive" surveillance camera recording. N560AR is visible in the lower right of each image.

"Office Parking" Camera (N560AR ground contact evidence), Attachment 8



Figure 7: Cropped and enlarged image sequence extracted from "Office Parking" surveillance camera recording. Ground contact evidence is visible in the center of each image.

6. Weight & Balance

The accident flight weight and balance was documented by maintenance records for the N560AR empty weight, operational records for the crew, passenger, and baggage weights, and FDR data for the fuel loading. The aircraft basic empty weight as of September 29, 2017 was 12,649.6 pounds located at a moment arm of 334.24 inches. The accident flight loading was 2 flight crew members with flight bags ($195+215=410$ lb.), 2 passengers ($140+190=330$ lb.), passenger baggage ($25+25=50$ lb.), crew baggage ($20+20=40$ lb.), and 6,720 pounds of fuel ($3,360+3,360=6,720$ lb.). The N560AR itemized weight and balance reconstruction is shown in Table 1 based on the supporting factual evidence provided in Attachment 9.

The left seat pilot-in-command (PIC) weight is based on 175 lb. at last medical, 170 lb. per Medical Examiner, and an assumed 20 lb. flight bag. The right seat co-pilot weight is based on 195 lb. at last medical, 185 lb. per Medical Examiner, and an assumed 20 lb. flight bag.¹ Pilot and co-pilot luggage weights were 20 lb. each, located at 431.00 inches aft of datum. Fuel quantity for the accident flight was recorded by the FDR as 3,360 lb. in each wing tank (FuelQtyL=3,360, FuelQtyR=3,360) for a total fuel load of 6,720 lb. (from the time the recorder was powered on until the time of the accident). Resolution on the fuel quantity parameter is 32 lbs. According to the airplane Type Certificate Data Sheet (TCDS), page 21 of 37, each wing has a fuel tank volume of 505.8 gallons, with 503.0 gallons usable.

¹ Pilot and co-pilot flight bags were not identified in the wreckage. However, these items were included in the component weight and balance buildup used in this study.

Table 1: N560AR Weight and Balance Buildup

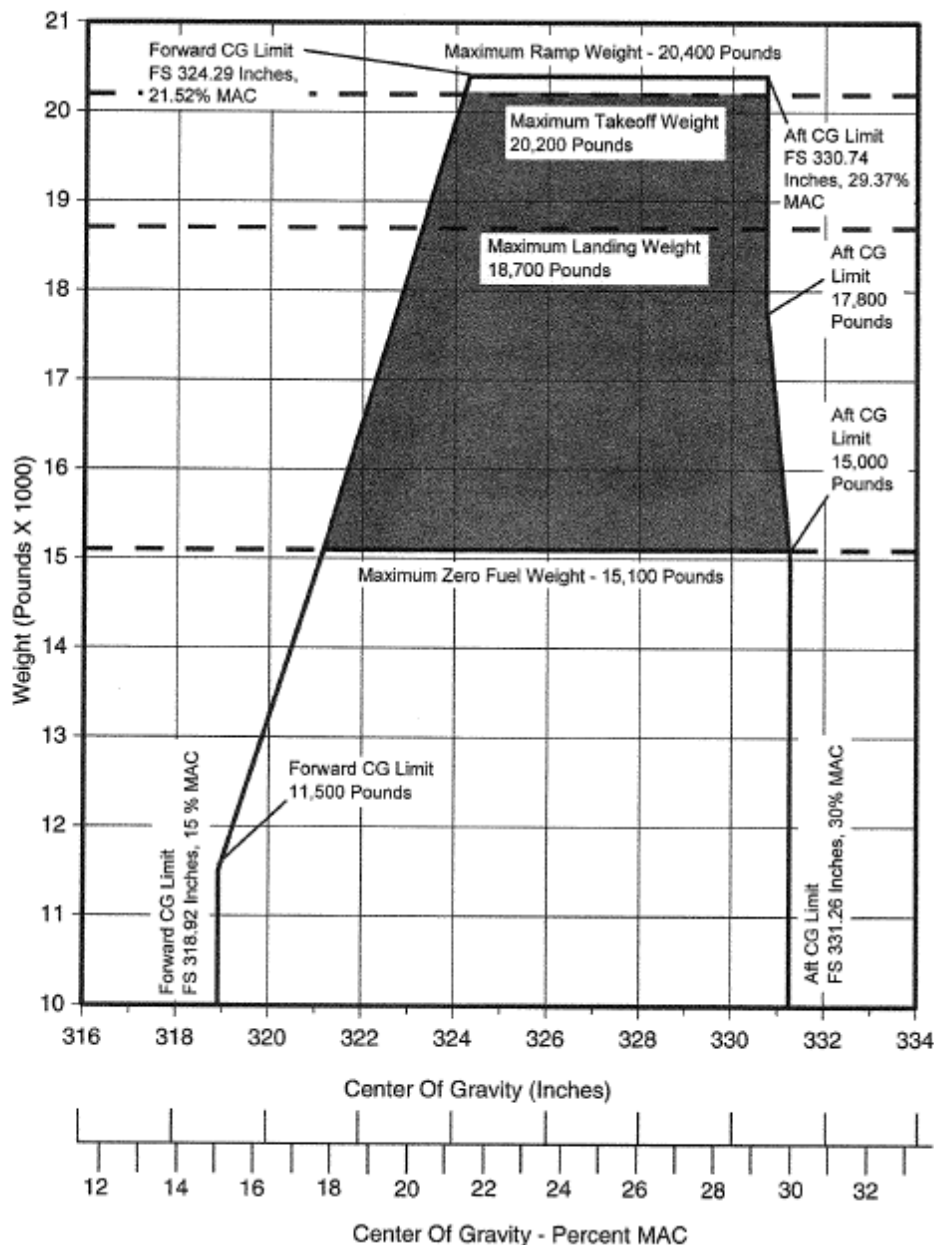
Description	Weight lb	Arm inches	Moment inch-lb	Limit lb
Empty Weight	12,649.6	334.24	4,228,005	
Fuel - Main	6,720	329.43	2,213,787	
Seat 1	175	136.32	23,856	
Seat 2	195	136.32	26,582	
Seat 9		187.44	-	
Seat 10		206.57	-	
Seat 11		357.99	-	
Seat 3		234.73	-	
Seat 4		234.73	-	
Seat 5	140	282.21	39,509	
Seat 6	190	282.21	53,620	
Seat 7		324.12	-	
Seat 8		324.12	-	
Chart case		158.10	-	
RHF closet	40	169.30	6,772	
LHF		172.23	-	
AFT closet		375.81	-	
Tailcone baggage	90	431.00	38,790	
Zero Fuel Weight	13,480		4,421,441	15,100
Ramp Weight	20,200	328.27	6,630,922	20,400
Taxi Fuel	200	335.60	67,119	
Takeoff Weight	20,000	328.20	6,563,803	20,200
Fuel Burn	5,220	329.62	1,720,607	
Landing Weight	14,780	327.69	4,843,195	18,700

The Cessna 560XLS+ weight and balance envelope shown in Figure 8 is published in the AFM for use in flight. TXTAV engineering staff indicated that there is only one flight envelope and that there is no published additional margin. The Cessna 560XL weight and balance envelope shape was developed using a multi-disciplinary iterative process. The forward and aft limits of the envelope are defined by mission loading profiles and fuel burn characteristics. The weight and balance envelope forward and aft limits have been verified by flight tests.

The Cessna Loads staff used airplane mass properties to calculate inertia data and define the maximum ramp weight and maximum zero fuel weight. Maximum takeoff weight is maximum ramp weight minus taxi fuel burn. The Cessna Propulsion staff provided taxi fuel burn data that was supported by validation tests. The Cessna Stress and Fatigue staff performed physical tests to verify loads such as wing bending. Maximum landing weight was established by landing gear design, structural capability, and other factors.

In response to an NTSB request, TXTAV engineering staff estimated the N560AR vertical center of gravity (c.g.) position relative to the main gear wheel/runway contact surface using an itemized component weight and balance buildup method. For the N560AR accident loading configuration, the vertical c.g. was estimated to be located 65.5 ± 0.5 inches above the main gear wheel/runway contact surface. A conservative vertical c.g. value $[(65.5 - 0.5)/12 \approx 5.4 \text{ feet}]$ was used in this study.

CENTER-OF-GRAVITY LIMITS ENVELOPE GRAPH



FORM NUMBER 2306, 30 May 2008

Figure 8: N560AR weight and balance envelope.

7. Paraphrased Cockpit Voice Recorder Events

Each aircraft performance group member was authorized by NTSB senior management to possess, assess, and discuss a paraphrased subset of CVR aural events to support group tasks. The paraphrased CVR events incorporated in this study are documented in Table 2. The time columns

in the table correspond to local time, FDR elapsed time in seconds, abbreviated FDR elapsed time in seconds (FDR elapsed time minus 49,000), and estimated time corresponding to the video timestamp in Attachments 3-5.

Table 2: Paraphrased CVR Events

Local Time hh:mm:ss	FDR Elapsed seconds	NTSB Ground		Paraphrased CVR Comment
		Track Model seconds	Video Image hh:mm:ss	
09:50:15.9	49815.9	815.9	09:52:00.2	[Sound of power advancing.]
09:50:31.2	49831.2	831.2	09:52:15.5	comment about airspeed
09:50:39.0	49839.0	839.0	09:52:23.3	eighty knot callout
09:50:42.7	49842.7	842.7	09:52:27.0	V1 callout
09:50:44.5	49844.5	844.5	09:52:28.8	rotation callout
09:50:45.2	49845.2	845.2	09:52:29.5	[sound similar to loud thunk]
09:50:48.9	49848.9	848.9	09:52:33.2	[sound of multiple low frequency thunks until end of recording]
09:50:49.2	49849.2	849.2	09:52:33.5	comment about rotating
09:50:54.9	49854.9	854.9	09:52:39.2	[sound of electronic stall warning]
09:50:55.0	49855.0	855.0	09:52:39.3	[sound of stick shaker activation]
09:50:57.0	49857.0	857.0	09:52:41.3	[automated voice] bank angle.
09:50:58.1	49858.1	858.1	09:52:42.4	[automated voice] bank angle.
09:50:59.3	49859.3	859.3	09:52:43.6	end of recording

8. Flight Data Recorder Parametric Data

The NTSB Flight Data Recorder Specialist's Factual Report documents the available FDR data. N560AR accident flight time history plots showing available longitudinal, lateral-directional, engine, and other FDR parameters are provided in Attachment 10 together with a list of N560AR FDR parameters recorded. TXTAV aviation safety and engineering staff confirmed that calibrated (as opposed to indicated) airspeed data were recorded by the N560AR FDR. In the Cessna 560XL takeoff speed range, calibrated airspeed is about 5 to 6 knots higher than indicated airspeed.

The NTSB FDR specialist reviewed the FDR anti-ice status words and initially determined that the data indicated a no computed data (NCD) signal, the word/bit information was invalid, or the decoder key was incorrect. Additional information from TXTAV enabled the NTSB FDR specialist to confirm that the engine anti-ice was on and the wing anti-ice was off during the accident flight.

The available FDR data indicated that N560AR was configured for flaps 15, takeoff thrust was set (per left and right engine throttle lever angle, N1, N2, fuel flow, and complementary FDR engine parameters), the airplane accelerated to the takeoff decision speed (V1) and takeoff rotation speed (VR), and sustained airplane nose up elevator surface deflections were recorded at and beyond VR. However, at and beyond VR, the airplane pitch attitude did not increase above 1° airplane nose up until after N560AR passed the departure end of runway 2 (where the terrain sloped away and the wheel/runway interface was no longer present). Between VR and the departure end of runway 2, the airplane experienced atypical lateral acceleration values (ranging between ± 0.3 g) and measurably reduced longitudinal acceleration values.

9. Airplane Speed and Acceleration

The FDR longitudinal acceleration data were used to calculate airplane groundspeed during the ground roll for the preceding takeoffs (T-4, T-3, T-2, and T-1) and the event takeoff. The change in speed as a function of time (dV/dt) is a measure of aircraft acceleration. The slope of the airspeed and groundspeed lines during the ground roll should be similar in steady wind conditions. The T-4, T-3, T-2, and T-1 data illustrate the expected match between airspeed and groundspeed slopes for speeds up to about 120 knots. The FDR airspeed and groundspeed data

for the accident flight indicate that N560AR accelerated to an airspeed in excess of 115 knots, well past the required V1 and VR targets.

The magnitude of aircraft acceleration is a function of engine thrust, environmental conditions, and aircraft loading, configuration, and airspeed. Cessna 560XL normal operations do not include derated takeoff thrust settings. N560AR demonstrated an airplane acceleration capability during the takeoff ground roll of about 6 to 8 knots/sec during the T-4, T-3, T-2, and T-1 takeoffs. Airplane loading similarities between the T-4, T-3, T-2, T-1, and the accident flight legs indicate that the accident takeoff acceleration should have been similar, at or above 6 knots/sec, but the demonstrated acceleration was reduced by about 1 knot/sec. Reduced takeoff acceleration capability equates to longer than expected takeoff time and distance required to reach the takeoff decision speed (V1), the takeoff rotation speed (VR), liftoff, and the initial obstacle clearance height of 35 feet (for dry runway operations). If aircraft acceleration is reduced during the takeoff roll due to inadvertent or unexpected wheel brake application, unintended brake disc heating will reduce aircraft deceleration capability in a rejected takeoff (accelerate-stop) scenario.

10. Control Surface Travel Ranges

The NTSB Aircraft Performance Group Chairman inspected N560AR pre-accident FDR data to observe unloaded flight control surface deflection ranges (for elevator, aileron, and rudder) as well as elevator surface deflection behavior during takeoff (subject to dynamic pressure loads during ground roll and flight). Observed FDR unloaded elevator surface deflections for N560AR ranged from 16° trailing edge down to 20° trailing edge up. Textron Aviation staff provided visibility to takeoff data from four (4) N560XL flight tests. Loaded elevator surface deflections during the takeoff ground roll for these flight tests ranged from 11° trailing edge down to 15° trailing edge up.

The following excerpt from the Cessna Citation 560XL TCDS documents expected control surface movements. TXTAV aviation safety and engineering staff confirmed that the TCDS control surface movement values correspond to flight control surface deflections rigged in the factory under zero external load conditions (i.e., geometric travel limits subject to zero dynamic pressure).

VII. Model 560XL (cont'd)

Control Surface Movements	Elevator (with stabilizer at + 1°)	Up 19° + 1°, - 0°	Down 15° ± 1°
	Elevator trim tab (with stabilizer at + 1°)	Up 5° ± 1°	Down 15° ± 1°
	Rudder (perpendicular to hinge)	Right 22° + 1°, -0° Left 22° + 1°, - 0°	
	For Aircraft with rudder bias system installed		
	Rudder (perpendicular to hinge)	Right 28 + 0.5°, -0° Left 28.5 + 0.5°, -0°	
	Rudder trim tab (perpendicular to hinge with Rudder centered)	Right 11.5° ± 0.5° Left 11.5° ± 0.5°	
	Aileron	Up 19° ± 1°	Down 15° ± 1°
	Aileron trim tab	Up 20° ± 2°	Down 20° ± 2°
	Wing flap	0°, and extend 7°, 15°, 35° ± 1°	
	Speed brake - Upper	Up 60° ± 2°	
- Lower	Up 65° ± 2°		
2-position Horizontal stabilizer			
T/O & Landing - 2° + 0°, - 0.1°			
Cruise + 1° + 0.1°, - 0°			
See Airplane Maintenance Manual for rigging instructions.			

11. Required Takeoff Field Length and Reference Speeds

Textron Aviation engineering staff calculated takeoff performance using FDR data from the N560AR accident flight and weather information from the NTSB Accident Preliminary Report. The TXTAV CPCalc program for the Citation XLS+ (supplied to 560XL customers) directly calculates the FAA required takeoff field length as a function of airport, runway, runway surface condition (dry/not dry), slope, barometric pressure, temperature, winds, weight, and flap configuration. The FAA required takeoff field length is the longest distance among the All Engines Operating (AEO) accelerate-go distance times 1.15, One Engine Inoperative (OEI) accelerate-go distance, AEO accelerate-stop distance, and the OEI accelerate-stop distance. The Airplane Flight Manual (AFM) provides an alternative approach to calculate the required takeoff field length. However, the AFM data may yield more conservative results than TXTAV CPCalc due to the simplified tabular presentation of variables that affect takeoff performance.

The Textron CPCalc and NTSB AFM-based scheduled takeoff field length results (rounded up to the nearest 5-foot increment and 1-knot increment) are summarized in Table 3. The common input variables are airport 4B8, runway 2, runway surface dry (based on METAR and video evidence), altimeter 29.77 in. Hg, ambient temperature 19°C, and airplane configuration flaps 15. The N560AR accident scenario assumes tower winds 350° at 12 knots with a takeoff weight of 20,200 lb. The second scenario evaluates zero wind with a takeoff weight of 20,000 lb.

Table 3: Cessna Citation XLS+ Required Takeoff Field Length

Method & Source	Weight lb.	Winds	Distance feet	Airspeed Targets		
				V1 KIAS / KCAS	VR KIAS / KCAS	V2 KIAS / KCAS
CPCalc direct TXTAV	20,200	350 @ 12	3,495	101 / 106	107 / 112	118 / 120
AFM interp. NTSB	20,200	350 @ 12	3,590	100 / 105	107 / 113	118 / 118
CPCalc direct TXTAV	20,000	No Wind	3,655	100 / 106	106 / 111	118 / 120
AFM interp. NTSB	20,000	No Wind	3,745	99 / 104	106 / 112	117 / 117

The AFM contains takeoff performance data tables for runway surface condition dry (or non-dry) and anti-ice on or off. Based on maximum takeoff weight (including full fuel), dry runway surface condition, and anti-ice off, takeoff target speeds V1, VR, and V2 for flaps 15 were calculated by NTSB to be 100, 107, and 118 knots, respectively. The FDR data indicate the crew began airplane nose up elevator deflection at about V1 and reached full (geometric limit 19° + 1°, FDR 16°) airplane nose up elevator deflection at VR. The NTSB AFM-based calculations indicate takeoff with the reported crew, passengers, luggage, full fuel, and the runway 2 slope required a 4-knot headwind (to keep takeoff field length less than 3,665 feet). As previously noted, the AFM results may be more conservative than the TXTAV CPCalc results. The supporting Cessna Citation 560XLS+ AFM performance data and NTSB calculation details are provided in Attachment 11.

Note: NTSB calculated KCAS values on rows 2 and 4 of Table 3 are based on the Cessna 560XLS+ AFM table documenting the relationship between indicated and calibrated airspeed. Per the AFM, no indicated to calibrated airspeed correction is applied to the AFM-based V2 values.

12. Airplane Braking Coefficient Extraction

The expected airplane braking coefficient during a normal takeoff ground roll is about 0.02 for free rolling (unbraked) wheels. A simplified NTSB aerodynamics and engine model was developed for the Cessna Citation 560XLS+ with Pratt & Whitney Canada PW545C engines to calculate the airplane braking coefficient as a function of time during the N560AR takeoff ground roll. The calculation began at an airspeed of 10 knots and continued until the aircraft departed the improved pavement surface at the departure end of runway 2.

A force and moment balance (or energy conservation) approach is used to calculate the airplane braking coefficient at each time step. This aircraft takeoff model accounts for recorded airplane acceleration parameters; calculates forces and moments due to aerodynamic lift, aerodynamic drag, engine thrust, aircraft loading, and runway slope; and solves for the resultant retarding force and equivalent airplane braking coefficient at the wheel/runway interface.

For conceptual reference, the airplane braking coefficient values expected for maximum manual wheel braking with an operative anti-skid system are about 0.40 or above for bare and dry pavement, 0.20 for good braking action, 0.10 for medium (fair) braking action, 0.05 for poor braking action, and 0.02 for unbraked rolling wheels (applicable for normal airplane taxi, takeoff, and unbraked landing rollout segments). The friction coefficient available at the wheel/pavement interface is dependent on environmental conditions (including temperature, precipitation, and contaminant type and depth), pavement conditions (material, grooving, installation quality, macrotexture, microtexture, drainage capability, rubber deposits, painted surfaces, state of repair), and wheel conditions (tire inflation pressure, tread depth, tread pattern). The available friction coefficient is allocated between traction (for longitudinal braking or acceleration effort) and steering or cornering, as conditions permit for the vehicle maneuvering requested.

12.1. Time-Varying Airplane Braking Coefficient Extraction (NTSB)

The N560AR calculated airplane braking coefficient results are compared in Figure 9. Engine thrust for each case is based on the accident environmental conditions. For the 4 preceding takeoffs, calculated airplane braking coefficient values during the takeoff ground roll are in the neighborhood of 0.02 to 0.03. During the accident takeoff ground roll (black line and symbols), calculated airplane braking coefficient values range from about 0.11 to 0.09 for groundspeeds below 100 knots and substantially increase (0.11 to 0.35) between 100 and 118 knots.

Proper interpretation of extracted airplane braking coefficient values is generally dependent on corroborating factual evidence. For example, without specific reference to the N560AR accident flight, hypothetical airplane braking coefficient values in the neighborhood of 0.10 for expected periods of wheel brake application could be explained by purposefully light wheel braking requested by the flight crew; poor runway pavement macrotexture or microtexture; heavy paint markings or rubber deposits on the runway; poor wheel/tire maintenance condition; the presence of significant runway surface contamination (typically due to some form of precipitation), a problem with the wheel brake or anti-skid system; errors or limitations in the underlying aerodynamics or engine models; or improper configuration/application of the aircraft models, engine models, and/or event environmental conditions relative to the event aircraft.

The corresponding N560AR values of airplane ground speed in knots and airplane acceleration in knots/sec are plotted in Figures 10 and 11. The slope of the line on a groundspeed (Y-axis) versus time (X-axis) plot indicates the aircraft acceleration relative to the earth reference frame (e.g., runway surface). The slope of the N560AR curves in Figure 10 are steep for the 4 preceding takeoff roll segments but comparatively shallow for the accident flight (black line and symbols). For the 4 preceding takeoff ground rolls, calculated acceleration values in Figure 11 range from about 6 to 8 knots/sec, decreasing about 1.5 knots/sec as groundspeed increases. For the

accident takeoff (black line and symbols) calculated acceleration values are 4 to 5 knots/sec up to 100 knots groundspeed but rapidly decrease toward 0 knots/sec by 118 knots.

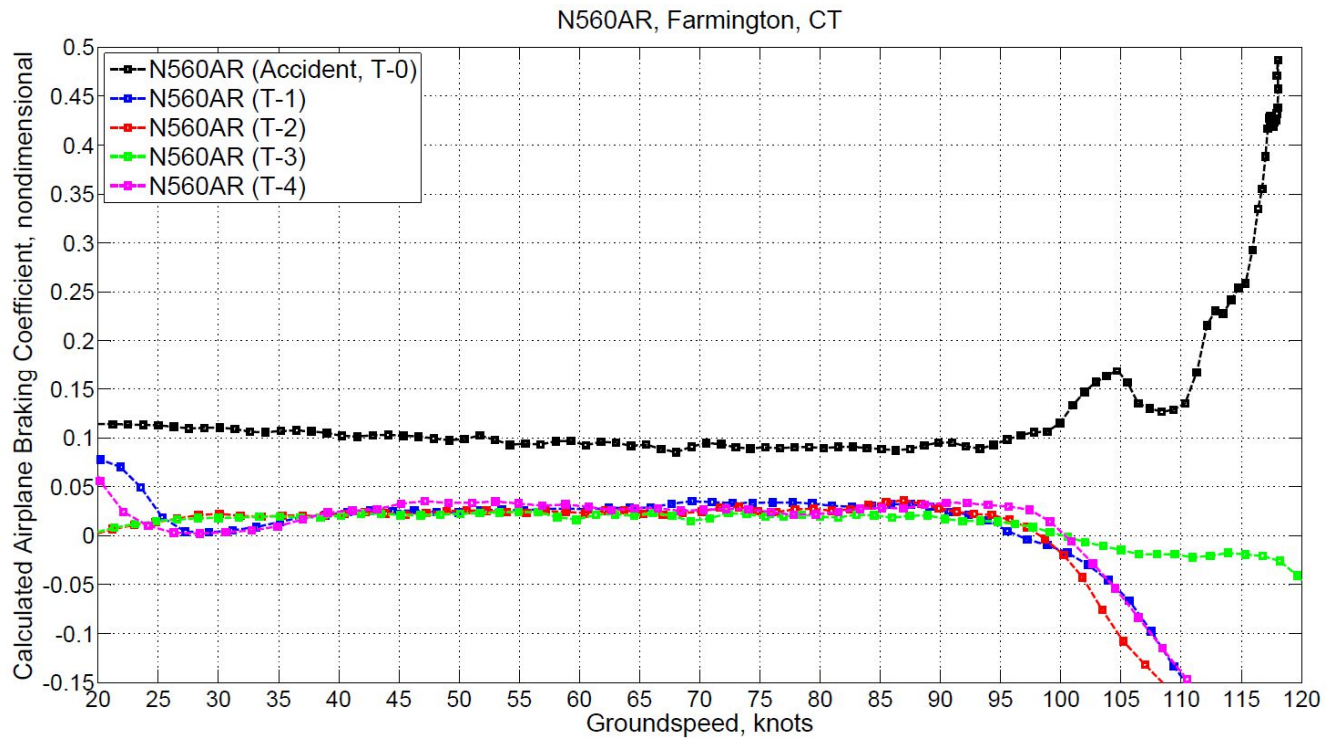


Figure 9: Calculated airplane braking coefficient as a function of groundspeed during the N560AR takeoff ground roll for the T-4, T-3, T-2, T-1, and accident (black line and symbols) takeoffs. Engine thrust for all cases is based on the accident environmental conditions.

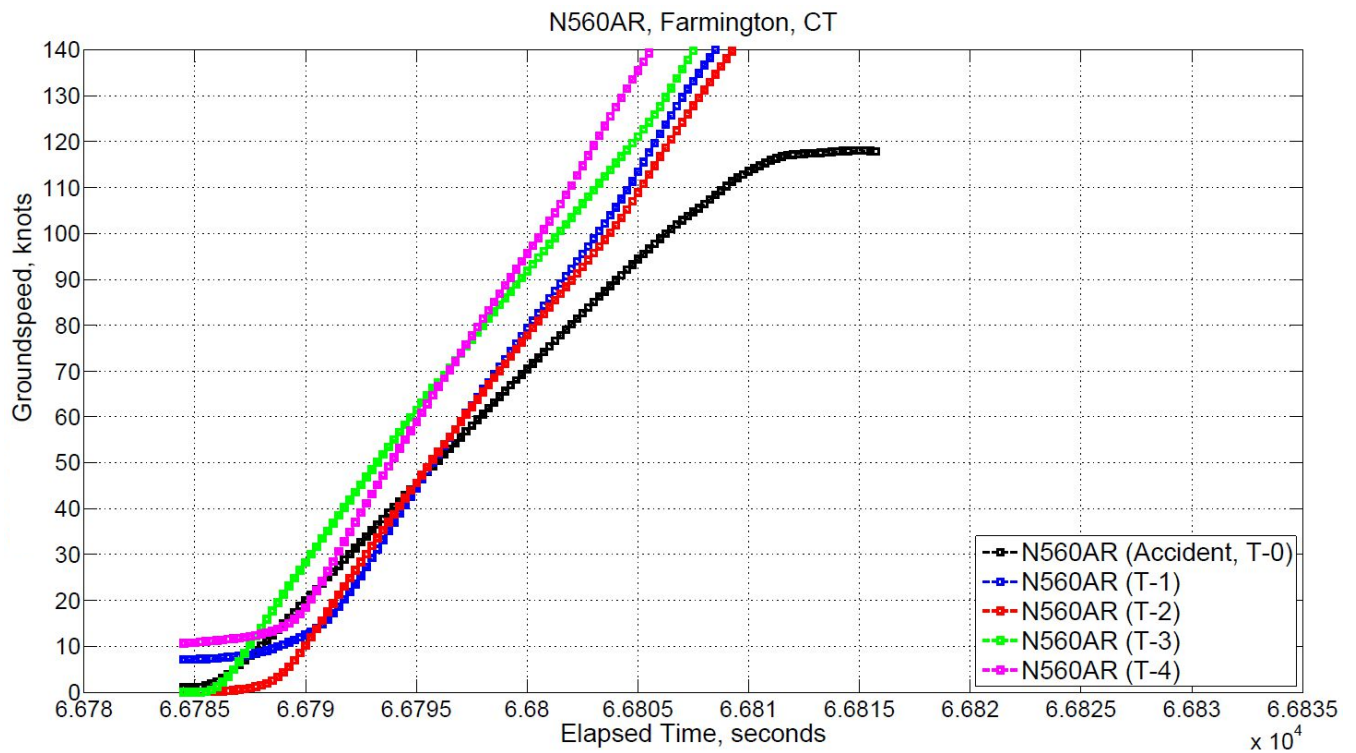


Figure 10: Airplane groundspeed as a function of elapsed time during the N560AR takeoff ground roll for the T-4, T-3, T-2, T-1, and accident (black line and symbols) takeoffs.

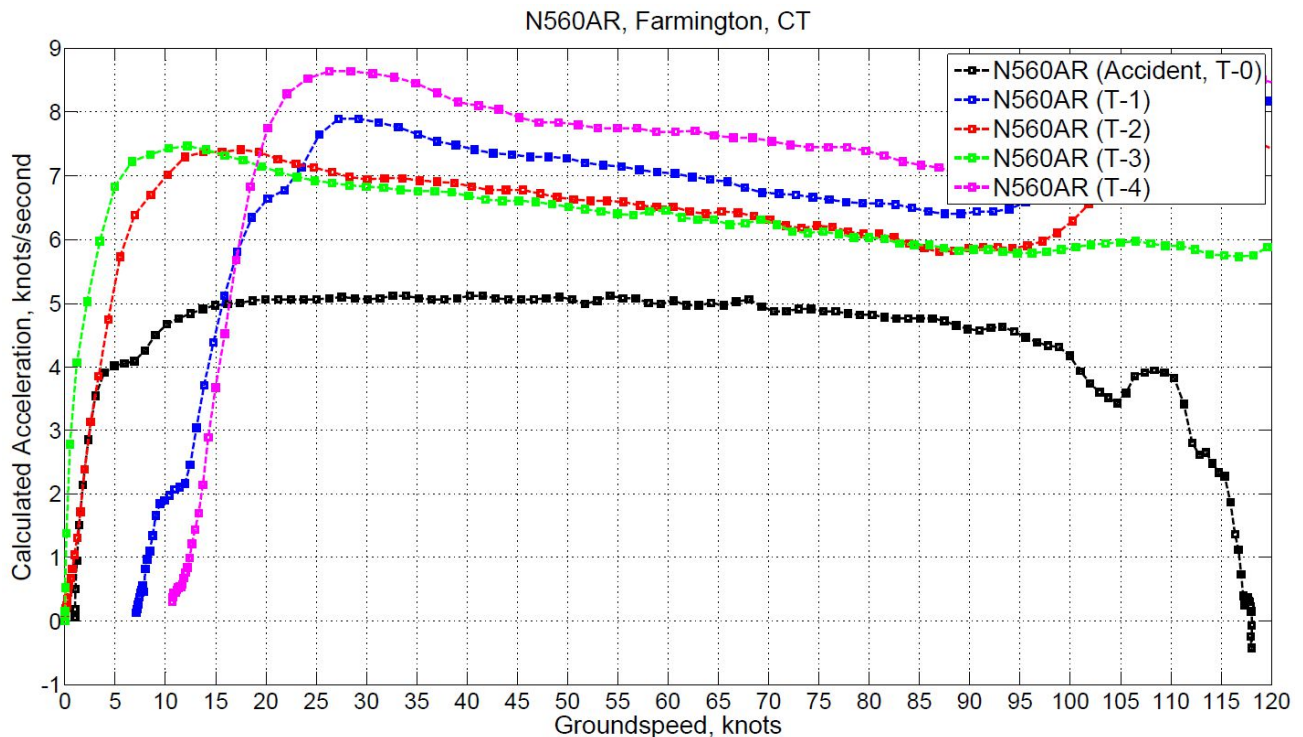


Figure 11: Calculated airplane acceleration as a function of groundspeed during the N560AR takeoff ground roll for the T-4, T-3, T-2, T-1, and accident (black line and symbols) takeoffs.

12.2. Average Equivalent Braking Coefficient (Textron Aviation)

Textron Aviation engineering staff calculated an average equivalent friction coefficient (μ) during the N560AR ground roll for three (3) distance segments, as summarized in Table 4. The TXTAV Citation XLS+ flaps 15 aerodynamics model was used to quantify lift and drag contributions during the ground roll. Engine thrust was provided by the PW545C engine simulator model supplied to TXTAV for the TXTAV-owned engine. The TXTAV engine model was assumed to be representative of the N560AR engine performance. Engine spool up during the first few seconds of the accident flight was modeled.

Calculation assumptions include takeoff weight 20,200 lb., ambient temperature 19°C, pressure altitude 350 feet, runway gradient +0.35 percent, and a headwind at a 6-foot height above the ground of 6.2 knots (based on the difference between the FDR ground speed and FDR calibrated airspeed parameters) during the ground roll segment. The average equivalent friction coefficient for the takeoff ground roll segment between 0 and 102 knots was 0.096 (first row of Table 4). The calculated value increased to 0.19 for the takeoff ground roll segment between 0 and 118 knots (second row of Table 4).

For the maximum friction scenario (third row of Table 4), distance was calculated by first finding the liftoff to 35 ft. agl (air segment) distance for an AEO takeoff for the accident conditions. The air segment distance was subtracted from the full runway length to give the maximum distance available for the takeoff roll. The final speed for the μ calculation is the scheduled AEO liftoff ground speed. Full takeoff thrust was used throughout but dynamics for rotation to liftoff were not considered.

Table 4: Average Equivalent Friction Coefficient, Mu (Textron Aviation Results)

Takeoff Roll Segment	Ground Speed (knots)	Distance (feet)	Average Friction Coef. (non-dimensional)
Nearly constant acceleration portion	0 to 102	1,810	0.096
Entire takeoff roll (to end of runway 2)	0 to 118	3,540	0.19
Maximum friction that allows AEO takeoff	0 to AEO liftoff	AEO takeoff - AEO air segment	0.17

13. Equivalent Retarding Force at Wheel/Runway Interface (NTSB)

The N560AR FDR was not configured to record the captain's or first officer's commanded brake pedal position, brake pressure upstream or downstream of the anti-skid valves, individual main gear wheel speeds, or parking brake position. Therefore, direct FDR time history evidence of flight crew maximum manual wheel braking requests, purposeful or inadvertent partial wheel brake requests, intentional or inadvertent left or right wheel braking requests for directional control, purposeful partial or full brake release, inadvertent parking brake application or inadvertent failure to fully release the parking brake is unavailable to the investigation. Similarly, there is no direct FDR time history record of the anti-skid system command(s) to release the brakes. The calculated equivalent retarding force time history for each case is presented in Figure 12. For groundspeeds less than 100 knots, the accident flight experienced an equivalent retarding force at the wheel/runway interface that was 3 to 4 times larger than the corresponding force during four (4) preceding N560AR takeoff ground roll segments.

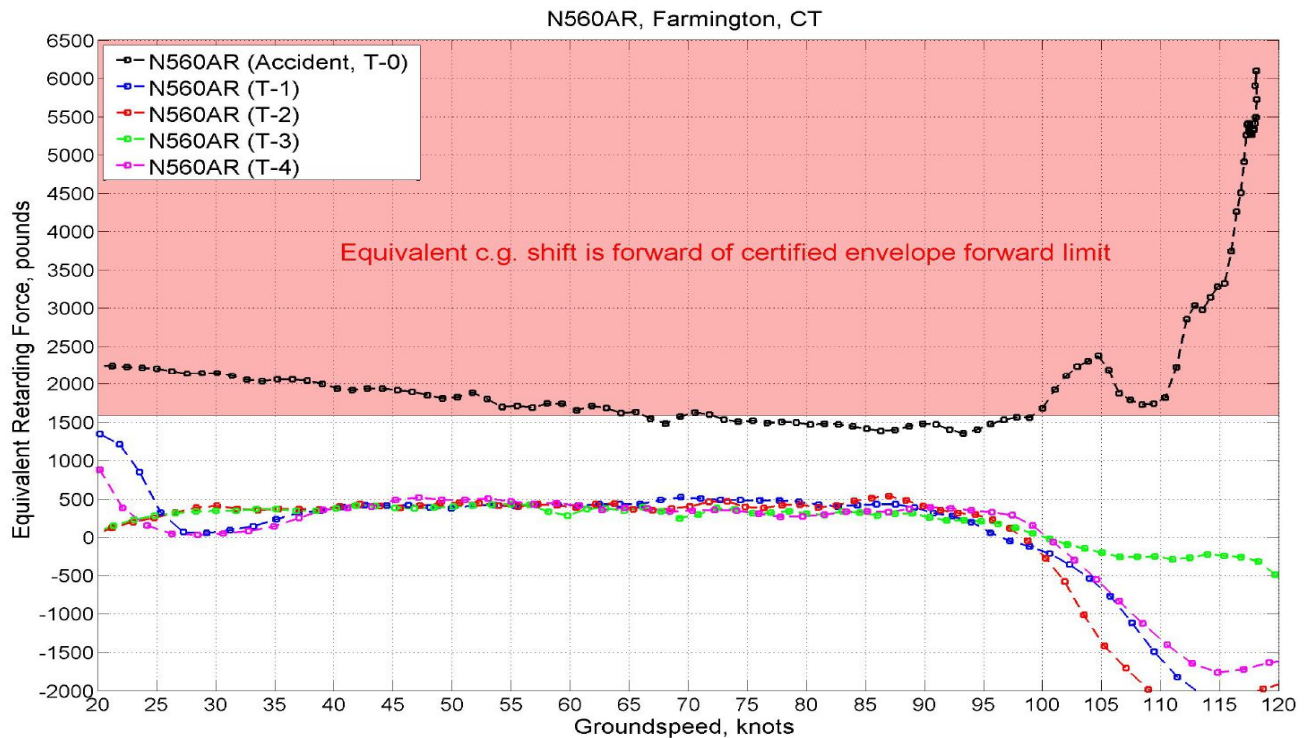


Figure 12: Calculated equivalent retarding force values during the N560AR takeoff ground roll as a function of groundspeed for the T-4, T-3, T-2, T-1, and accident (black line and symbols) takeoffs. Engine thrust for all cases is based on the accident environmental conditions.

14. N560AR Ground Track Reconstruction

The paraphrased CVR events in Table 2 were aligned with FDR time history data based on target speed callouts. Paraphrased CVR events generally represent machine-generated annunciations or flight deck, outbound, or inbound communications.

The FDR data were aligned with runway 2 based on main gear witness mark evidence near and at the departure end, FDR accelerometer integration results, and FDR normal load factor, longitudinal acceleration, and pitch attitude cues consistent with N560AR departing the improved pavement surface. These data establish the time alignment necessary conditions (required event sequence) and sufficient conditions (integrated FDR acceleration yields distance traveled in time documented by FDR and an independent airport video source).

The laser scanner and drone aerial surveys of runway 2 document N560AR witness mark evidence. Witness marks attributed to the N560AR left main gear (LMG) wheel path and right main gear (RMG) wheel path were added to an NTSB Google Earth ground track reconstruction model.

The time aligned paraphrased CVR events and FDR data were positioned on the N560AR event ground track reconstruction to yield the exemplar runway 2 overview plot shown in Figure 13. The sequence of plots in Attachment 12 illustrate the N560AR ground track reconstruction from initial takeoff roll to initial ground contact.

FDR altitude, airspeed, groundspeed, accelerations (normal, longitudinal, lateral), pitch, roll, heading, elevator, rudder, left and right engine N1 (fan speed), left and right engine N2 (core speed), left and right engine fuel flow, and distance relative to the runway 2 threshold were incorporated in the ground track model. Factual evidence downrange of the runway 2 departure end, such as witness marks associated with the telephone pole or initial ground contact were not used to position N560AR in time or space.

When N560AR exited the departure end of runway 2, the adverse retarding force and the landing gear ground reaction forces were suddenly removed due to a significant step downward in the local terrain. Available video evidence, CVR data, and FDR data indicate that N560AR began a slight descent, rolled toward 5° left wing down, and rapidly pitched up toward 22° (at an airspeed 11 knots above VR) in response to preceding airplane nose up elevator inputs. Within 2 seconds of exiting the departure end of runway 2, as the wing angle of attack quickly increased, elevator inputs were reduced from full airplane nose up to near neutral elevator over a 1-second period before the airplane struck (and broke) a telephone pole, which damaged the right, aft fuselage-mounted turbofan engine. The N560AR flight path reconstruction model indicates that the pole strike occurred at a pitch attitude of 22°, coincident with two CVR cues (electronic warning and stick shaker activation) that the airplane was approaching the wing stall angle of attack. After the pole strike, the wing angle of attack remained above the approach to stall warning threshold and the bank angle progressively increased to 142° right wing down as the airplane descended to ground impact.

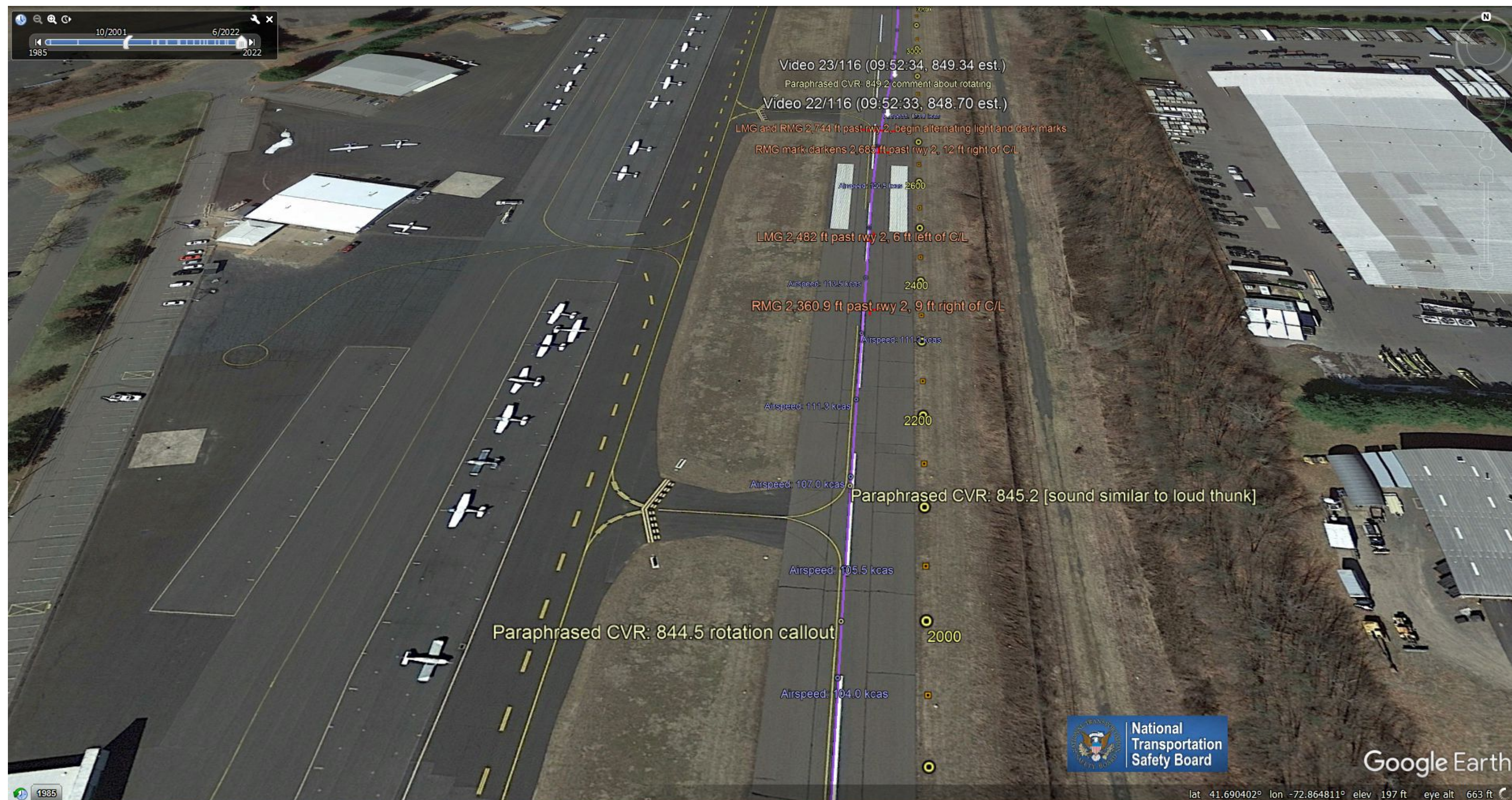


Figure 13: Example of N560AR accident flight reconstruction looking toward the departure end of runway 2, showing 2,000 to 3,000 feet along the runway. Ground track reconstruction is based on paraphrased CVR, FDR, video, and runway witness mark evidence. Due north and aircraft direction of travel are toward the top of the page. This image is a duplicate of Attachment 12, Figure A12.3.

15. Cessna Citation 560XL Pitching Moment Capability

The NTSB Aircraft Performance Group sought to quantify the N560AR airplane nose up (A.N.U.) pitching moment capability of the elevator and horizontal tail for comparison to the airplane nose down (A.N.D.) pitching moment generated by the adverse retarding force acting at the wheel/runway interface. TXTAV engineering staff indicated that Cessna 560XL(S/+) wing, horizontal tail, and elevator aerodynamic lift, drag, and pitching moment models were not required to support the airplane certification effort. As a result, these component aerodynamic models were never constructed.

N560AR was equipped with an FDR that recorded reliable airplane airspeed, pitch attitude, engine N1, flap, horizontal stabilizer, and elevator surface position. These data indicate that the airplane airspeed exceeded V1 and VR and the elevator surface position deflected to the full airplane nose up position, yet the airplane pitch attitude did not increase above 1° prior to the airplane's departure from the improved pavement surface.

The airplane weight and balance diagram in Figure 8 can be used to quantify the minimum A.N.U. elevator authority available to counteract the adverse A.N.D. pitching moment generated by the inadvertent retarding force. The N560AR c.g. position is 328.20 inches and the forward c.g. limit at a weight of 20,000 pounds is 324 inches. Since the N560AR c.g. is aft of the forward limit, additional A.N.U. pitching moment should be available (beyond the A.N.U. pitching moment required for a normal configuration takeoff). The minimum additional A.N.U. pitching moment capability in foot-pounds is

$$(\text{N560AR c.g.} - \text{forward limit c.g.}) \times (\text{weight}) = (328.20 - 324)/12 \times (20,000) = 7,000 \text{ ft-lb A.N.U.}$$

Aerodynamic lift is a function of flap configuration, angle of attack, dynamic pressure, and wing (or tail) planform area. The forward c.g. limit generally defines an elevator pitching moment capability sufficient to rotate the airplane nose up at a target pitch rate at the most adverse combination of flap, weight, c.g., airspeed, and altitude parameters. The most adverse combination of these parameters may equate to an A.N.U. elevator authority for the accident takeoff configuration, loading, and conditions that exceeds 7,000 ft-lb.

TXTAV engineering staff provided the nominal 560XLS+ c.g. waterline location relative to the wheel/runway contact point for the accident airplane loading configuration. The TXTAV vertical moment arm of 65.5 ± 0.5 inches was used to estimate the corresponding A.N.D. pitching moment acting on N560AR. The A.N.D. pitching moment as a function of groundspeed due to the calculated equivalent retarding force at the wheel/runway interface is quantified in Figure 14. The pitching moment values range from about $1,350 \times 5.4 = 7,290$ ft-lb to $6,100 \times 5.4 = 32,940$ ft-lb.

The airplane nose down pitching moment due to the calculated equivalent retarding force can be equated to an airplane nose down moment due to a hypothetical (more forward) center of gravity shift. The equivalent center of gravity position is estimated as the actual N560AR c.g. position minus the equivalent retarding force (less the rolling wheel retarding force of about 277 lb. at 111 knots airspeed) times the vertical moment arm in inches, divided by the takeoff weight:

$$\text{Minimum forward c.g. position} = 328.20 - (1,350 - 277) \times 5.4 \times 12 / 20,000 = 324.72 \text{ inches}$$

$$\text{Maximum forward c.g. position} = 328.20 - (6,100 - 277) \times 5.4 \times 12 / 20,000 = 309.33 \text{ inches}$$

The upper portion of the N560AR weight and balance envelope is shown in Figure 15 with the equivalent range of c.g. positions identified by the black symbols. For speeds at and beyond VR, a successful takeoff with the unexpected, adverse retarding force at the wheel/runway interface required an airplane nose up pitching moment capability that exceeded the Cessna 560XLS+ certified envelope, as measured by the forward c.g. limit of the weight and balance envelope.

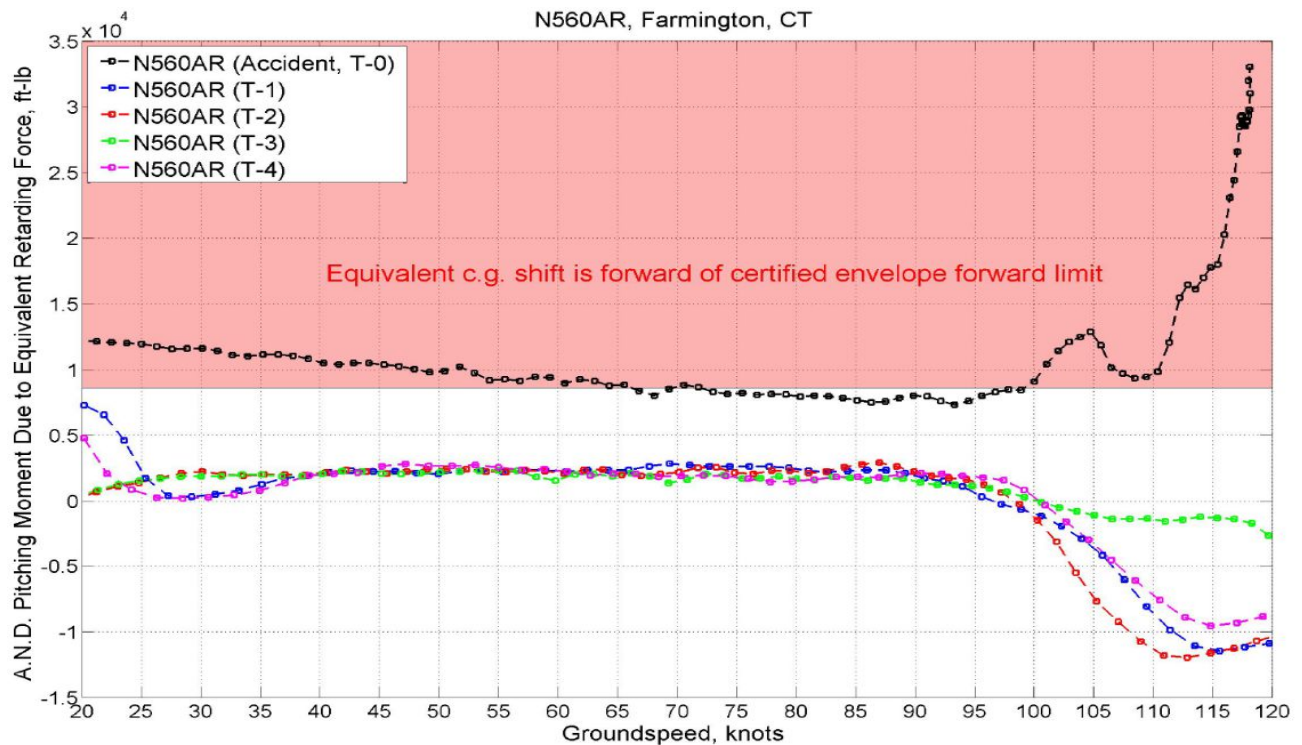


Figure 14: Calculated A.N.D. pitching moment due to calculated equivalent retarding force during the accident takeoff ground roll. Assumed moment arm value is 5.4 feet based on N560AR vertical center of gravity location calculated by Textron Aviation engineering staff.

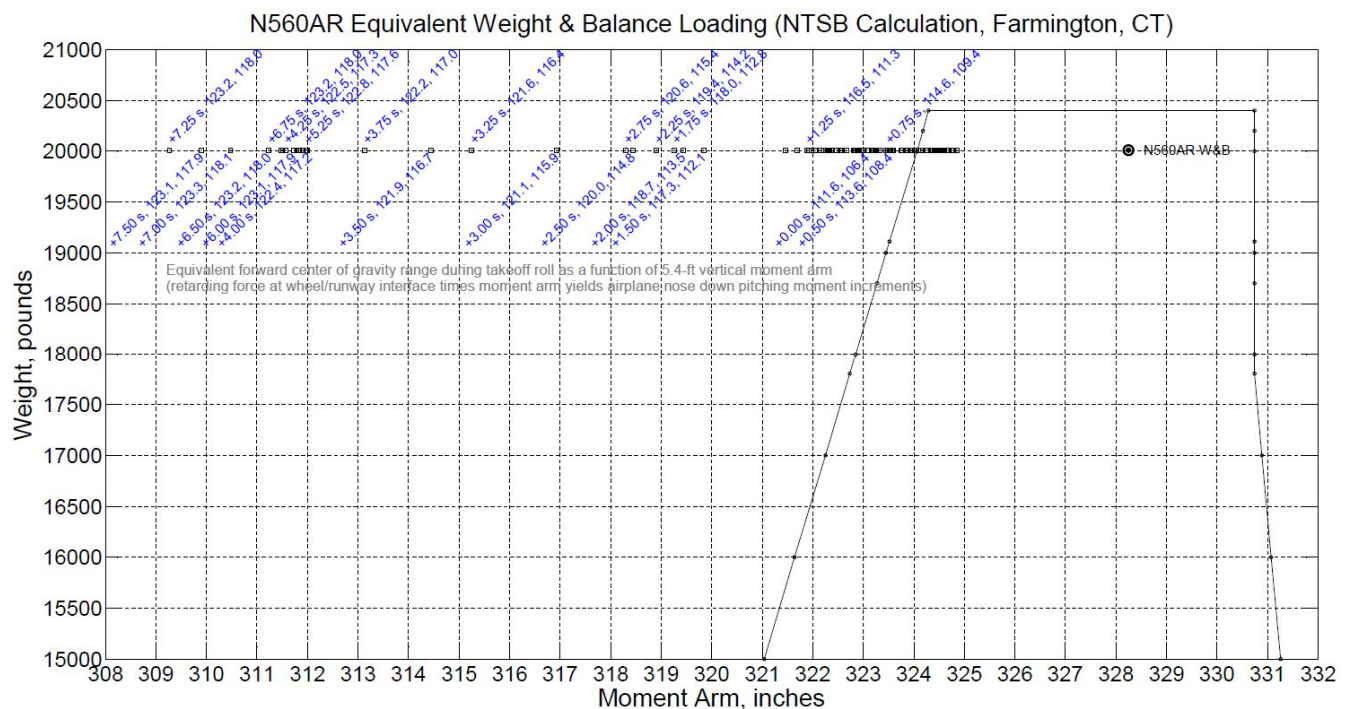


Figure 15: Equivalent N560AR weight and balance loading (black squares) if the airplane nose down pitching moment due to the calculated equivalent retarding force is equated to airplane nose down moment due to a hypothetical more forward center of gravity shift. Blue text indicates elapsed time (seconds) relative to VR, calibrated airspeed (knots), and groundspeed (knots). For the accident flight VR = 111 knots calibrated airspeed (reached near 105 knots groundspeed).

3.0 SUMMARY

A review of the available Flight Data Recorder (FDR), Cockpit Voice Recorder (CVR), and external surveillance camera factual evidence indicated that N560AR was able to accelerate to the rotation speed required for airplane liftoff. Further, N560AR had adequate takeoff performance capability to safely lift off from runway 2 when configured for a normal takeoff. However, the factual evidence and engineering models indicate that N560AR performance was substantially degraded during the accident takeoff roll by an unexpected retarding force acting at the wheel/runway interface. The magnitude and direction of this unexpected retarding force adversely affected N560AR acceleration, airplane nose up pitch rotation, wing angle of attack increase, and airplane liftoff during the attempted takeoff, despite appropriate takeoff flap, horizontal stabilizer position, and airplane nose up elevator inputs beyond VR.

When N560AR exited the departure end of runway 2, the adverse retarding force and the landing gear ground reaction forces were suddenly removed due to a significant step-down in local terrain. Available video evidence, CVR data, and FDR data indicate that N560AR began to descend, roll toward 5° left wing down, and rapidly pitch toward 22° airplane nose up (at an airspeed 11 knots above VR) in response to preceding airplane nose up elevator inputs. Within 2 seconds of exiting the departure end of runway 2, the airplane nose up elevator inputs were reducing to near neutral, N560AR struck a telephone pole (which damaged the right, aft fuselage-mounted turbofan engine), the wing angle of attack rapidly approached the stall angle of attack, and stick shaker activated. The airplane subsequently rolled 142° right wing down and descended to ground impact.

4.0 ATTACHMENTS

- Attachment 1: Cessna 560XL three-view drawing
- Attachment 2: Robertson Field Airport (4B8)
- Attachment 3: "Airport" camera image sequence (N560AR taxi segment)
- Attachment 4: "Airport" camera image sequence (N560AR takeoff ground roll segment)
- Attachment 5: "Airport" camera image sequence (N560AR near or beyond end of runway 2)
- Attachment 6: "Parking" camera image sequence (N560AR in flight)
- Attachment 7: "Main Drive" camera image sequence (N560AR in flight)
- Attachment 8: "Office Parking" camera image sequence (N560AR ground contact evidence)
- Attachment 9: Weight and balance data (N560AR)
- Attachment 10: Flight Data Recorder (FDR) data
- Attachment 11: N560XL takeoff performance
- Attachment 12: N560AR accident flight reconstruction