

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



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AIRCRAFT PERFORMANCE STUDY

February 29, 2024

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A. ACCIDENT

Location: Middle River, Maryland
Date: March 7, 2022
Time: 1045 Eastern Standard Time (EST)
1545 Coordinated Universal Time (UTC)
Airplane: Cessna Citation 525B CJ3, N22AU, 525B-0304

B. AIRCRAFT PERFORMANCE SPECIALIST

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

C. SUMMARY

On March 7, 2022, at 1045 Eastern Standard Time, a Cessna Citation 525B airplane, N22AU, was substantially damaged after it landed at Martin State Airport (MTN), Middle River, Maryland and overran the departure end of runway 15. The airline transport pilot and copilot were not injured. The airplane was operating under the provisions of Title 14 *Code of Federal Regulations* Part 135 Air Taxi and Commuter – Non-scheduled as an on-demand charter flight from Dulles International Airport (IAD) to MTN.

1. Introduction

The accident airplane was equipped with a Cessna Aircraft Recording System (AReS) and a Cockpit Voice Recorder (CVR). The AReS data were collected, processed by Textron/Cessna staff, and provided to the NTSB investigation. The CVR data were collected and processed by an NTSB recorder specialist. Witness marks near the departure end of runway 15 were reported on the pavement and visible between the pavement and the airplane final rest position. Video footage from two (2) airport surveillance cameras documented respective portions of the N22AU approach and landing ground rollout. Federal Aviation Administration (FAA) and ADSB Exchange Automatic Dependent Surveillance Broadcast (ADS-B) data that documented the airplane flight path were collected. Other specialists gathered additional factual evidence including wreckage location, 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 not convened for this investigation. Textron Aviation/Cessna (TXTAV) air safety and engineering staff provided timely technical support. Documents were exchanged via email or through an NTSB document server.

The aircraft performance investigation was 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 (expected and actual), 4) preparation of data required to support airplane and engine model simulation, 5) calculation of the longitudinal forces and moments acting on the airplane during the landing ground rollout, and 6) review of the airplane deceleration device systems.

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

The objectives of the study were to 1) quantify the expected and actual airplane stopping performance capability, 2) estimate the equivalent airplane braking coefficient at the wheel/runway interface during the N22AU landing ground rollout, 3) reconstruct the accident airplane

flight path and ground track, and 4) review the airplane deceleration device systems (including ground flaps, speed brake, wheel brake, emergency brake, and parking brake) and the related aircraft functional hazard and system safety assessment documents.

3. Summary of Results

Based on Cessna Citation 525B Airplane Flight Manual (AFM) landing performance data and Textron/Cessna landing performance models, N22AU had adequate performance capability to safely land at Martin State Airport (MTN) on runway 15 for the documented airplane flaps configuration, loading, flight conditions, and field length. The factual evidence indicates that main gear touchdown occurred at about 110 knots airspeed and about 104 knots groundspeed, about 2,000 feet beyond the approach end of runway 15, within the first third of the landing distance available, on a dry runway surface. However, Cessna Citation 525B aerodynamics and Williams International engine thrust models indicate that during the landing ground rollout, configured with ground flaps and speed brakes deployed, N22AU experienced a prolonged period of low equivalent retarding force at the wheel/runway interface. The NTSB simplified Cessna Citation 525B airplane performance model indicated that, during the ground rollout, N22AU deceleration was primarily due to aerodynamic drag and free rolling (unbraked) wheel friction. N22AU did not slow to a safe taxi speed over a pavement rollout distance of about 5,000 feet, despite crew-reported wheel braking inputs and CVR evidence of crew effort to locate the emergency brake. The unexpected, prolonged, low equivalent retarding force at the wheel/ runway interface during the ground rollout substantially reduced aircraft deceleration and prevented N22AU from dissipating sufficient energy to slow to a safe taxi speed or stop prior to the runway departure end. N22AU overran the departure end of runway 15 at a groundspeed of about 58 knots, traversed about 450 feet of grass and water-saturated soil in the runway safety area, and was arrested after striking and deforming an airport perimeter fence.

D. DETAILS OF THE INVESTIGATION

1. Method

This aircraft performance study provides data-driven, quantified assessments of expected Cessna Citation 525B landing performance capability and identifies factors that affected the observed N22AU landing performance. The study is based on available N22AU factual evidence and Cessna Citation 525B aerodynamics data that Cessna engineering and flight test/operations staff used to develop, test, and validate landing, stopping performance, and other engineering models; construct the Aircraft Flight Manual (AFM); and certify the airplane. The Textron Aviation/Cessna foundational factual data and models used in this study predated the accident. Engine thrust data were obtained directly from Williams International.

A review of the available FAA and ADSB Exchange ADS-B data, Cessna Aircraft Recording System (ARes) data, CVR content, and airport video surveillance camera factual evidence indicated that N22AU main gear touchdown occurred about 2,000 feet beyond the approach threshold of MTN runway 15, within the first third of the landing distance available. The airplane configuration and energy state during the landing ground rollout are the focus of this study. The study scope is primarily from airplane main gear touchdown to the airplane departure from the end of runway 15.

2. Cessna Citation 525B

The Cessna Citation 525B is a medium-size business jet powered by two medium bypass ratio, Williams International FJ44-3A turbofan engines (about 2,780 pounds of static takeoff thrust at sea level, flat-rated to 22°C) mounted on the aft fuselage. A three-view drawing of the Cessna Citation 525B is provided in Attachment 1.

3. Martin State Airport (MTN) Runway 15/33

Martin State Airport (MTN) is located about 13 miles east, northeast of Baltimore, Maryland. Runway 15/33 is 6,997 feet long, 180 feet wide, constructed of grooved asphalt, and has non-precision markings. The runway 15 heading is 146° magnetic and 135° true, which equates to a magnetic variation of 11°W. The runway 15 approach end elevation is 21.3 feet and the departure end elevation is 9.2 feet, resulting in an average runway 15 downslope of 0.17 percent $[(9.2 - 21.3) / 6,997 = -0.0017]$. A MTN airport diagram and an aerial image are included in Attachment 2.

The NTSB Investigator-in-Charge (IIC) indicated that the runway 15/33 pavement was in good condition and the runway surface was dry when N22AU landed at MTN.

4. Meteorological Conditions

The hourly MTN Automated Surface Observing System (ASOS) data near the accident time were:

KMTN 071153Z 00000KT 10SM CLR 11/09 A2991
KMTN 071253Z 00000KT 10SM CLR 13/10 A2990
KMTN 071354Z 19010G17KT 10SM CLR 20/13 A2988
KMTN 071454Z 18016G23KT 10SM CLR 22/13 A2984

KMTN 071553Z 21012G21KT 10SM CLR 23/13 A2979 (closest to accident time)

At 1053 EST, the MTN ASOS reported winds from 210° at 12 knots gusting to 21 knots, visibility of 10 statute miles or greater, clear skies to 10,000 feet above ground level (agl) or greater, temperature of 23° Celsius (C), dew point temperature of 13°C, and altimeter setting of 29.79 inches of mercury.

KMTN 071654Z 20012G20KT 10SM CLR 23/13 A2977
KMTN 071754Z 20018G27KT 10SM SCT049 25/13 A2974
KMTN 071854Z 19013G23KT 10SM SCT050 25/13 A2971
KMTN 071954Z 19014G21KT 10SM SCT055 OVC090 25/13 A2969

5. Video Surveillance Camera Evidence

Two (2) airport 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 herein. 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 and/or scaled, the original image aspect ratio was preserved. The resulting image sequence from each camera is provided in Attachments 3-5. Multiple images per page enable comparison of adjacent images and reduce page count.

Image content in Attachments 3-5 is most easily viewed in full screen mode (e.g., in Adobe Acrobat Reader), maximizing the view (with CTRL-L) and using the mouse wheel or arrow keys to sequentially page forward or backward through the file contents (Walt Disney flip-book style animation). With adequate computer CPU/graphics capability, this mouse/arrow technique can be used to "animate" the images and "reconstruct" the video. A pictorial summary of the video camera evidence (camera view and aircraft position) follows in Figures 1 through 3. The video images have not been time-aligned with the ADS-B, ARoS, or CVR data.

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

"Airport" Camera (N22AU on short final approach), Attachment 3

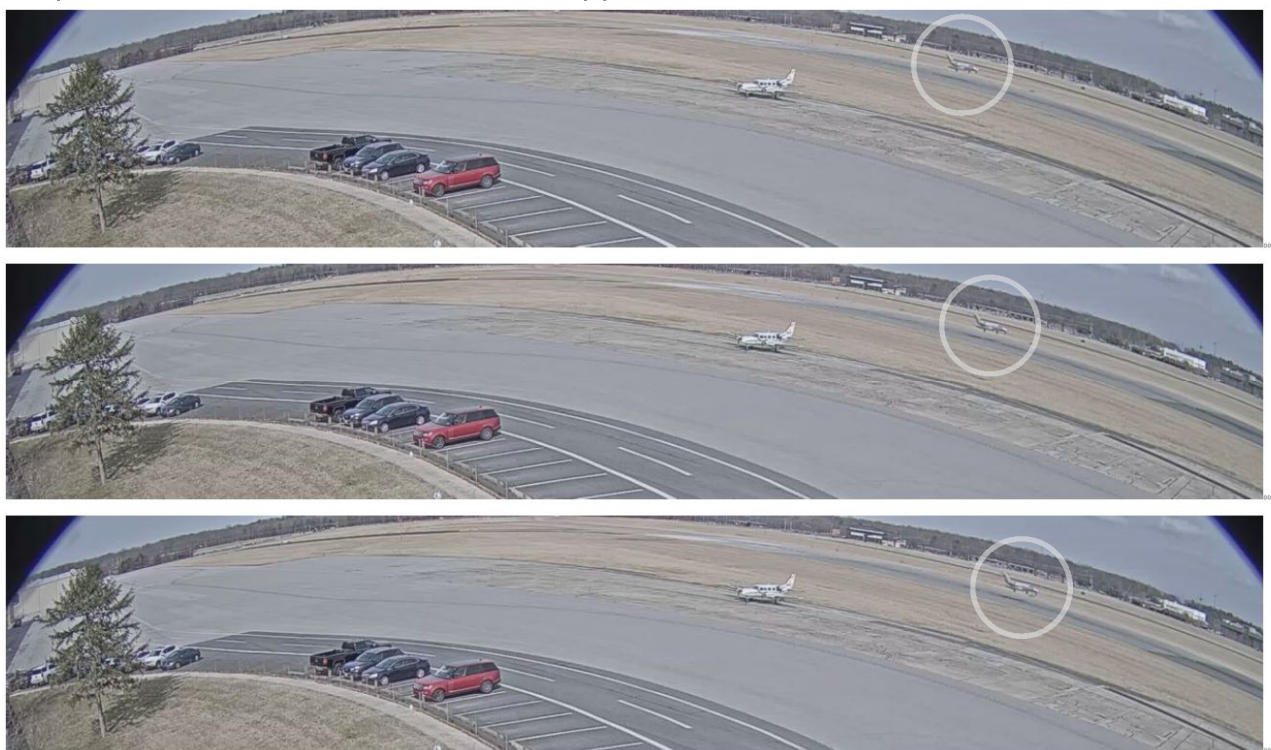


Figure 1: Exemplar cropped and enlarged image sequence extracted from "Airport" surveillance camera recording. N22AU is on short final approach to MTN runway 15, moving left to right.

"Airport" Camera (N22AU landing ground rollout segment), Attachment 4



Figure 2: Cropped and enlarged image sequence extracted from "Airport" surveillance camera recording. N22AU moving left to right during ground rollout toward departure end of runway 15.

“Airport” Camera (N22AU landing ground rollout segment, digital zoom), Attachment 5



Figure 3: Cropped, further enlarged image sequence extracted from “Airport” surveillance camera recording. N22AU moving left to right during ground rollout toward departure end of runway 15.

6. Photographic Evidence

Photographs of N22AU at final rest were provided by the Maryland Department of Transportation, Maryland Aviation Administration (see Attachment 6). The photographs document the four corners of the airplane, the airplane ground track (landing gear wheel paths) through the runway safety area, the airplane lateral position relative to the runway 15 extended centerline, and the flap and speed brake deployment positions.

7. Weight & Balance

The accident flight weight and balance was documented by maintenance records for the N22AU empty weight, assumed crew, crew flight bag, and crew luggage weights, and the crew-reported fuel loading. The aircraft basic empty weight and balance as of May 2021 was 8,480.2 pounds located at a moment arm of 306.13 inches. The accident flight loading was 2 flight crew members, 2 flight bags, 2 crew bags, and 4,320 lb. of fuel. The N22AU itemized weight and balance reconstruction is shown in Table 1 based on the supporting evidence provided in Attachment 7.

The left seat pilot-in-command (PIC) and the right seat co-pilot (SIC) weights were each assumed to be 200 lb. for a combined weight of $200+200=400$ lb. The pilot and co-pilot flight bags were each assumed to weigh 20 lb. for a total weight of $20+20=40$ lb. Similarly, the pilot and co-pilot luggage weights were each assumed to weigh 30 lb. for a combined weight of $30+30=60$ lb., located at 414.60 inches aft of datum. Fuel quantity for the accident flight was reported to be 640 gallons which was equated to a fuel load of 4,320 lb. (640 gal. x 6.75 lb./gal.).

8. Calculated Landing Distance and Target Speeds

Textron/Cessna engineering staff used a Cessna Citation 525B landing performance model to calculate the expected landing distance for the N22AU accident flight as a function of weight, flap,

Table 1: N22AU Weight and Balance Buildup

N22AU Estimated W&B (BEW per AirShare, May 2021)

Item	Arm inches	Weight pounds	Moment/ 100		Weight pounds	Moment/ 100	CG inches	CG %m.a.c.	Note
Pilot	131.0	200	262.0	Basic Empty Weight	8480.2	25960.6	306.13	30.91	> Aft Limit
Copilot	131.0	200	262.0						
Seat 3	202.5	0	0	Payload	500	839.7			
Seat 4	202.5	0	0						
Seat 5	260.5	0	0	Zero Fuel Weight	8980.2	26800.3	298.44	20.62	
Seat 6	260.5	0	0						
Seat 7	295.5	0	0	Fuel Loading	4320	13406.5			640.0 gal.
Seat 8	295.5	0	0						
Toilet	322.5	0	0	Ramp Weight	13300.2	40206.8	302.30	25.79	
Side Facing Seat	174.2	0	0						
				Taxi Fuel	200	619.4			29.6 gal.
LH Chart Case	150.9	0	0						
RH Ref Center	167.3	40	66.9	Takeoff Weight	13100.2	39587.4	302.19	25.64	
LH Evap Cabinet	156.3	0	0						
Vanity Storage	335.2	0	0	Fuel to Destination	351	1087.8			52.0 gal.
Nose Baggage	74.0	0	0	Landing Weight	12749.2	38499.6	301.98	25.36	
Cab Storage	330.2	0	0						
Tailcone Baggage	414.6	60	248.8						
Payload		500.0	839.7						

and deceleration device configuration; airport barometric pressure and temperature; runway, slope, and surface condition (dry/not dry); and reported winds. The Airplane Flight Manual (AFM) provides an alternative approach to calculate the required landing distance.

The AFM presents actual landing distance values, defined as the sum of the air distance from 50 feet to main gear touchdown, the transition distance from main gear touchdown through nose wheel touchdown and full deceleration device configuration, and the ground rollout distance to aircraft full stop. Interpolation of the AFM data may yield more conservative results than the TXTAV model due to the simplified tabular presentation of variables that affect landing performance.

The TXTAV and NTSB AFM-based landing performance results (rounded up to the nearest 5-foot increment for distance and 1-knot increment for speed) are compared in Table 2. The common input variables are airport MTN, runway 15, runway surface condition dry (based on METAR and video evidence), altimeter 29.79 in. Hg, ambient temperature 23°C, and airplane configuration flaps 35 (LAND) transitioning to flaps 55 (GROUND). The N22AU accident scenario assumes a landing weight of 12,750 lb. and that winds were from 210° at 12 knots gusting to 21 knots.

Based on maximum landing weight, dry runway surface conditions, and anti-ice either on or off, the TXTAV and NTSB calculated flaps 35 landing distances are comparable, requiring a maximum actual landing distance of 2,900 feet (runway 15 distance available is 6,997 ft). The two methods yield identical target speeds of VAPP 117 kias and VREF 108 kias. The NTSB AFM interpolated landing distances are slightly less conservative than the TXTAV landing performance tool results. The NTSB AFM interpolation calculation details are shown in Table 3.

The landing performance results in Table 2 assume a stable airplane approach (speed and descent rate) on a 3° glideslope, appropriate two-engine thrust setting, landing flap selected, gear down, anti-ice either on or off, airspeed VREF at 50 feet, engine thrust set to flight idle at 50 feet and maintained to aircraft full stop, normal rotation rate to landing attitude, maximum wheel braking (with antiskid system ON) initiated at nose wheel touchdown and maintained to aircraft full stop, and ground flaps selected immediately after wheel brake application.

Table 2: Cessna Citation 525B Calculated Landing Performance (flaps 35 to 55)

Method & Source	Weight lb.	Winds	Distance feet	Δ Distance feet	Airspeed Targets	
					VAPP KIAS	VREF KIAS
TXTAV landing perf. tool	12,750	210 @ 12	2,900	---	117	108
AFM interp. NTSB	12,750	210 @ 12	2,850	-50	117	108
TXTAV landing perf. tool	12,750	210 @ 21	2,830	---	117	108
AFM interp. NTSB	12,750	210 @ 21	2,785	-45	117	108

Table 3: NTSB Interpolation of AFM landing performance data (N22AU conditions)

Rwy Heading	146.4 deg. true						
Rwy Slope	-0.17 percent						
Temperature	23 C		HW		CW		
Winds 1	210	12 knots	5.3		10.7		
Winds 2	210	21 knots	9.3		18.8		
Weight	12750 lb						
	slope	0	-0.17	-1	-2		
	factor	1	1.034	1.2	1.73		
Pressure Alt., ft	0						
	TW	Zero	HW	HW	HW	HW	HW
Temperature, C	-10	0	5.34	9.34	10	20	30
20	3380	2810			2650	2490	2340
23	3410	2834	2745	2679	2668	2514	2364
25	3430	2850			2680	2530	2380
	50	40			30	40	40
			12 kt	21 kt			
Pressure Alt., ft	143		2756.6	2689.9	ft, interpolated		
			2850.3	2781.4	ft, rwy slope correction		
Pressure Alt., ft	1000						
	TW	Zero	HW	HW	HW	HW	HW
Temperature, C	-10	0	5.34	9.34	10	20	30
20	3480	2890			2720	2570	2410
23	3504	2914	2823	2755	2744	2588	2434
25	3520	2930			2760	2600	2450
	40	40			40	30	40
Results			TXTAV	NTSB	Delta Dist.	TXTAV & NTSB	TXTAV & NTSB
Wind, kt	Gradient, %	Gradient, %	Dist., ft	Dist., ft	feet	VAPP, kias	VREF, kias
12	9.6	25.9	2896	2850.3	-45.7	117	108
21	9.8	26.4	2830	2781.4	-48.6	117	108

The supporting AFM performance data are provided in Attachment 8. Note that the **Cessna Citation 525B "actual" landing distance data include no additional safety factor (margin)** that might account for actual variations from planned, trained, or assumed operational technique, threshold crossing height, descent rate, air distance, speed, deceleration device deployment schedule (i.e., timing, magnitude, and/or duration), winds, non-dry runway surface condition, etc. The AFM landing procedures and data apply for normal landings at or below 12,750 pounds.¹

9. Paraphrased Cockpit Voice Recorder Events

A paraphrased subset of CVR aural events was requested to support aircraft performance investigation tasks. The paraphrased CVR events incorporated in this study are documented in Table 4 and Attachment 9. The time columns in the table correspond to local time (HH MM SS) and elapsed time in seconds. Elapsed time in Attachment 11 is abbreviated as elapsed time in seconds minus 38,000.

Table 4: Paraphrased CVR Events

<u>HH</u> <u>MM</u> SS	Elapsed	Paraphrased CVR event
10 29 30.2	37770.2	"Comment regarding landing gear retraction after takeoff."
10 34 08.9	38048.9	"0954 MTN ATIS - wind 180 @ 16 gust 23, visibility of 10 statute miles, no clouds under 12k (clear), localizer approach runway 15 in use."
10 46 20.0	38780.0	"Comment regarding landing reference speed."
10 46 35.9	38795.9	"Automated 500 feet AGL callout."
10 47 30.9	38850.9	"Comment regarding ground flaps."
10 47 32.5	38852.5	"Aircraft touchdown."
10 47 39.4	38859.4	"Comment regarding issues with braking."
10 48 11.7	38891.7	"Aircraft departed paved surface."

10. Automatic Dependent Surveillance Broadcast (ADS-B) Parametric Data

Federal Aviation Administration (FAA) and ADSB Exchange Automatic Dependent Surveillance Broadcast (ADS-B) data that documented the airplane flight path were collected. The FAA ADS-B data did not capture the N22AU landing ground rollout segment, runway overrun, or final rest position. Therefore, NTSB staff gathered supplementary ADS-B data from third party commercial providers. The ADS-B data presented in this study were obtained from ADSB Exchange.

Available ADS-B time history parameters used in this study include latitude, longitude, altitude, groundspeed, and course over ground. NTSB staff recalculated aircraft groundspeed and course over ground from the ADS-B latitude and longitude data to validate these ADS-B parameters.

11. Cessna Aircraft Recording System (AReS) Data

The accident airplane was equipped with a Cessna Aircraft Recording System (AReS) that captured time history data at the rate of 10 samples per second for left and right main gear state (in air or on ground), left and right engine Full Authority Digital Engine Control (FADEC) throttle lever angle, left and right aircraft altitude, left and right true airspeed, speed brake deployment, and speed brake state (gear on ground). The specific Cessna AReS parameters recorded for N22AU were: Left MLG GOG, Right MLG GOG, Left Main GOG, Right Main GOG, Left Main GIA, Right Main GIA, RH FADEC B TLA, LH FADEC A TLA, RH Current Aircraft Altitude, LH Current

¹ Textron/Cessna Citation 525B AFM landing performance data for weights that exceed 12,750 pounds are provided only for use in an emergency landing at a weight that exceeds the maximum design landing weight of 12,750 pounds.

Aircraft Altitude, RH True Airspeed, LH True Airspeed, LH Throttle Lever Angle, RH Throttle Lever Angle, Speed Brake GOG, and Speed Brake Extend, where MLG=main landing gear, GOG=gear on ground, GIA=gear in air, LH=left hand, RH=right hand, and TLA=throttle lever angle.

Cessna AReS and ADSB Exchange ADS-B parametric data for the N22AU approach and landing are plotted as a function of time in Attachment 10. These recorded parameters and the paraphrased CVR events were used to confirm the aircraft main gear touchdown location and the sequence of events throughout the airplane ground rollout.

12. Airplane Speed and Deceleration

The N22AU groundspeed calculated from ADSB Exchange ADS-B latitude and longitude data is compared to AReS left and right true airspeed data in Figure 4. The change in groundspeed as a function of time (dV/dt) is a measure of aircraft deceleration. The aircraft deceleration magnitude is a function of aircraft loading, configuration (flaps, speed brakes, wheel brakes), environmental conditions, airspeed, engine thrust, runway surface conditions (dry/non-dry), and the friction developed at the wheel/runway interface. The slope of the airspeed and groundspeed lines during the ground rollout should be similar in steady wind conditions. The N22AU airspeed and groundspeed slopes generally match throughout the ground rollout, as expected. The airspeed variation is consistent with reported gusting winds (from 210° at 12 knots gusting to 21 knots).

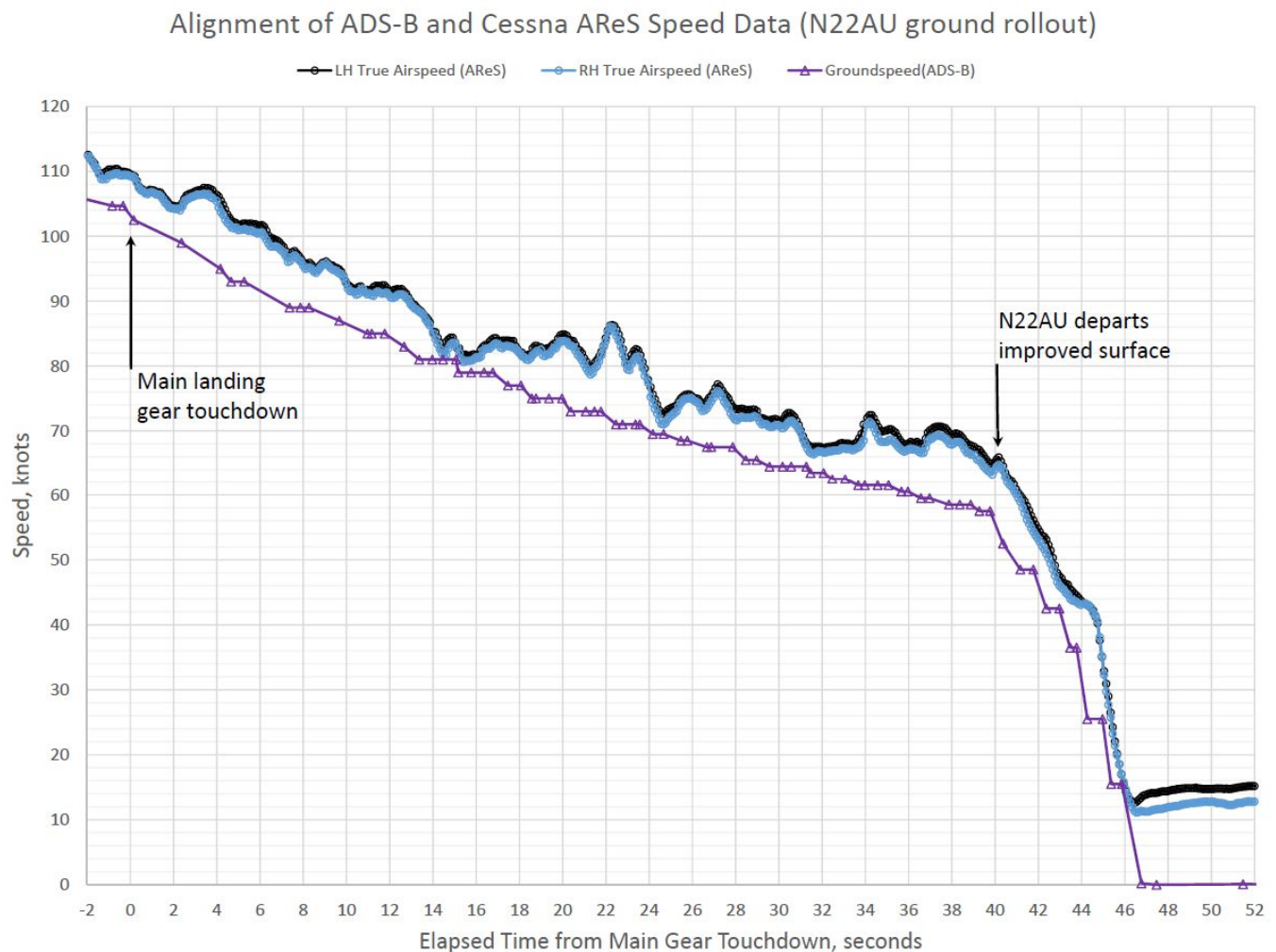


Figure 4: Comparison of N22AU recorded ADSB Exchange ADS-B ground speed and AReS true airspeed data.

As configured, N22AU demonstrated an average equivalent deceleration capability of about 1.25 knots/sec during the ground rollout on runway 15, from an initial speed of about 104 knots groundspeed to a final speed of about 58 knots groundspeed, over a distance of about 5,000 feet. The expected Cessna Citation 525B maximum deceleration capability can be estimated from the landing performance results in Table 2. Given a landing distance of 2,900 feet and VREF of 108 knots, assume 1) sea level, zero wind, 2) the air distance is 800 feet accompanied by a 5 percent speed decay, 3) the transition distance is defined by a 3-second period at constant groundspeed to derotate the airplane nose, apply maximum wheel brakes, deploy ground flaps, and deploy speed brakes, and 4) aerodynamic drag and wheel braking must dissipate the remaining energy (and energy added via two engines at flight idle) within the remaining distance (2,900 - 800 - 0.95 x VREF ft/sec x 3 sec) feet. The distance remaining is

$$2,900 - 800 - 3 \times (0.95 \times 108 \text{ nm/hr}) \times (6,076.115 \text{ ft/nm}) \times (1 \text{ hr}/3,600 \text{ seconds}) \approx 1,580 \text{ ft}$$

and the distance traveled prior to wheel brake application is $2,900 - 1,580 = 1,320$ feet. The constant equivalent acceleration (a) needed to stop the airplane within the remaining 1,580 feet is

$$\begin{aligned} a &= [(V_F)^2 - (V_I)^2] / [2 \times (X_F - X_I)] \\ a &= [((0 \text{ nm/hr}) \times (6,076.115 \text{ ft/nm}) \times (1 \text{ hr}/3,600 \text{ sec}))^2 - \\ &\quad ((0.95 \times 108 \text{ nm/hr}) \times (6,076.115 \text{ ft/nm}) \times (1 \text{ hr}/3,600 \text{ sec}))^2] / [2 \times (2,900 \text{ ft} - 1,320 \text{ ft})] \\ a &= [0 - ((0.95 \times 108 \text{ nm/hr}) \times (6,076.115 \text{ ft/nm}) \times (1 \text{ hr}/3,600 \text{ sec}))^2] / [2 \times (2,900 \text{ ft} - 1,320 \text{ ft})] \\ a &= -9.5 \text{ ft/sec}^2 \times (3600 \text{ sec}/1 \text{ hr}) / (6,076.115 \text{ ft}/1 \text{ nm}) \\ a &= -5.6 \text{ knots/sec} \end{aligned}$$

This airplane constant equivalent deceleration capability of 5.6 knots/sec is about 4.5 times greater than the average equivalent deceleration demonstrated by N22AU during the accident ground rollout. Reduced landing deceleration equates to longer than expected stopping time and distance required to reach a safe taxi speed or a full stop.

Calculation assumptions include landing weight 12,750 lb., ambient temperature 23°C, pressure altitude 143 feet, runway gradient -0.17 percent, and a headwind at a 6-foot height above the ground of 9.3 knots (based on the difference between the ADS-B ground speed and AReS true airspeed parameters) during the ground roll segment. **The N22AU equivalent airplane friction coefficient for the landing ground roll segment between 104.7 and 58 knots was 0.015**, which is a typical value associated with free rolling (unbraked) wheels during normal taxiing, takeoff, and unbraked segments of landing operations.

13. Cessna Citation 525B Simplified Aerodynamics and Engine Model (NTSB)

NTSB staff developed a Cessna Citation 525B simplified aerodynamics and engine model to evaluate N22AU deceleration and stopping performance. TXTAV provided total airplane lift and drag coefficients for the airplane in the ground landing rollout attitude, configured gear down, ground flaps deployed, with both engines at flight idle thrust. The engine thrust model used by Textron Aviation/Cessna for landing performance calculations is based on engine flight idle thrust for the duration of the stop. As a result, TXTAV did not create or validate an engine model for ground idle thrust.

Turbofan engine thrust is a function of airspeed, pressure altitude, temperature, and typically either engine fan speed (engine N1) or engine pressure ratio (EPR). NTSB staff developed an engine flight-idle thrust model based on Williams International proprietary engine data.

14. 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 525B with Williams International FJ44-3A engines to calculate the airplane braking coefficient as a function of time during the N22AU landing ground rollout. The calculation began at a groundspeed of 104.7 knots and continued until the aircraft departed the improved pavement surface at the departure end of runway 15 at a groundspeed of 58 knots.

A force and moment balance (or energy conservation) approach is used to calculate the airplane braking coefficient at each time step. The aircraft simulation model accounts for 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.

The N22AU recorded airspeed (black and blue lines and symbols) and recorded groundspeed (purple line and symbols) are presented in Figure 5 as a function of time. The NTSB calculated airspeed (green line) and groundspeed (red line) results based on a steady wind and constant airplane braking coefficient value of 0.015 are shown for comparison. The NTSB simulation results are based on TXTAV proprietary aerodynamic lift and drag coefficient data, the simplified NTSB flight-idle engine model, and N22AU environmental conditions. For groundspeeds between 105 and 58 knots, the NTSB simulation groundspeed (red line) closely matches the ADS-B ground speed data derived from N22AU position measurements (purple line and symbols).

Proper interpretation of extracted airplane braking coefficient values is generally dependent on corroborating factual evidence. For example, without specific reference to the N22AU 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 slope of the line on a groundspeed (Y-axis) versus time (X-axis) plot indicates the aircraft deceleration relative to the earth reference frame (e.g., runway surface). The expected Cessna Citation 525B deceleration capability in knots per second is roughly shown by the constant deceleration lines in Figure 5, ranging from deceleration due only to aerodynamic drag and free rolling wheels to deceleration with sustained maximum wheel braking throughout the stop on a dry runway. The slope of the N22AU curve is shallow for the accident flight (purple line & symbols).

NTSB simplified aerodynamics and engine model (N22AU landing ground rollout)

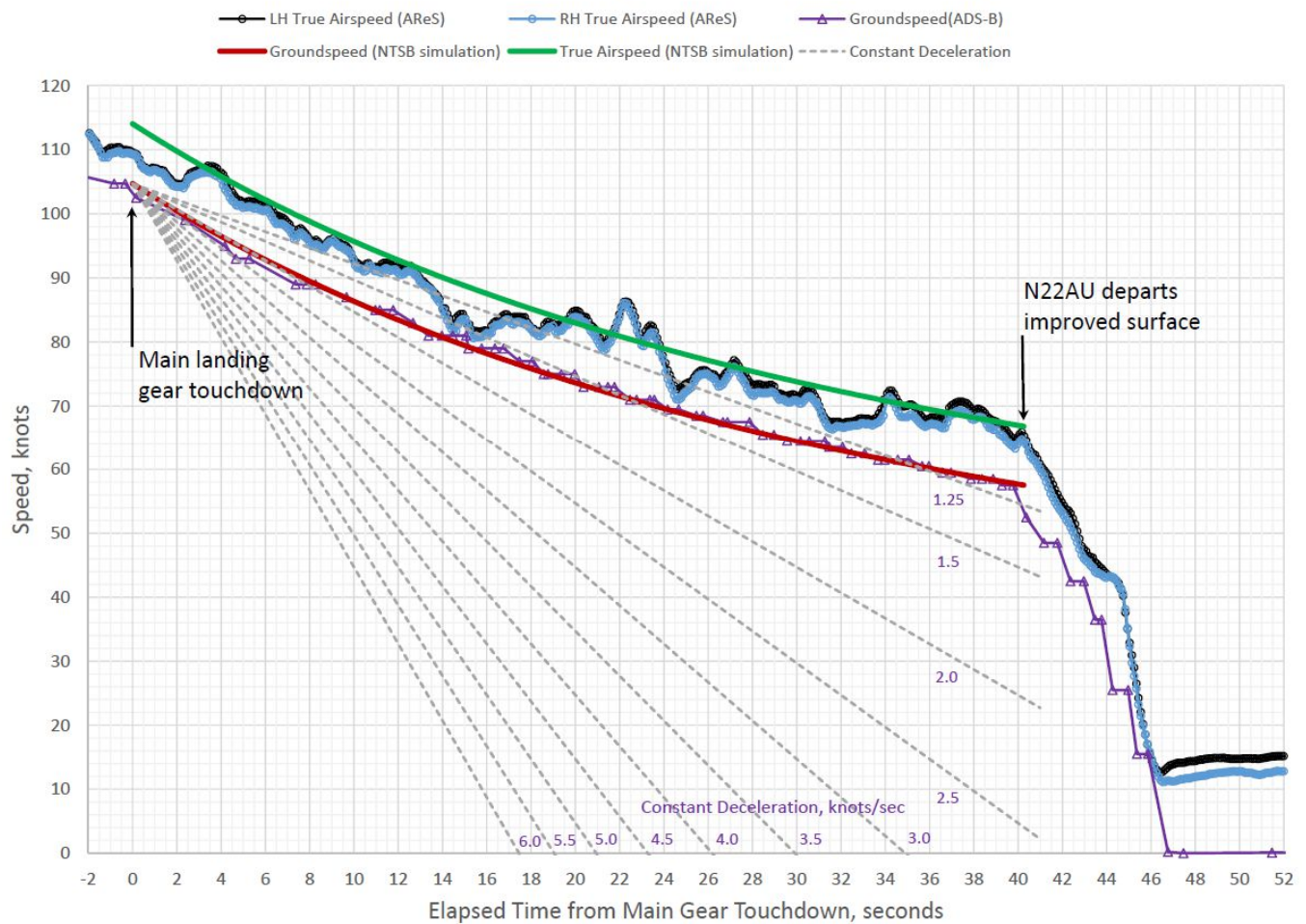


Figure 5: Comparison of N22AU recorded ADSB Exchange ADS-B ground speed and AReS true airspeed data to corresponding NTSB simplified aerodynamics and engine model parameters as a function of time.

Note that aircraft deceleration profiles are not linear in practice (unlike the constant deceleration reference lines in Figure 5) because aerodynamic lift and drag are quadratic functions of airspeed, meaning that aerodynamic deceleration devices such as speed brakes and ground flaps are more effective at high speeds than at low speeds. This effect is observed in the N22AU groundspeed profile, as the slope transitions from more negative values to less negative values as time and distance increase (and speed decreases).

The Cessna Citation 525B deceleration capability required to slow N22AU to a safe taxi speed or reach a full stop is between 1.75 and 2.0 knots per second (about 1.85 knots per second yields a total landing distance of 6,920 feet), as illustrated by the constant deceleration lines in Figure 6.

NTSB simplified aerodynamics and engine model (N22AU landing ground rollout)

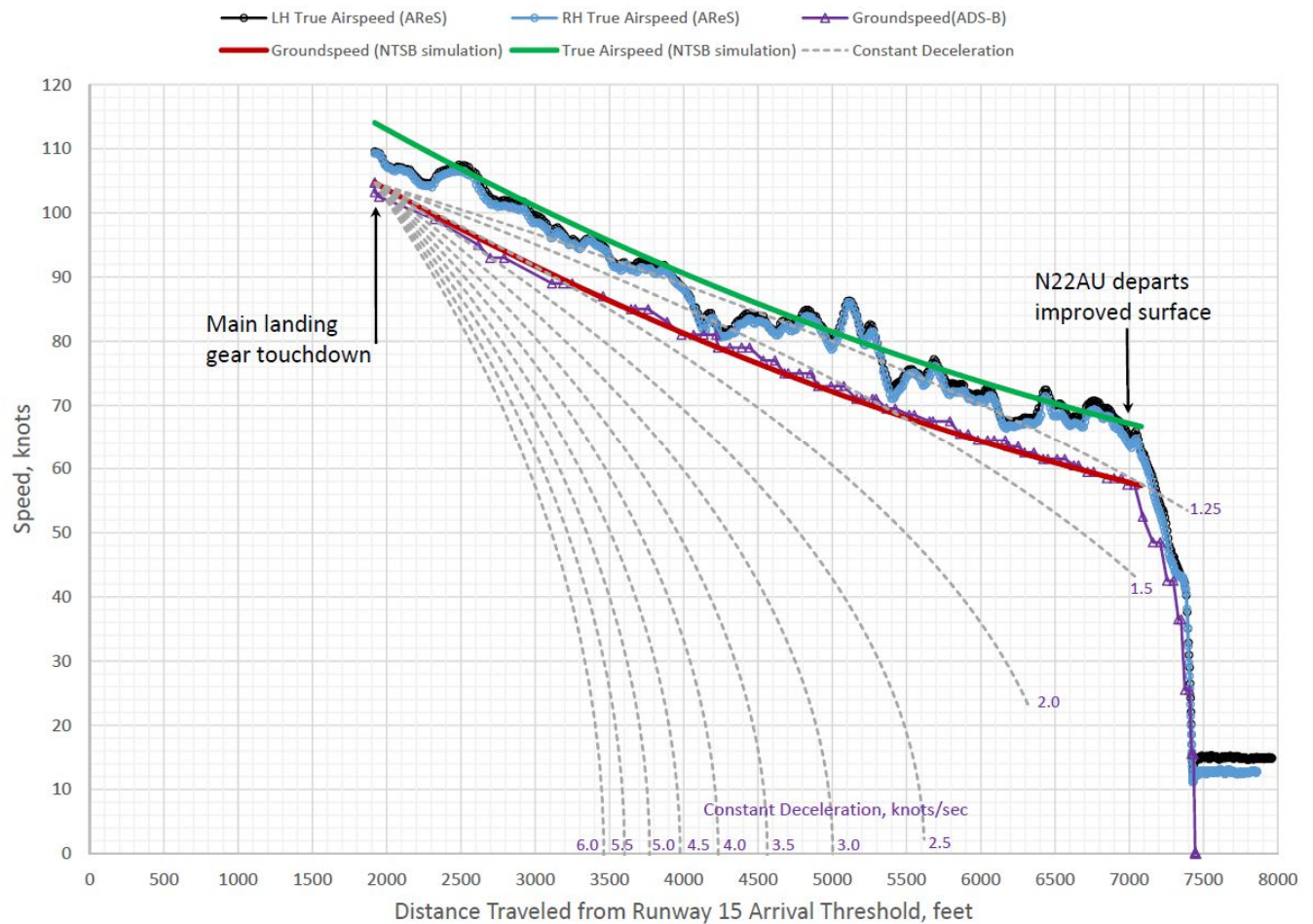


Figure 6: Comparison of N22AU recorded ADSB Exchange ADS-B ground speed and AReS true airspeed data to corresponding NTSB simplified aerodynamics and engine model parameters as a function of distance.

15. N22AU Ground Track Reconstruction

The paraphrased CVR events in Table 4 were aligned with ADS-B and AReS time history data based on the main landing gear touchdown, altitude, airspeed, and groundspeed parameters, including cues that the airplane had departed from the improved pavement surface. Paraphrased CVR events generally represent machine-generated annunciations or flight deck, outbound, or inbound communications.

The ADS-B data were aligned with runway 15 based on the recorded latitude and longitude data. The time alignment necessary conditions (required event sequence) and sufficient conditions (integrated groundspeed yields distance traveled in time documented by ADS-B data) were validated. A composite Google Earth flight path model was then constructed based on the available ADS-B data, AReS data, and paraphrased CVR event data.

The time aligned paraphrased CVR events, ADS-B data, and AReS data were positioned on the N22AU event ground track reconstruction to yield the exemplar runway 15 overview plot shown in Figure 7. The sequence of plots in Attachment 11 illustrate the reconstructed N22AU ground track from short final approach to the airplane final rest position.



Figure 7: Example of N22AU accident flight reconstruction showing main gear touchdown and deceleration device configuration segment (between 800 and 3,400 feet along MTN runway 15). Ground track is based on ADS-B, Cessna AReS, paraphrased CVR, video, and runway witness mark evidence. Aircraft direction of travel is upper left to lower right. Due north is toward the top of the page. This image is a duplicate of Attachment 11, Figure A11.6.

The ADS-B groundspeed and AReS altitude, airspeed, engine throttle lever angle, main landing gear GOG, main landing gear GIA, and speed brake parameters were incorporated in the ground track model. Factual evidence downrange of the runway 15 departure end, such as witness marks associated with landing gear rutting were not used to position N22AU in time or space.

At the time of the event, N22AU was in a landing configuration with flaps and speed brakes deployed. The landing weight was reported to be about 12,750 lbs. There were no engine thrust reversers. The timing, magnitude, and/or duration of pilot/copilot commands for wheel brake, emergency brake, and/or parking brake events were not recorded.

Regarding wheel witness marks on the runway during the ground rollout, the NTSB IIC indicated that the crew applied the parking brake during the last several hundred feet leaving some light skid marks on the runway surface. Off the runway, the wheel marks continued through the grass and mud for about 450 feet. N22AU was arrested after striking and deforming an airport perimeter fence.

16. Cessna Citation 525B Deceleration Devices

This section provides a brief description of available airplane deceleration devices. Supporting AFM page excerpts are provided in Attachment 12.

Flap System

Normal flap travel is from 0° (UP) to 35° (LAND) and any intermediate position can be selected. There is a mechanical detent installed on the flap lever for flaps 15° (TAKEOFF AND APPROACH) and a landing gate that precedes selection of flaps 55° (GROUND FLAPS). There are no wing leading edge high-lift devices. System failures may dictate landing with abnormal flap settings (0° or 15°) but that is uncommon and additional landing distance factors apply for these cases.

Ground Flap System

Selecting ground flaps transitions flaps from the selected in-flight landing flap position to flaps 55° and deploys speed brakes on the upper and lower surface of each wing. The AFM landing performance data assume ground flaps are selected immediately after maximum wheel brake application, which in turn is initiated on nose wheel contact and continued throughout the landing roll. The N22AU CVR evidence indicates that ground flaps were deployed. Per system design, with both throttles at idle, automatic speed brake deployment would follow when the flap surfaces pass 38°. The ground flap position is not locked out in flight but continued safe flight and landing with ground flaps deployed has been demonstrated.

Speed Brake System

The speed brake system is comprised of two speed brakes on each wing, one on the upper surface and one on the lower. The speed brakes can be deployed in flight or on the ground. The upper and lower speed brake surfaces operate together to either the fully deployed or fully retracted position. The upper and lower (and likewise, left and right) speed brake surfaces cannot be selected independently or modulated to any intermediate positions. Speed brake deployment is generally intended to decrease aerodynamic lift (to increase the descent rate in flight or to increase main gear loading and wheel braking on the ground) and increase aerodynamic drag (to dissipate aircraft energy in flight or on the ground). **Cessna Citation 525B landing performance data do not incorporate a distance credit for speed brake deployment.**

There are no speed brake lockouts with gear-on-ground (GOG), wheel speed, or other factors. Speed brakes automatically deploy when ground flaps are selected (which is a landing checklist item). The crew can alternatively deploy/retract speed brakes using an on/off toggle switch

(extend/retract) located next to elevator trim under the throttles. Independent N22AU AReS parametric evidence confirms that speed brakes were deployed during the ground rollout. The post-accident photographs of N22AU in situ show ground flaps and speed brakes deployed (see Attachment 6).

Wheel Brake System

The AFM landing performance data assume maximum wheel braking (with antiskid system ON) initiated at nose wheel touchdown and maintained to aircraft full stop. This wheel brake application timing, magnitude and duration is typical of airplane manufacturer flight testing to quantify the airplane maximum stopping performance capability. This aggressive stopping technique is available to the flight crew but is not generally used in line operations due to increased crew and passenger discomfort as well as added wheel, tire, and brake maintenance requirements. The **AFM normal landing procedures** (p. 3-92) state, "**CAUTION** If during landing a no braking condition is encountered, operate the emergency brake system. Maintenance is required before the next flight." and "**NOTE** To obtain maximum braking performance from the antiskid system, the pilot must apply continuous maximum effort (no modulation) to the brake pedals."

N22AU was not equipped 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, emergency brake position, or parking brake position. Therefore, direct time history evidence of flight crew maximum manual wheel braking requests, purposeful or inadvertent partial wheel braking requests, intentional or inadvertent left or right wheel braking requests for directional control, purposeful partial or full brake release, or inadvertent or purposeful emergency brake or parking brake application is unavailable to the investigation. Similarly, there is no parametric time history record of the anti-skid system command(s) to release the wheel brakes.

In response to questions about the status of the N22AU main gear wheel brakes, tires, antiskid control unit, hydraulic systems, and nose gear, the NTSB IIC indicated that no anomalies were discovered with the main gear wheel brakes or brake system during the NTSB post-accident examination conducted with a Textron Aviation mechanic. However, no N22AU wheel brake or antiskid system components such as wheel speed transducers or the brake control unit were removed and bench tested. In response to an NTSB request, Textron Aviation/Cessna air safety staff provided access to the Model 525B Aircraft Functional Hazard Assessment Report; the Model 525B Landing Gear, Wheel, Tire and Brake System Functional Hazard Assessment; and the Model 525B Landing Gear, Wheel and Brake System, System Safety Assessment.

Antiskid System

The AFM normal procedures on p. 3-126 state in part that, "The antiskid system provides power assisted braking with skid protection. It is designed to provide maximum braking efficiency on all runway surfaces. The system consists of two wheel speed generators, power brake relay/antiskid valve, control box, oversize reservoir, accumulator and an electrically-driven hydraulic pump." For normal wheel brake and antiskid system operation, power [hydraulic wheel] braking is available at all speeds and antiskid protection is enabled for speeds above about 12 knots. Antiskid protection is designed/optimized to accept maximum pilot-applied brake pressure, meaning pilots should not modulate brake pressure when maximum braking is desired. The AFM text advises that, "... When the [antiskid] system detects a skid and releases the applied brake pressure, any attempt by the pilot to modulate braking can result in an interruption of the applied brake signal and may increase stopping distance significantly."

Antiskid System, Power Brake System, and Wheel Brake System Abnormal Procedures

The Antiskid Inoperative abnormal procedure on p. 3-67 of the AFM states in part, "4. Landing Distance - Multiply by 1.5" followed by, "**CAUTION** Differential power [hydraulic wheel] braking is available. However, since the antiskid is inoperative, excessive pressure on the brake pedals may cause wheel brakes to lock, resulting in tire blowout" and "5. Be prepared to use the emergency brake system."

The Power Brake Low Pressure and Antiskid Inoperative abnormal procedure on p. 3-67 of the AFM states in part, "2. Plan to use the emergency brake system for landing" and "3. Landing Distance - Multiply by 1.7." The continued abnormal checklist items on AFM p. 3-68 state, "4. Brake Pedals - REMOVE FEET FROM BRAKE PEDALS" and "5. Emergency Brake Handle - PULL AS REQUIRED." The AFM text then advises "**CAUTION** Antiskid system does not function during emergency braking. Excessive pressure on emergency brake handle can cause both wheel brakes to lock, resulting in blowout of both tires..." and "**NOTE** Best performance can be obtained using a smooth, steady, continuous pull of handle to obtain the desired deceleration rate. Multiple pulls and releases of the handle will deplete the nitrogen charge."

The Wheel Brake Failure abnormal procedures on AFM p. 3-68 are very similar to the Power Brake Low Pressure and Antiskid Inoperative abnormal procedures, essentially composed of items 4 and 5, the accompanying **CAUTION** and **NOTE** content, and a supplementary statement that, "Landing distance will increase by a factor of 1.7."

Emergency Brake System

The emergency brake system is an independent pneumatic system designed to provide wheel braking in the event of a normal hydraulic brake system failure. The pilot pulls the emergency brake lever with a red knob located to the left of the AUX GEAR CONTROL T-handle to release compressed nitrogen from an emergency air reservoir (backup wheel brake application and/or landing gear deployment) and apply equal pneumatic pressure to the left and right main landing gear brake assemblies. Allowing the emergency brake lever to move forward relieves pneumatic pressure to the left and right main landing gear brake assemblies and vents nitrogen to the atmosphere. Managing pilot-applied pressure on the emergency brake lever enables modulated, symmetric, main gear wheel braking to obtain the desired aircraft deceleration rate but differential main gear wheel braking and antiskid protection are not available.

Parking Brake System

The parking brake is a part of the normal hydraulic brake system. The pilot sets the parking brakes by depressing the toe brakes to the desired position and then pulling out the black parking brake handle (located under the lower left side of the instrument panel near the pilots left knee). The parking brake handle operates a check valve in each LH and RH brake path that traps existing or subsequent pressure applied to the brakes (prevents the return of hydraulic fluid). Pushing the black parking brake handle all the way in releases the trapped hydraulic fluid and the wheel brakes.

Williams International FJ44-3A Engines

The Cessna Citation 525B is equipped with two Williams International FJ44-3A turbofan engines mounted on the aft fuselage. Each engine produces 2,780 pounds of static takeoff thrust at sea level, flat-rated to 22°C (72°F). Engine thrust must be managed by the pilot within the limits prescribed in the AFM. N22AU was not equipped with engine thrust reversers.

E. FINAL SUMMARY

The aircraft performance study provides video image sequence summaries of the N22AU short final approach and landing from two MTN airport video surveillance cameras. The event airplane flight path and ground track were reconstructed in a Google Earth model based on ADS-B, AReS, and paraphrased CVR event data. A simplified NTSB airplane simulation model was constructed to evaluate the observed N22AU landing ground rollout performance based on Cessna Citation 525B aerodynamics and Williams International engine thrust data. The study includes summaries of the respective aircraft ground flap, speed brake, wheel brake, emergency brake, and parking brake system roles and capabilities.

A review of the available ADS-B, AReS, CVR, and external video surveillance camera factual evidence indicated that N22AU main gear touchdown occurred about 2,000 feet beyond the approach threshold of runway 15, within the first third of the available landing distance, at an airspeed of about 110 knots (VREF 108 knots) and a groundspeed of about 105 knots, on a dry runway surface.

The aircraft performance study evaluated the expected Cessna Citation 525B and the actual event airplane stopping performance capability. Based on the AFM landing performance data, N22AU had adequate performance capability to safely land at Martin State Airport on runway 15, when configured for a normal landing. However, the N22AU factual evidence and the airplane aerodynamics and engine models indicate that N22AU stopping performance was substantially degraded during the landing ground rollout by an unexpected, prolonged duration, low magnitude retarding force acting at the wheel/runway interface. The substantially low magnitude retarding force at the wheel/runway interface equated to airplane deceleration due primarily to aerodynamic drag and free rolling (unbraked) wheel friction.

The N22AU constant airplane braking friction coefficient for the landing ground roll segment between 104.7 and 58 knots was 0.015, which is commonly equated to free rolling (unbraked) wheels during normal taxiing, takeoff, and unbraked segments of landing operations. N22AU did not slow to a safe taxi speed over a pavement rollout distance of about 5,000 feet, despite ground flap configuration, speed brake deployment, crew-reported wheel braking inputs, and CVR evidence of crew effort to locate the emergency brake. During the landing rollout, the N22AU crew/aircraft/runway combination did not dissipate sufficient energy to slow the aircraft to a safe taxi speed or full stop prior to the runway 15 departure end. N22AU overran the departure end of runway 15 at a groundspeed of about 58 knots, traversed grass and water-saturated soil in the runway safety area, displaced soil (evidenced by heavy landing gear rutting), struck the airport perimeter fence, and deformed portions of the aircraft and the perimeter fence as it came to rest.

F. ATTACHMENTS

Attachment 1: Cessna Citation 525B three-view drawing

Attachment 2: Martin State Airport (MTN)

Attachment 3: "Airport" camera image sequence (N22AU short final approach segment)

Attachment 4: "Airport" camera image sequence (N22AU landing ground rollout segment)

Attachment 5: "Airport" camera image sequence (N22AU landing ground rollout segment - zoom)

Attachment 6: Photographic evidence (N22AU final rest position)

Attachment 7: Weight and balance data (N22AU)

Attachment 8: Cessna Citation 525B landing performance

Attachment 9: Cockpit Voice Recorder (CVR) data (paraphrased event subset)

Attachment 10: Cessna Aircraft Recording System (AReS) data

Attachment 11: Accident flight path reconstruction (N22AU)

Attachment 12: Cessna Citation 525B Airplane Flight Manual (AFM) excerpts