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CEN22FA214

AIRCRAFT PERFORMANCE STUDY

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A. ACCIDENT

Location: Wauwatosa, Wisconsin
Date: May 26, 2022
Time: 14:56 Central Daylight Time (CDT)
19:56 Coordinated Universal Time (UTC)
Airplane: Cessna 152, registration N4978B

B. AIRCRAFT PERFORMANCE GROUP

Chairman: John O'Callaghan
National Transportation Safety Board (NTSB), RE-60
Washington, D.C.

Members: N/A

C. SUMMARY

C.1. Introduction

On May 26, 2022, at 14:56 CDT, a Cessna 152 (C152), N4978B, sustained substantial damage when it crashed shortly after taking off following a touch-and-go on runway 22R at Lawrance J. Timmerman Airport (KMWC) near Wauwatosa, Wisconsin. The pilot was fatally injured. The airplane was operated as a Title 14 *Code of Federal Regulations* Part 91 personal flight.

The touch-and-go followed the accident flight's initial departure from KMWC runway 22R and entry into a left traffic pattern for that runway. A witnesses reported that during the touch-and-go, the airplane touched down long, and then took off again. According to the witness, when the airplane lifted off the ground, the flaps remained down, and the airplane appeared to be laboring. The airplane climbed just above tree height in a nose-high attitude. Shortly thereafter, the left wing dropped, and the airplane descended "straight down."

During the climb, the pilot reported to air traffic control that he had an engine failure. Shortly thereafter, he reported that he "didn't have [his] flaps up."

The airplane impacted the ground in a residential neighborhood about 1,770 ft. (0.29 nm) from the departure end of the runway. The airplane came to rest nose down with the engine in a deep impact crater. Both wings remained partially attached to the fuselage and their leading edges sustained aft crush damage. The airplane was recovered to a secure location for further examination.

C.2. Objective and scope of the *Aircraft Performance Study*

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

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

- Automatic Dependent Surveillance – Broadcast (ADS-B) data.
- Wreckage location and condition.
- Weather information.
- Airplane performance information in the Airplane Flight Manual.
- Supplemental performance information provided by the airplane manufacturer.

The airplane was not equipped (and was not required to be equipped) with a Flight Data Recorder (FDR) or Cockpit Voice Recorder (CVR). Consequently, the control inputs, engine power, airspeed, and acceleration of the airplane during the touch-and-go and subsequent climb could not be determined with precision. In addition, the precise weight of the airplane during the accident flight is unknown, because the basic empty weight of N4978B is unknown. In this *Study*, a basic empty weight of 1,200 lb. is assumed.

However, the airplane's altitude, position, ground speed, and rate of climb during the initial takeoff, subsequent landing, and accident takeoff were obtained from ADS-B data. This information, together with reported wind data and airplane performance data published in the C152 Pilot's Operating Handbook (POH, Reference 1) and additional performance information provided by Textron (the manufacturer) is used in this *Study* to estimate the drag characteristics of the C152 and the engine power developed by the airplane during the initial takeoff, subsequent landing, and accident takeoff.

C.3. Summary of results

Based on the witness report of the airplane lifting off with the flaps extended, and the pilot's report to Air Traffic Control (ATC) that flaps were not up, it is assumed that the accident takeoff and climb were performed with the flaps fully extended to 30°. The computed lift coefficient (C_L) of the airplane reached the C152 flaps 30° maximum lift coefficient (C_{Lmax}) of 1.84 at 14:55:55.6, indicating, by definition, an aerodynamic stall at that time. The decrease in the computed flight path angle (γ) and pitch angle (θ) following this event are also consistent with an aerodynamic stall and loss of control.

Given the pilot's report of an engine failure, the power developed by the engine prior to the stall is of interest. At the estimated airplane weight of 1,488 lb., the calculated engine power required during the accident climb is lower than the estimated engine power available, based on the C152 flaps 30° performance and engine power information provided by Textron. However, the calculated engine power required during the climb is comparable to the calculated engine power required during the initial takeoff, assumed to correspond to approximately the same airplane weight, but with the flaps up instead of at 30°. Furthermore, the calculated engine power required during the accident climb matches the estimated power available if the airplane maximum gross weight of 1,670 lb. is assumed. Hence, some possible reasons for the differences between the estimates of power required and power available include:

- The provided engine power data overestimates the performance of the engine on N4978B.
- N4978B's drag at flaps 30° and flaps up is underestimated in the calculations.
- The actual gross weight of N4978B was greater than the assumed 1,488 lb. in the calculations.
- A combination of these factors is involved.

As expected, the calculated power required during the landing (assumed to have been performed with flaps 30°) is much lower than that required during both the initial takeoff and climb (assumed to have been performed with flaps up) and the accident takeoff and climb (assumed to have been performed at flaps 30°). This result, along with the comparable engine power required during the initial and accident takeoffs, and the relatively stable total energy of N4978B during the seconds prior to the stall, suggest that N4978B's engine was producing power comparable to that produced during the initial takeoff, and that a significant loss of engine power did not occur prior to the stall. After the stall, the calculations of the airplane's performance, including the required engine power, are unreliable, since the aerodynamic data available for the airplane is not representative of a stalled condition.

The sections that follow present the data used in this *Study* (as listed above), and describe the methods used to calculate additional performance information from this data. The results of these calculations are presented in the Figures and Tables described throughout the *Study*.

D. DETAILS OF THE INVESTIGATION

D.1. The Cessna 152 airplane

The Cessna 152 is a 2 seat, unpressurized light airplane, powered by a Lycoming O-235-L2C reciprocating engine producing 110 brake horsepower (*BHP*), with a maximum gross weight of 1,670 pounds.

Figure 1 shows a 3-view schematic of the airplane, taken from Reference 1. Figure 2 is a pre-accident photograph of N4978B.

No weight-and-balance information for the accident flight, other than the pilot weight, was available for this *Study*. Consequently, the accident weight of N4978B is estimated using assumed values for the airplane empty weight, fuel weight, and the weight of baggage / miscellaneous items as shown in Table 1. The total airplane weight used in the performance calculations is 1,488 pounds.

Item	Weight (pounds)
Airplane empty weight	1,200
Pilot	175
Fuel	108 (18 gallons @ 6 lb./gal.)
Baggage / miscellaneous	5
Total	1,488

Table 1. Estimated accident weight of N4978B.

D.2. Wreckage location and condition

KMWC runway 22R is 3,203 ft. long and 75 ft. wide, at an elevation of 738 ft.¹ As depicted in Figure 3, N4978B impacted the ground in a residential neighborhood about 0.7 nm south and 0.4 nm west of the runway 22R threshold, or about 1,675 ft. (0.28 nm) south and 577 ft. (0.09 nm) west of the departure end of runway 22R.

As noted above, the airplane came to rest nose down with the engine in a deep impact crater. Both wings remained partially attached to the fuselage and their leading edges sustained aft crush damage.

¹ See <https://enasr.faa.gov/eNASR/nasr/Current/Airport/2807>.

D.3. ADS-B data

D.3.1. Overview

Automatic Dependent Surveillance – Broadcast (ADS-B) capability enables aircraft to broadcast their three-dimensional position (latitude, longitude, and altitude) to other ADS-B equipped aircraft and to ADS-B ground stations.² ADS-B data broadcast from N4978B during its operations from KMWC runway 22R was received and recorded by Federal Aviation Administration (FAA) and provided to the NTSB.

ADS-B latitude and longitude are determined using Global Navigation Satellite System (GNSS) signals, including those from Global Positioning System (GPS) satellites, and altitudes determined both barometrically and by GNSS are included in ADS-B messages. The GNSS positions are very accurate compared to radar data; radar range uncertainty alone (without even considering azimuth uncertainty) is about $\pm 1/16$ nm, or ± 380 ft., and GNSS positions are generally accurate to within 60 ft. (see Reference 2). Furthermore, ADS-B data are available at a higher frequency than radar data: typically at 1 sample/second for ADS-B, and at best, 1 sample every 4.5 seconds for radar.

The recorded ADS-B data includes the following parameters:

- UTC time of the ADS-B report, in hours, minutes, and seconds. CDT = UTC – 5 hours.
- Aircraft identifying information.
- Latitude and longitude, to a resolution of 0.01 arc-seconds (≈ 1 ft.)
- Pressure altitude in feet, to the nearest 25 ft. (an uncertainty band of ± 12.5 ft.)
- Geometric (GNSS) altitude in feet, to the nearest 25 ft. The GNSS altitude is the height above the WGS84 ellipsoid, which differs from MSL altitude by the height of the geoid.³ In this *Study*, GNSS altitudes are corrected to MSL altitude by adding 116 ft.⁴
- North-south and east-west components of ground speed, to a resolution of 1 kt.
- Rate of climb, to a resolution of 1 ft./min.
- Numerous parameters documenting the quality and accuracy of each reported GNSS position.

² For more information about ADS-B, see https://www.faa.gov/air_traffic/technology/adsb.

³ "The geoid ... is the shape that the ocean surface would take under the influence of the gravity of Earth, including gravitational attraction and Earth's rotation, if other influences such as winds and tides were absent." (Wikipedia.org, accessed 10/10/2022.)

⁴ Per <https://geographiclib.sourceforge.io/cgi-bin/GeoidEval>, the geoid at KMWC is 35.4 m (116 ft.) below the surface of the WGS84 ellipsoid.

The time interval between ADS-B data points for N4978B is about 1 second. The last ADS-B data point from N4978B was received at 14:56:02.4, at an altitude of 159 ft. MSL (about 22 ft. above and 1,770 ft. (0.29 nm) from the KMWC runway 04L threshold).

The ADS-B data are presented in Figures 3 and 6-8 and discussed throughout the *Study*. In this *Study*, the position of the airplane is described by its north and east coordinates relative to the KMWC runway 22R threshold. The airplane's ADS-B latitude and longitude coordinates are transformed into east and north coordinates from the threshold using the WGS84 ellipsoid model of the earth, and the latitude and longitude coordinates of the threshold:

43° 06' 51.13" N latitude / 88° 01' 51.80" W longitude / elevation 738 ft. MSL.

D.3.2. Calculation of additional performance parameters from ADS-B data

To calculate performance parameters (such as ground speed, track angle, pitch and roll angles, etc.) from surveillance data, it is convenient to express the position of the airplane in rectangular Cartesian coordinates. The Cartesian coordinate system used in this *Study* is centered on the KMWC runway 22R threshold, and its axes extend east, north, and up from the center of the Earth. Figure 3 presents a plan view of N4978B's flight track during the accident climb.

If the position (latitude, longitude, and altitude) of an airplane is known as a function of time, then its orientation (that is, its Euler angles – pitch (θ), roll (ϕ), and heading (ψ)) can also be estimated as long as the following are true:

- The motion of the air mass relative to the Earth, i.e., the wind, is known;
- The lift coefficient (C_L) of the airplane as a function of angle of attack (α) is known;
- The gross weight of the airplane is known;
- The sideslip angle and lateral acceleration are negligible (corresponding to coordinated flight).

In this *Study*, the winds and altimeter setting are based on the KMWC surface conditions at 15:03 cited in the NTSB preliminary report of the accident (Reference 3; see also section D.4).

The Cessna 152 lift curves (C_L vs. α) for flaps up and flaps 30° are assumed to be identical to those for the Cessna 182. During a previous investigation, Textron provided the NTSB with data with which to compute the lift curves of the Cessna 182.

A gross weight of 1,488 lb. is assumed, corresponding to weight estimate shown in Table 1.

The position coordinates of an airplane as a function of time define its velocity and acceleration components. In coordinated flight, these components lie almost entirely in the plane defined by the airplane's longitudinal and vertical axes. Furthermore, any change in the *direction* of the velocity vector is produced by a change in the lift vector, either by increasing the magnitude of the lift (as in a pull-up), or by changing the direction of the lift (as in a banked turn). The lift vector also acts entirely in the aircraft's longitudinal-vertical plane, and is a function of the angle between the aircraft longitudinal axis and the velocity vector (the angle of attack, α). These facts allow the equations of motion to be simplified to the point that a solution for the airplane orientation can be found given the additional information about wind and the airplane lift curve.

The results of the performance calculations based on the ADS-B data for N4978B's initial takeoff and climb, its landing approach, and its accident takeoff and climb are presented in Figures 3 and 6-13 and discussed in subsequent sections.

D.4. Meteorological data

Since during the accident takeoff and climb N4978B remained within 200 ft. above ground level (AGL), the surface wind and temperature conditions cited in the preliminary report of the accident (Reference 3) are used in this *Study*. These conditions closely match those reported in the KMWC 14:45 Aviation Routine Weather Report (METAR), as shown in Table 2:

Item	Preliminary Report	KMWC 14:45 METAR
Report time	15:03	14:45
Wind direction (°true)	180	190
Wind speed (knots)	6	9
Visibility (statute miles)	-	10 statute miles
Present weather	none	none
Sky condition (ft. AGL)	3,100 ft. scattered	3,100 ft. scattered
Temperature (°C)	23	23
Dew point (°C)	15	14
Altimeter setting ("Hg)	29.75	29.76

Table 2. KMWC surface weather conditions near the time of the accident.

As discussed below, the wind speed used in the evaluation of N4978B's climb performance was adjusted so as to lower the computed C_{Lmax} to 1.84, the value corresponding to the flaps 30° stall speed published in the C152 POH (since it is assumed that a C_{Lmax} higher than this value is impossible to achieve). At an assumed weight of 1,488 lb., the required wind is 180° at 8.3 knots; at an assumed weight of 1,670 lb., the required wind is 180° at 10.6 knots.

D.5. Air Traffic Control Communications

The FAA provided the NTSB with an audio recording of the radio communications between N4978B and the KMWC airport traffic control tower (ATCT). A transcript of these communications, produced by the author of this *Study*, is shown in Table 3. These communications are also depicted on several Figures of this *Study*, correlated to the time and / or location at which they occurred.

Time (HH:MM:SS CDT)	Source	Content
14:55:43	N4978B	Reporting engine failure it's not working
14:55:49	LC	4978B Tim tower roger
14:55:51	N4978B	I'm stalling I'm stalling I don't know what to do
14:55:53	LC	Are you solo?
14:55:56	N4978B	I'm sorry I'm sorry I didn't have my flaps up
14:56:01	LC	Increase speed ... are you able to make the (?)

Table 3. Transcript of radio communications between Cessna N4978B and the KMWC ATC Local Controller (LC). The (?) symbol depicts an unintelligible communication.

D.6. Manufacturer-provided airplane performance data

Textron Aviation acquired the Cessna Aircraft Company in 1992, and as the manufacturer is a party to NTSB investigations involving Cessna aircraft. In support of this investigation, Textron provided plots of the C152's maximum climb rate (at the best-rate-of-climb speed, V_y) vs. altitude with flaps 30°, as well as tables of the *BHP* available from the engine, the propeller efficiency, and the flaps-up maximum climb rate (at V_y) at altitudes of 0, 5,000, and 10,000 ft. As noted previously, in this *Study*, the flaps up and flaps 30° lift curves of the Cessna 152 are assumed to be identical to those of the Cessna 182.

The information cited above is used along with data in the POH to estimate the Cessna 152's flaps-up and flaps 30° lift and drag characteristics, its engine power, and its resulting climb performance at different airspeeds and weights, at a density altitude of 2,000 ft. (the maximum density altitude achieved in the accident). These calculations are presented below, along with a comparison of the estimated climb performance capabilities of the airplane with the performance achieved during the accident climb.

D.7. Estimating drag characteristics from rate-of-climb data

D.7.1. Modeling drag and other forces on an airplane in climb

The “drag polar” of an airplane, that is, the relationship between its drag coefficient (C_D) and lift coefficient (C_L) in a given configuration, is typically modeled as a quadratic function (see, for example, References 4 and 5):

$$C_D = C_{D0} + \frac{C_L^2}{\pi(AR)e} = C_{D0} + kC_L^2 \quad [1]$$

Where AR is the aspect ratio of the wing, and e is a constant describing the wing planform's aerodynamic efficiency. Values for C_{D0} and k can be computed using climb performance data for the airplane specified at V_y , as described below. With C_{D0} and k in hand, the C_D model given by Equation [1] can be used (along with information about the available engine power) to estimate the climb performance of the airplane over a range of airspeeds, while matching the provided rate of climb data at V_y . The model can also be used to compute the engine power required for the airplane to achieve a prescribed flight path, such as that described by ADS-B data (see section D.8).

Figure 4 depicts a free-body diagram of the forces on the airplane in a climb. The equation of motion along the stability x -axis is

$$-g \sin \gamma + F_{x|aero} + F_{x|thrust} = m(\dot{u} + wQ + vR) \quad [2]$$

Where:

g = acceleration due to gravity

γ = flight path angle

$F_{x|aero}$ = aerodynamic forces along stability x axis = $-D$, where D = drag

$F_{x|thrust}$ = thrust forces along stability x axis

m = airplane mass (= W/g , where W = weight)

$\dot{u} = du/dt$ = rate of change of u , where u = linear velocity along the stability x axis⁵

v = linear velocity along the stability y axis

w = linear velocity along the stability z axis

Q = pitch rate (angular velocity about the stability y axis)

R = yaw rate (angular velocity about the stability z axis)

For wings-level steady climb, $Q = R = 0$. Assuming that the angle of attack (α) is small, then

$$F_{x|thrust} = T \cos \alpha \cong T \quad [3]$$

Where T is the total thrust from the engine, and it is assumed that the thrust acts along the body x -axis.

With these assumptions and simplifications, Equation [2] becomes

$$\left(\frac{T-D}{W}\right) = \frac{\dot{u}}{g} + \sin \gamma \quad [4]$$

⁵ From Figure 4, u is aligned with V_T and so in calm wind $\dot{u} = \dot{V}_T$. However, u is the inertial velocity along the stability x axis, and V_T is the true airspeed along that axis, which depends on both u and the wind. Changes in wind directly change V_T but not u , so to be rigorous, $\dot{u}$ is written here instead of $\dot{V}_T$.

The rate of climb is given by multiplying Equation [4] by the true airspeed, V_T :

$$\dot{h} = V_T \sin \gamma = V_T \left[\left(\frac{T-D}{W} \right) - \frac{\dot{u}}{g} \right] \quad [5]$$

For climbs with zero acceleration (such as those corresponding to the climb rates published in the POH for flaps up and provided by Textron for the C152 at flaps 30°), $\dot{u} = 0$, and the drag (D) can be computed from Equation [5] knowing $\dot{h}$, W , V_T , and T . $\dot{h}$, W and V_T are specified in the climb rate data,⁶ and T can be estimated using the known engine power, an assumed propeller profile efficiency, and the ideal propeller efficiency determined from propeller thrust momentum theory.

D.7.2. Thrust from engine power and propeller efficiency

As noted above, Textron provided the NTSB with the brake horsepower (BHP) developed by the C152's engine at altitudes of 0, 5,000, and 10,000 ft., along with the corresponding total propeller efficiency at each altitude.

The actual power delivered to the airframe is less than the BHP produced by the engine because of losses involved in producing thrust with the propeller. The power delivered to the airframe by the engine (that affects the energy state of the airplane) is equal to the propeller thrust multiplied by the true airspeed of the airplane. This is less than the BHP produced by the engine; the *propeller efficiency* is defined as

$$\eta_P = \frac{HP}{BHP} = \frac{(T)(V_T)}{BHP} \quad [6]$$

Where:

η_P = propeller efficiency

HP = horsepower delivered to the airframe

BHP = brake horsepower produced by the engine

T = thrust produced by the propeller

V_T = true airspeed

η_P is less than 1 as a result of both the limited *ideal efficiency* of the propeller (η_i , associated with the physics of producing thrust by accelerating air through the propeller), and the propeller *profile efficiency* (η_0 , associated with drag losses in the boundary layer of the propeller itself). Consequently,

$$\eta_P = \eta_i \eta_0 \quad [7]$$

⁶ Actually, calibrated airspeed is specified in the POH climb data, but true airspeed can be computed from calibrated airspeed and the specified pressure altitude and ambient temperature.

η_i depends on the flight condition and propeller diameter, and can be computed along with the propeller thrust by considering the changes in the momentum and kinetic energy of the air passing through the propeller. In this *Study*, η_0 is selected so that the overall η_p computed using Equation [7] matches the propeller efficiency data provided by Textron.

Figure 5 shows air flowing through a thrusting propeller. The air approaches the propeller at the airplane's true airspeed V_T ; it accelerates and passes through the propeller with velocity V_1 ; and it accelerates further to a final velocity of V_2 . Since the air density (ρ) is constant, conservation of mass requires that the stream tube of air accelerated by the propeller shrink in diameter as the air is accelerated, as shown in Figure 5.

The thrust produced by the propeller is equal to the change in momentum of the air in front of and behind the propeller:

$$T = \frac{d}{dt}(mv) = v \frac{dm}{dt} + m \frac{dv}{dt} \quad [8]$$

Since mass is constant,

$$\frac{dm}{dt} = 0 \quad [9]$$

The mass of air in a differential length dx at the propeller disk is

$$m = \rho A dx \quad [10]$$

Where A is the propeller disk area ($A = \pi(d/2)^2$, where d is the propeller diameter). The air velocity at the propeller disk is

$$\frac{dx}{dt} = V_1 \quad [11]$$

Consequently

$$m \frac{dv}{dt} = \frac{\rho A dx dv}{dt} = \rho A V_1 dv \quad [12]$$

The total change in air velocity dv is

$$dv = V_2 - V_T \quad [13]$$

Combining Equations [8], [9], [12], and [13] gives

$$T = \rho A V_1 (V_2 - V_T) \quad [14]$$

Now consider the work done on the air passing through the propeller, which increases the air's kinetic energy. The work done is equal to the thrust of the propeller multiplied by the differential distance dx at the propeller disk. Consequently,

$$Tdx = \frac{1}{2}\rho A dx V_2^2 - \frac{1}{2}\rho A dx V_T^2 \quad [15]$$

$$T = \frac{1}{2}\rho A (V_2^2 - V_T^2) \quad [16]$$

The right-hand side of Equation [15] is the change in the kinetic energy of the air. Combining Equations [14] and [16] gives, after some algebraic manipulation,

$$V_1^2 = V_T V_1 + \frac{T}{2\rho A} \quad [17]$$

The engine brake power (BHP), multiplied by the propeller profile efficiency η_0 , is the power delivered to the air at the propeller disk, and is equal to the thrust of the propeller multiplied by the speed of the air passing through the propeller disk:

$$(BHP)\eta_0 = TV_1 \quad [18]$$

Solving Equation [18] for V_1 , substituting into Equation [17], and rearranging terms results in the following cubic polynomial for the propeller thrust T , in terms of the known quantities ρ, A, V_T, BHP , and η_0 :

$$T^3 + [2\rho A V_T (BHP)\eta_0]T - 2\rho A [(BHP)\eta_0]^2 = 0 \quad [19]$$

Equation [19] can be solved numerically for T . The propeller efficiency η_p can then be computed using Equation [6].

η_p increases with the airplane's airspeed V_T and with propeller disk area A . The thrust of the propeller is proportional to the change in the momentum (velocity) of air produced by the propeller, but the energy required to produce this thrust is proportional to the *square* of the velocity change (change in kinetic energy). Hence it is more efficient to produce a given amount of thrust by accelerating a greater volume of air through a smaller velocity change, than a smaller volume of air through a greater velocity change.

The total engine thrust at the climb airspeeds, engine BHP values, and altitudes provided by Textron can be computed using Equation [19]. The resulting thrust can be used in Equation [5] to solve for D . The drag coefficient C_D and lift coefficient C_L then follow from

$$C_D = \frac{D}{\bar{q}S} \quad [20]$$

$$C_L = \frac{L}{\bar{q}S} \quad [21]$$

Where S is the airplane's reference wing area (159.5 ft.²), and $\bar{q}$ is the dynamic pressure of the air meeting the airplane, defined as

$$\bar{q} = \frac{1}{2}\rho V_T^2 \quad [22]$$

From Figure 4, the lift L is given by

$$L = W \cos \gamma - T \sin \alpha \quad [23]$$

As a first approximation, Equation [23] can be evaluated assuming $\sin \alpha \cong 0$. The α corresponding to the resulting L (and C_L) can then be estimated if the lift-curve (C_L as a function of α) at the corresponding configuration is known, and used in Equation [23] to update the calculation of L (and C_L). As noted above, for this *Study* the lift-curves of the Cessna 152 at flaps up and flaps 30° are assumed to be identical to those of the Cessna 182 at similar flap settings (data for the Cessna 182 was provided to the NTSB by Textron during a previous investigation).

D.7.3. Calculating $\dot{h}$ as a function of V_T : flaps up

Equation [5] can be used to compute the rate of climb $\dot{h}$ at any airspeed V_T and acceleration $\dot{u}$, if the thrust T and drag D are known. T can be computed from engine power and the flight condition using Equation [19], and D is given by Equation [20] if C_D is known. The C_D can be computed from C_L (itself given by Equations [23] and [21]) if the drag polar of the airplane in a given configuration is known.

As noted above, drag polars are classically modeled using Equation [1]. The C_L and C_D corresponding to the C152 climb rate data provided by Textron (C_{Lc} and C_{Dc}) can be computed as described in section D.7.2, and then used to determine the values of C_{D0} and k as follows. From Equation [1], in the climb condition

$$C_{Dc} = C_{D0} + kC_{Lc}^2 \quad [24]$$

This is one equation containing two unknowns, C_{D0} and k . But C_{Lc} and C_{Dc} correspond to the airspeed for which $\dot{h}$ is a maximum (V_y), and the airplane is not accelerating. This fact can be used to find a second equation to help solve for the two unknowns.

For $\dot{u} = 0$, Equation [5] can be written

$$\sin \gamma = \left(\frac{T-D}{W} \right) \quad [25]$$

For small α and γ , $L \cong W$ (see Equation [23]) and Equation [25] becomes

$$\sin \gamma \cong \left(\frac{T}{W} - \frac{C_D}{C_L} \right) \quad [26]$$

As can be inferred from Equation [19], T is a function of V_T , and so for steady flight also varies with C_L (since C_L varies with V_T). However, in case of engine failure, $T = 0$ is constant, and γ (the engine-out glide angle) is maximized when C_D/C_L is minimized. From Equation [1],

$$\frac{C_D}{C_L} = \frac{C_{D0}}{C_L} + kC_L \quad [27]$$

The C_L (and airspeed) at which C_D/C_L is minimized is that at which the derivative of C_D/C_L with respect to C_L is equal to zero. Taking the derivative of Equation [27] with respect to C_L and setting it equal to zero gives

$$\frac{\partial(C_D/C_L)}{\partial C_L} = -\frac{C_{D0}}{C_L^2} + k = 0 \quad [28]$$

But the C_L at this condition is simply the C_L at the speed corresponding to the maximum glide angle (V_g). Hence

$$k = \frac{C_{D0}}{C_{Lg}^2} \quad [29]$$

Where C_{Lg} is the C_L corresponding to flight at V_g . Combining Equations [24] and [29],

$$C_{Dg} = C_{D0} + kC_{Lg}^2 = C_{D0} + \left(\frac{C_{D0}}{C_{Lg}^2} \right) C_{Lg}^2 = 2C_{D0} \quad [30]$$

$$C_{D0} = \frac{C_{Dg}}{2} \quad [31]$$

Finally, substituting Equation [31] into Equation [29] gives

$$k = \frac{C_{Dg}}{2C_{Lg}^2} \quad [32]$$

C_{Dg} is given by Equation [26], with $T = 0$ and γ (a negative number in this case) computed from the engine-out glide performance data provided in the POH (usually specified as a plot of altitude loss as a function of horizontal distance travelled):

$$C_{Dg} = -C_{Lg} \sin \gamma \quad [33]$$

The POH provides V_g and the resulting engine-out glide performance with the flaps up, since this configuration minimizes C_D/C_L . Consequently, a flaps-up drag polar that matches the glide data in the POH can be constructed using Equation [1] and values of C_{D0} and k given by Equations [31] and [32].

The POH does not provide engine-out glide data at flaps 30°, and so Equations [31] and [32] cannot be used to construct a drag polar for this configuration. However, the climb performance data provided by Textron can be used to construct a drag polar for flaps 30°, using a similar method as described above, but accounting for the fact that in a climb T is not zero and varies with V_T .

D.7.4. Calculating $\dot{h}$ as a function of V_T : flaps 30°

The flaps 30° and flaps-up climb data provided by Textron specify the maximum $\dot{h}$ (rate of climb) and corresponding V_y as a function of altitude. At a given altitude, V_y corresponds to the V_T at which the $\dot{h}$ given by Equation [5] (with $\dot{u} = 0$) is maximized. This in turn occurs when the derivative of Equation [5] with respect to V_T is equal to zero:

$$\frac{d\dot{h}}{dV_T} = \frac{d}{dV_T} \left[\frac{V_T}{W} (T - D) \right] = \left(\frac{1}{W} \right) \left\{ \frac{d[V_T(T-D)]}{dV_T} \right\} = 0 \quad [34]$$

$$\frac{d(V_T T)}{dV_T} = \frac{d(V_T D)}{dV_T} \quad [35]$$

$$T + V_T \left(\frac{dT}{dV_T} \right) = D + V_T \left(\frac{dD}{dV_T} \right) \quad [36]$$

$$T - D = V_T \left(\frac{dD}{dV_T} - \frac{dT}{dV_T} \right) \quad [37]$$

Combining Equations [20] and [22],

$$D = \frac{1}{2} \rho V_T^2 C_D S \quad [38]$$

Combining Equations [1], [21], and [22],

$$C_D = C_{D0} + k C_L^2 = C_{D0} + k \left(\frac{2W}{\rho S V_T^2} \right)^2 \quad [39]$$

Substituting Equation [39] into Equation [38] and taking the derivative of D with respect to V_T gives

$$\frac{dD}{dV_T} = \rho S C_{D0} V_T - \frac{4W^2 k}{\rho S V_T^3} \quad [40]$$

Substituting Equations [40], [38], [21], and [22] into Equation [37] leads to:

$$3\bar{q}SC_{D0} + k(\bar{q}SC_L^2 - 2WC_L) = T + V_T \left(\frac{dT}{dV_T} \right) \quad [41]$$

Equations [1] and [41] are two equations for the two unknowns C_{D0} and k . These can be solved to yield the following expression for k , recognizing that at the maximum climb rate condition in question $V_T = V_y$ and $C_L = C_{Lc}$ (the lift coefficient corresponding to V_y):

$$k = \frac{3\bar{q}SC_{Dc} - T - V_y(dT/dV_T)}{2(\bar{q}SC_{Lc}^2 + WC_{Lc})} \quad [42]$$

The rate of change of T with V_T , that is, dT/dV_T , can be determined at V_y for a given value of BHP after solving Equation [19] for T over a range of V_T . The resulting dT/dV_T can then be used in Equation [42] to compute k . The value of C_{Dc} in Equation [42] is the C_D corresponding to the climb condition at V_y and C_{Lc} , and can be computed from Equation [20] after solving Equation [5] for D . This value of C_{Dc} and the value of k from Equation [42] can be used to solve for C_{D0} using Equation [24]:

$$C_{D0} = C_{Dc} - kC_{Lc}^2 \quad [43]$$

Separate flaps up and flaps 30° drag polars that match the provided climb data for these configurations can be constructed using Equation [1] and values of C_{D0} and k (for each flap configuration) given by Equations [43] and [42]. The flaps-up drag polar constructed using this method is similar to but differs slightly from the flaps-up drag polar constructed using the POH engine-out glide data as described in section D.7.3. The reasons for the difference are unknown, but might be the result of propeller wash effects on C_D while the engine is operating, and of propeller drag when it is not. The flaps-up climb performance of the C152 over a range of airspeeds, and the flaps-up power required during N4978B's first takeoff from runway 22R, are presented below based on the drag polar constructed from the flaps-up climb data provided by Textron (not on the POH engine-out glide data).

D.8. Performance calculation results

D.8.1. Airplane performance during the accident takeoff and climb

The results of the performance calculations based on the ADS-B data for N4978B, and of the calculation of the nominal C152 climb performance over a range of airspeeds based on the drag polars computed from the climb and engine power data provided by Textron, are presented in Figures 3 and 6-13.

Figure 3 presents a plan view of the ADS-B data over a background image depicting the KMWC airport environment. The airplane's height above the ground is labeled

along with the local time every 5 seconds along the flight track. The ATC communications listed in Table 3 are also depicted along the flight track at the locations at which they occurred. The red star indicates the point at which the computed C_L reached the flaps 30° C_{Lmax} , where the airplane likely stalled. The red asterisk symbol depicts the crash site southeast of the last ADS-B data point.

The blue line in Figure 3 depicts the flight track resulting from integrating (with time) the ground speeds recorded in the ADS-B data during the accident takeoff and climb. This integrated track is used for the performance calculations, which depend strongly on the ground speed computed (through differentiation) from the flight track. The computed ground speed closely matches the ADS-B recorded ground speed, though is slightly “smoother” as a result of numerical effects associated with the integration and differentiation steps. The performance parameters computed using the flight track defined by the integrated ADS-B speeds are much better behaved (less noisy) and more realistic than those that would result from the ground speed computed by taking the derivatives of the as-recorded ADS-B positions.

Figure 6 presents the ADS-B north and east coordinates as function of time, and compares these with the north and east components of the flight track obtained by integrating the north and east components of the ADS-B ground speed. The red vertical line labeled C_{Lmax} in this and other Figures indicates the time (14:55:55.6) at which N4978B’s C_L reached the flaps 30° C_{Lmax} , and the airplane likely stalled.

Figure 7 presents the ADS-B altitude data as a function of time during the accident takeoff and climb. The altitude resulting from integrating (with time) the vertical speed recorded in the ADS-B data is also shown. The integrated altitude is used for the performance calculations, in order to obtain computed climb rates that match the recorded ADS-B vertical speed, and that are smoother and more realistic than those that would result from taking the time derivative of the recorded altitudes (which are recorded to a resolution of ± 12.5 ft. and so exhibit step increments of 25 ft.)

Figure 8 presents N4978B’s speeds and rate of climb during the accident takeoff and climb. The ADS-B recorded ground speed and vertical speed are shown, along with the smoothed ground speed and rate of climb resulting from integrating the ADS-B speeds (to get positions) and then differentiating the results to get back to speeds. The smoothing results from the numerical effects of these operations on relatively low-sample rate data (the result would match the original speeds more closely if the data were sampled at a higher rate).

The airspeeds shown in the top plot of Figure 8 are based on the smoothed ground speed and an assumed wind from 180° (true) at 8.3 knots. The wind speed was adjusted up from the 6 knots reported in Reference 3 in order to lower the peak C_L

achieved by the airplane to the flaps 30° C_{Lmax} , since the airplane cannot achieve a C_L higher than this value. The 8.3 knots is in the range of 6-9 knots shown in Table 2.

Figure 9 presents the pitch angle, flight path angle, angle of attack, and roll angle computed from the ADS-B data and assumed wind during the accident takeoff and climb. Notice that after the airplane reaches C_{Lmax} at 14:55:55.6, the pitch angle, angle of attack, and flight path angle all drop suddenly, consistent with an aerodynamic stall. Also note that the computed roll angle drops from about 1° left to about 23° left between 14:55:58 and 14:56:02, consistent with the flight track shown in Figure 3 and the witness statement that the “left wing dropped.”

Figure 10 presents the computed C_L and normal load factor (nlf) during the accident takeoff and climb. The C_L is shown for two values of weight: the weight estimate shown in Table 1 (1,488 lb.), and the maximum gross weight of the C152 (1,670 lb.). If the wind speed of 6 knots reported in Reference 3 is assumed, the computed C_L for both weight cases exceeds the flaps 30° C_{Lmax} , which is not possible; the flaps 30° C_{Lmax} is the highest C_L the airplane can achieve (the C_{Lmax} at lower flap settings is lower than that at flaps 30°). In order to reduce the computed C_L to the flaps 30° C_{Lmax} , a wind speed of 8.3 knots is required at a weight of 1,488 lb., and a wind speed of 10.6 knots is required at a weight of 1,670 lb.

The bottom plot of Figure 10 shows that the computed nlf at the time C_{Lmax} was reached (the stall) was about 0.92, and decreased afterwards, reaching about 0.82 at the end of the data. The oscillations in C_L mirror those in nlf , which are in turn driven by changes in vertical speed and the associated pitch angle and pitch rate.

Figure 11 presents N4978B’s total energy (potential energy + kinetic energy), rate of change of total energy, and horsepower required (based on the flaps 30° drag polar developed as described in section D.7) during the accident takeoff and climb. The calculations are shown for weights of 1,488 lb. and 1,670 lb. Note that the total energy of the airplane does not decrease significantly, but actually increases slightly, after the pilot reported an engine failure at 14:55:43. The total energy does not drop significantly until after C_{Lmax} is reached and the altitude drops quickly. Similarly, the horsepower required at the time C_{Lmax} is reached is not much different from that at the time of the reported engine failure. The computed total energy and horsepower required during this time are not consistent with an actual loss of power (engine failure). If the engine had failed, the effect on the total energy and horsepower required calculations would have been immediate and significant, as can be confirmed by comparing the values of these parameters during the accident takeoff and climb with their values during the preceding landing approach (for which engine power is deliberately reduced). Comparisons of the power required during the accident takeoff and climb with that required during the previous landing and the initial takeoff and climb are considered below.

D.8.2. Accident performance compared to previous and nominal performance

Figure 12 is similar to Figure 11, but compares the total energy, rate of change of total energy, and horsepower required for the accident takeoff and climb (at flaps 30°) with those for the previous landing (at flaps 30°) and for the initial takeoff and climb (at flaps up). The airplane weight in all cases is 1,488 lb. The large negative rate of change of energy during the landing differs significantly from the rate of change of energy during the climbs. The rate of change of energy is also significantly different between the initial and accident climbs; during the initial climb, rate of change is about 32 HP, while during the accident climb it is initially between 10 and 20 HP and decreases to between 0 and 10 HP before the stall. However, during the landing the rate of change of energy is between -40 and -50 HP, and so during the accident climb the airplane is not losing energy as it is during the landing approach, which is evidence that the engine was producing significant power during the accident climb.

In fact, Figure 12 shows that the power required during the initial and accident climbs are initially very similar (about 55 to 60 HP). The power required is the actual power delivered to the airframe (equal to $(T)(V_T)$), and is less than the *BHP* developed by the engine because of the losses involved with producing thrust with the propeller (see Equation [6]). The power required reflects the power necessary to both overcome drag and increase the energy state of the airplane; if most of the power is used to overcome drag, little will be left to increase the airplane's energy. The accident climb performance is consistent with this scenario, as the power required is high (50 - 60 HP), but the rate of change of energy is low. During the initial takeoff with the flaps up, the drag is lower, and so more power is left over to increase the airplane's energy, and the consequent rate of change of energy is higher.

Figure 12 shows that though the power required during the initial and accident climbs are initially similar, the power required during the accident climb drops off as the climb progresses, unlike the power required during the initial climb. This is the result of the loss of airspeed during the accident climb (see Figure 8), which in turn reduces the propeller efficiency and power delivered to the airframe.

The effect of airspeed on the power available to the airframe (equal to $(BHP)(\eta_p)$) is shown in the top plot of Figure 13, which plots power available vs. calibrated airspeed, and compares this with the power required during N4978B's previous (initial) and accident climbs, and during the previous landing. The drop in power available as airspeed decreases, which is the effect of the decrease in η_p , is apparent. The *BHP*

used in this calculation is obtained by interpolating the *BHP* data provided by Textron to a density altitude of 2,000 ft. Note that the resulting power available is higher than the power required calculation for *both* the accident climb (at flaps 30°) and the previous climb (at flaps up), at a weight of 1,488 lb. This suggests that N4978B's engine produced less power than nominal, or that the drag for both flaps 30° and flaps up is higher than estimated, or that N4989B's weight was more than 1,488 lb., or that a combination of these factors is involved. The power required during the accident climb can be raised closer to the power available line if the weight is increased to 1,670 lb. In any case, Figure 13 indicates that the engine power developed during the accident climb was consistent with that developed during the previous climb, and that the decreasing power delivered to the airframe during the accident climb can be attributed to the decreasing airspeed and propeller efficiency during that climb. These observations indicate that the engine was producing takeoff power at the time the pilot reported an engine failure.

The bottom plot of Figure 13 presents the predicted rate of climb with flaps 30° vs. calibrated airspeed at weights of 1,490 lb. and 1,670 lb., compared to the rate of climb achieved during the accident climb and previous climb. The rate of climb achieved during the previous climb, with flaps up, was greater than the predicted climb with flaps 30° because of the lower drag at flaps up. The rate of climb achieved during the accident climb is roughly consistent with the predicted rate of climb with flaps 30° at a weight of 1,490 lb.

The green lines in Figure 13 indicate that the power required during the flaps 30° landing approach, with a rate of descent of about 800 ft./min., is significantly lower than the power required for climb, as expected. These landing approach results are presented in Figure 13 to confirm that the calculations can easily identify a low-power condition, such as reduced power during descent, or an engine failure. Such a low power condition is not consistent with the data for the accident climb.

E. CONCLUSIONS

The material in this *Study* supports several observations and conclusions regarding the performance of N4978B during its second takeoff and climb from KMWC runway 22R. According to a witness who observed the accident and a statement the pilot made to ATC, N4978B took off and attempted to climb with the flaps extended after performing a touch-and-go. The performance of the airplane described in this *Study* is consistent with this scenario. Before telling ATC that the flaps were not up, the pilot reported an engine failure; however, the energy state of the airplane, and the computed power required during the accident climb at flaps 30°, are inconsistent with a loss of power. Instead, the performance calculations indicate that the engine was producing power consistent with the power levels achieved during the previous (initial) takeoff and climb, which was performed with the flaps up.

The airplane lift coefficient (C_L) computed using the ADS-B data and wind speeds consistent with the reported weather indicate that the flaps 30° maximum lift coefficient (C_{Lmax}) was reached at 14:55:55.6, about 13 seconds after the pilot reported an engine failure, and nearly coincident with the time that the pilot reported that the flaps were not up. The increase of C_L to C_{Lmax} , and the rapid drop in pitch angle, angle of attack, and flight path angle that followed, are consistent with an aerodynamic stall and subsequent loss of control.

Submitted by:

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National Resource Specialist - Aircraft Performance

F. REFERENCES

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G. GLOSSARY

Acronyms

ADS-B	Automatic Dependent Surveillance – Broadcast
AFM	Airplane Flight Manual
AGL	Above ground level
BHP	Brake horsepower
CDT	Central Daylight Time
CFR	Code of Federal Regulations
CG	Center of Gravity
CVR	Cockpit Voice Recorder
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
"Hg	Inches of mercury
HP	Horsepower
KCAS	Knots calibrated airspeed
KIAS	Knots indicated airspeed
KMWC	Lawrence J. Timmerman Airport (KMWC), Wauwatosa, Wisconsin
KTAS	Knots true airspeed
METAR	Meteorological Terminal Air Report
MSL	Mean Sea Level
NTSB	National Transportation Safety Board
POH	Pilot's Operating Handbook
UTC	Universal Coordinated Time

Symbols

α	Angle of attack
γ	Flight path angle
θ	Pitch angle
η_0	Profile propeller efficiency
η_i	Ideal propeller efficiency
η_P	Total propeller efficiency
ρ	Air density
A	Propeller disk area
AR	Wing aspect ratio = span ² /area
BHP	Brake horsepower produced by the engine
C_D	Drag coefficient
C_{D0}	Drag coefficient at $C_L = 0$
C_{Dc}	Drag coefficient at best rate of climb
C_L	Lift coefficient
C_{Lc}	Lift coefficient at best rate of climb
d	Propeller diameter
D	Drag
e	Oswald's wing efficiency factor (see Equation [1])
F_x	Force along x axis
g	Acceleration due to gravity
h	Altitude
$\dot{h}$	Rate of climb (time derivative of $h = dh/dt$)
HP	Power delivered to the airplane to increase its energy state (less than the BHP of the engines because of losses due to propeller efficiency)
k	Induced drag coefficient constant (see Equation [1])
L	Lift
m	Mass
Q	Pitch rate (angular velocity about the y axis)
$\bar{q}$	Dynamic pressure
R	Yaw rate (angular velocity about the z axis)
RC	Rate of climb
S	Wing area
t	Time
T	Thrust
u	Airplane velocity along x axis
$\dot{u}$	Time derivative of $u = du/dt$
v	Airplane velocity along y axis, or velocity of air in propeller's stream tube
V_1	Air velocity at the propeller disk or final ground speed
V_2	Final velocity of air accelerated through propeller disk
V_T	True airspeed
W	Weight
w	Airplane velocity along z axis
x	Distance along stream tube flowing through propeller

FIGURES

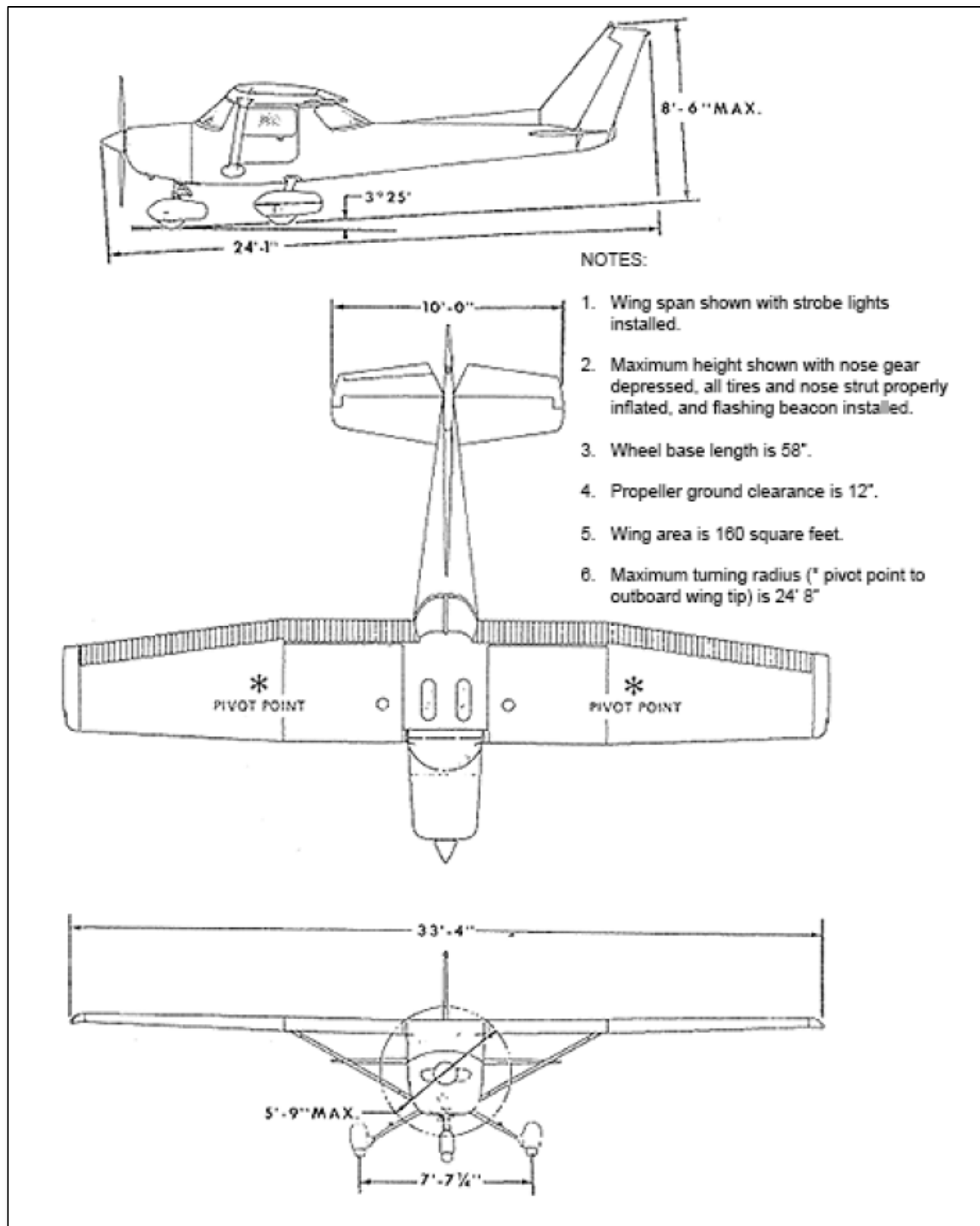


Figure 1. 3-view of the Cessna 152 airplane (from Reference 1).



Figure 2. Pre-accident photograph of N4978B (photo credit: Andrew Salisbury).

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Plan view of flight path

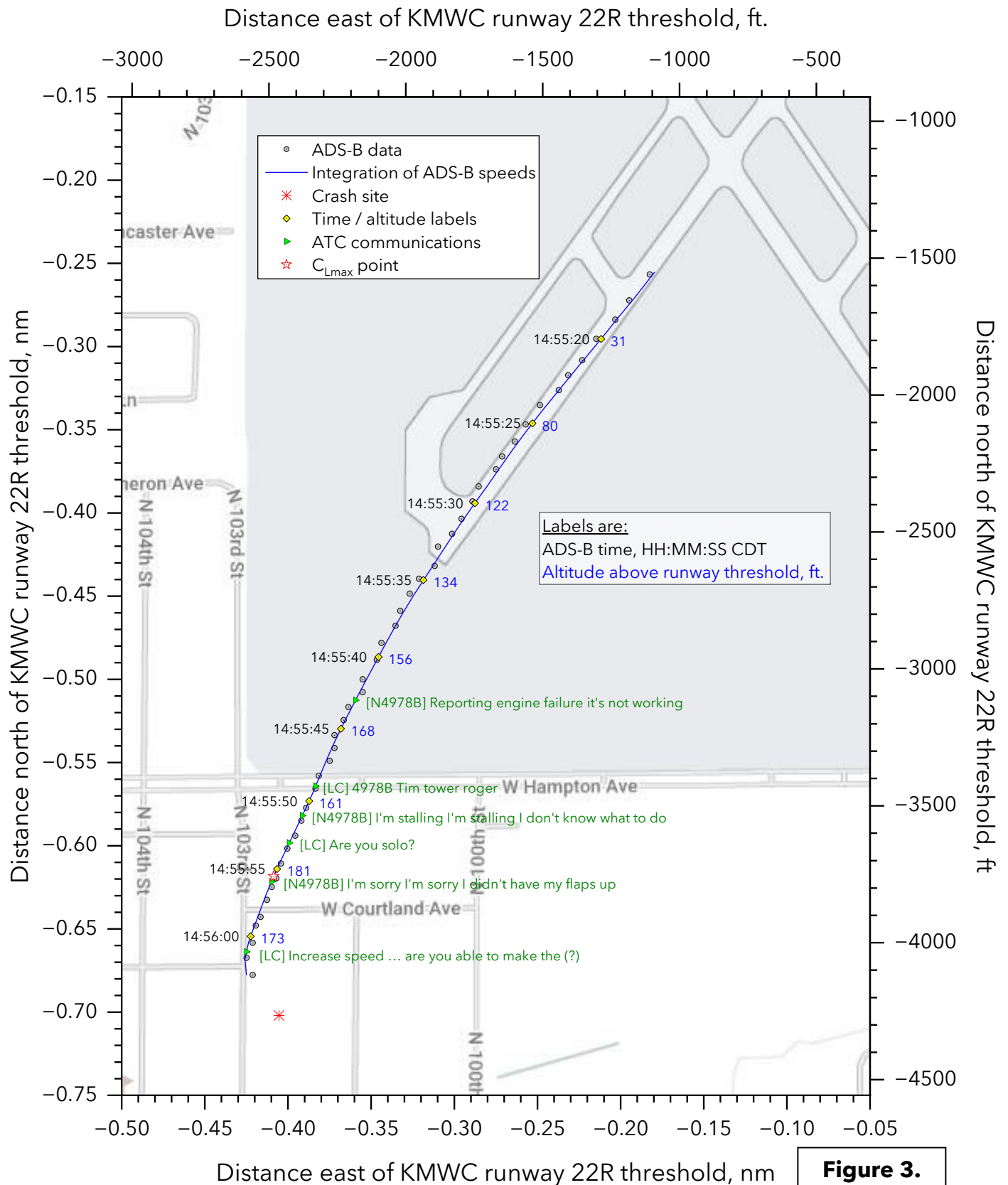


Figure 3.

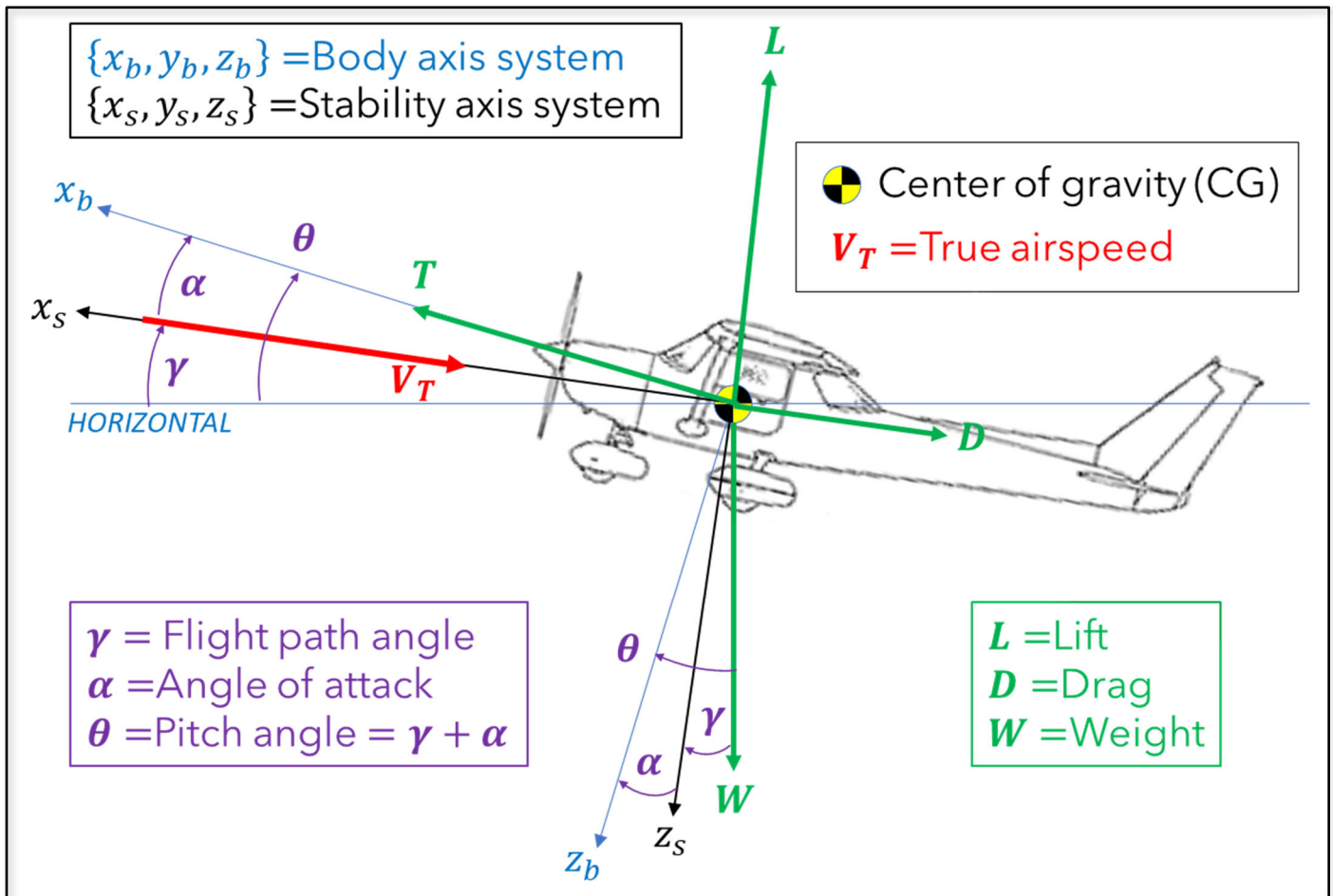


Figure 4. Forces on an airplane in a wings-level climb.

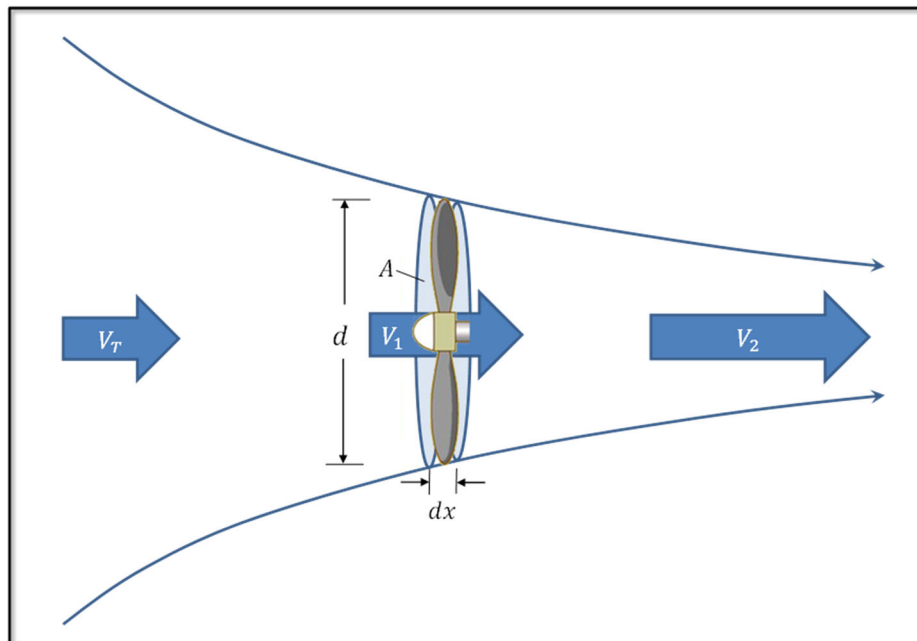
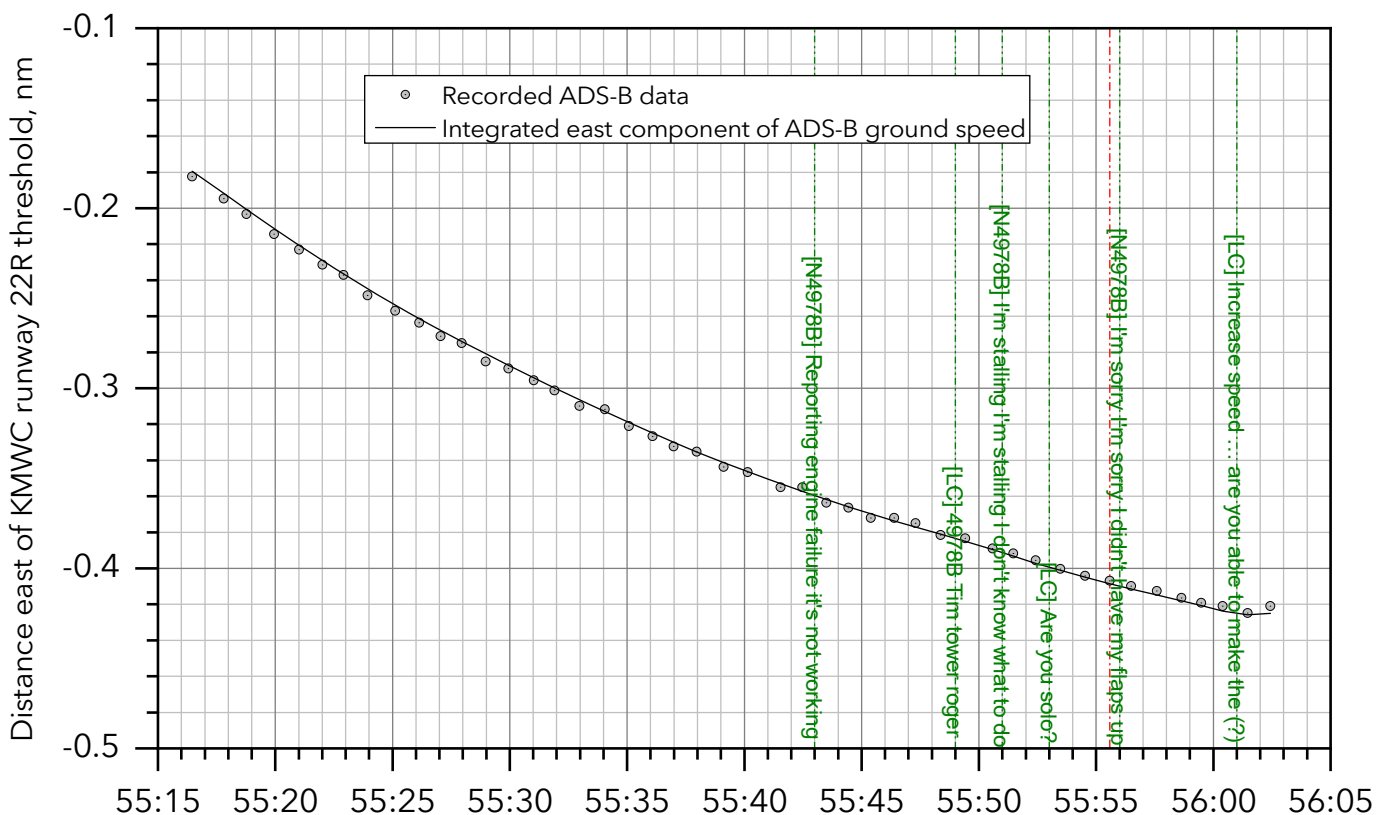
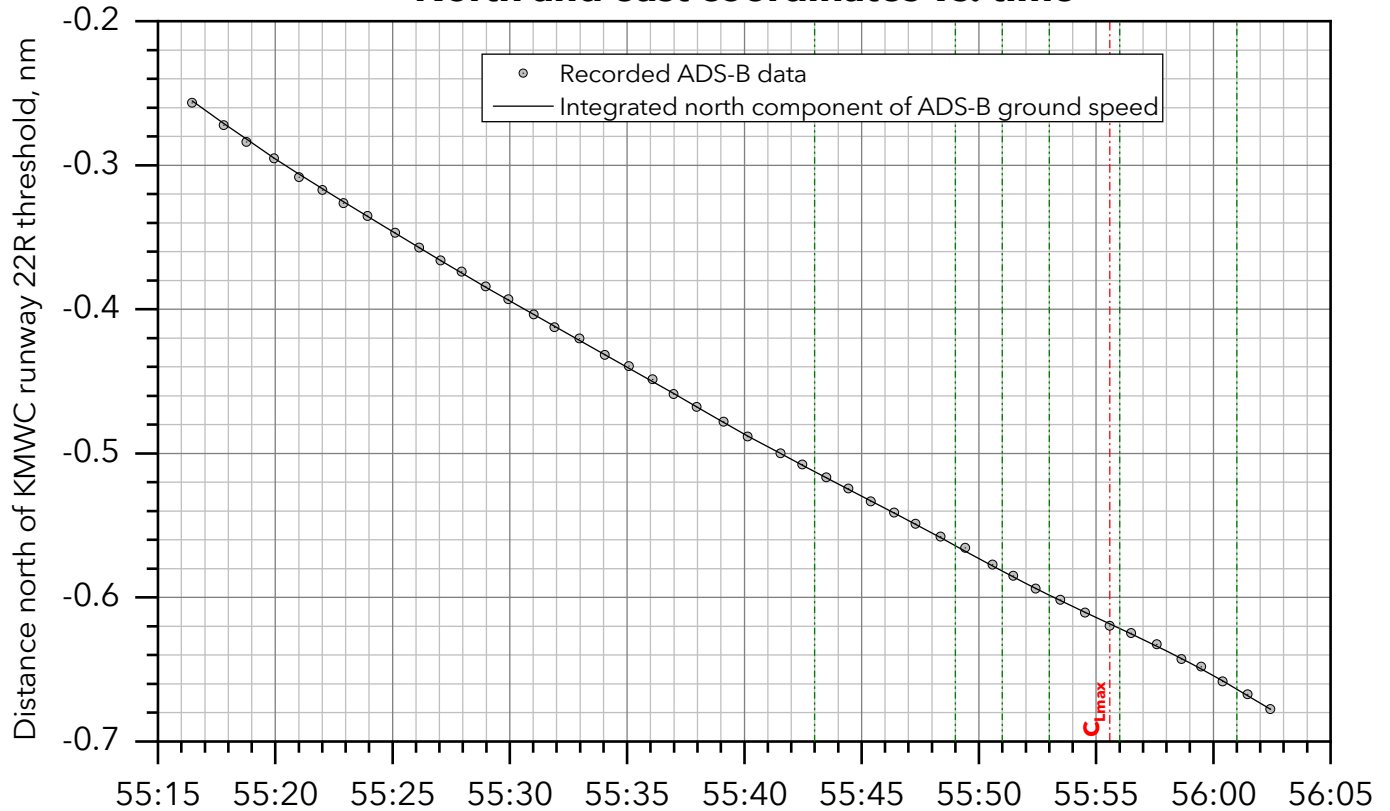


Figure 5. Diagram of a stream tube of air being accelerated through a propeller.

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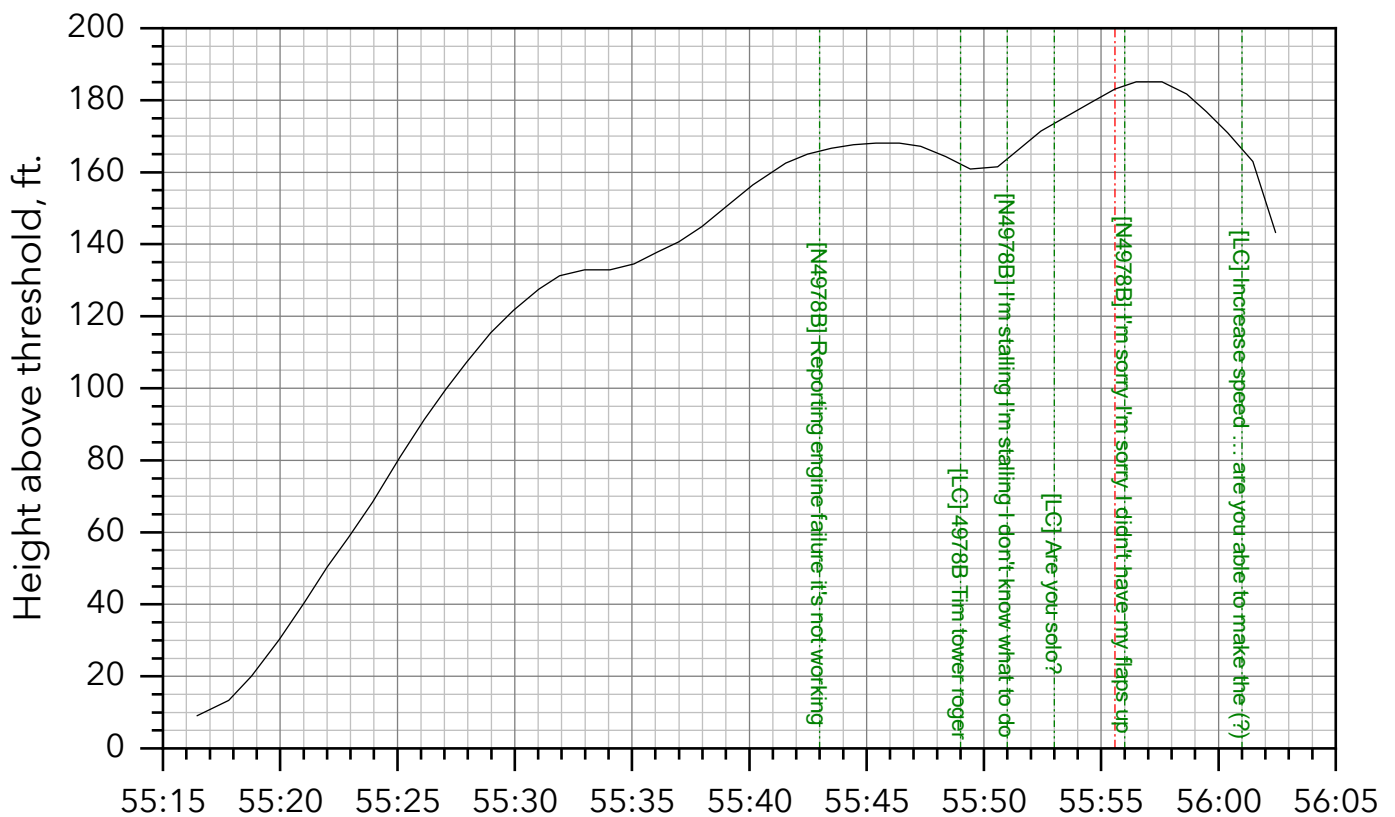
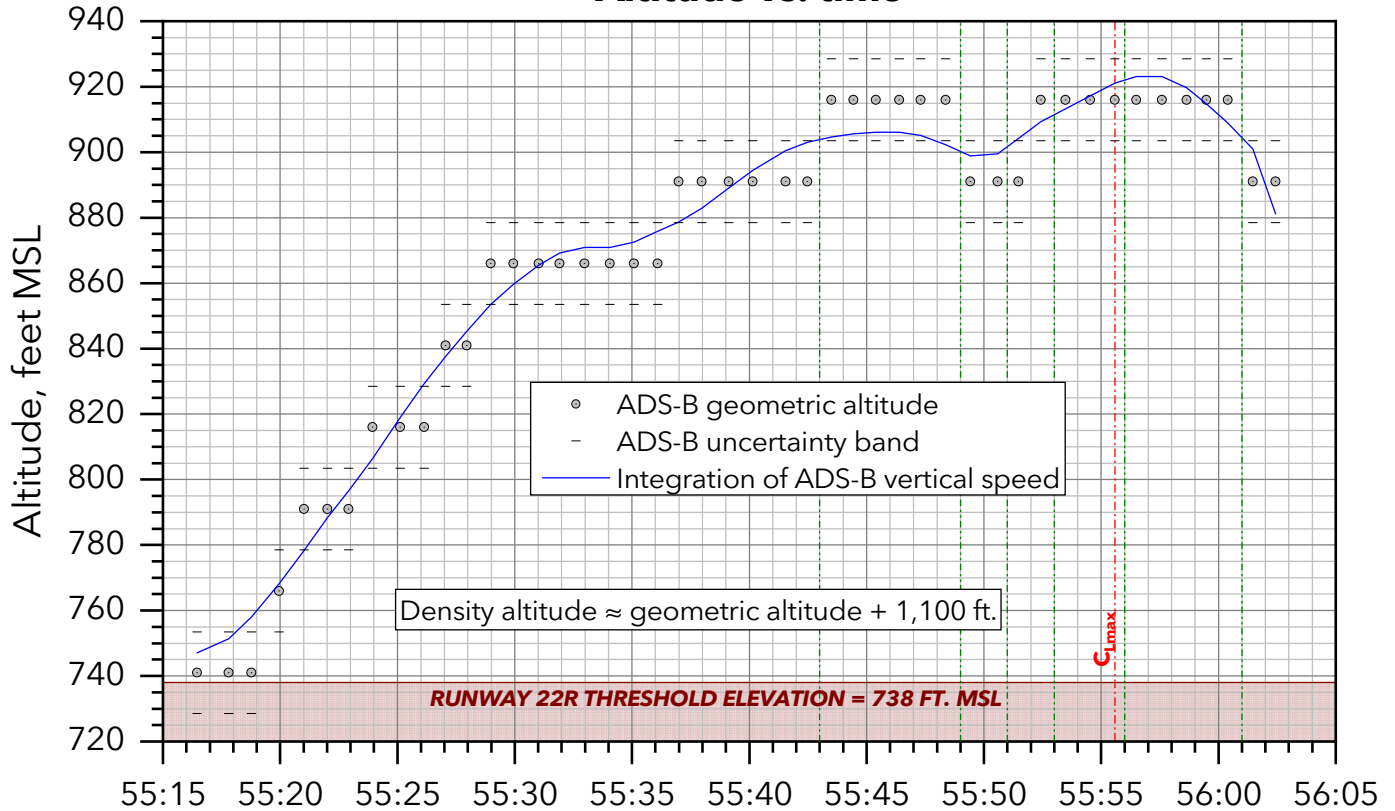
North and east coordinates vs. time



ADS-B time, MM:SS after 14:00:00 CDT

Figure 6.

Altitude vs. time



ADS-B time, MM:SS after 14:00:00 CDT

Figure 7.

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Speeds vs. time

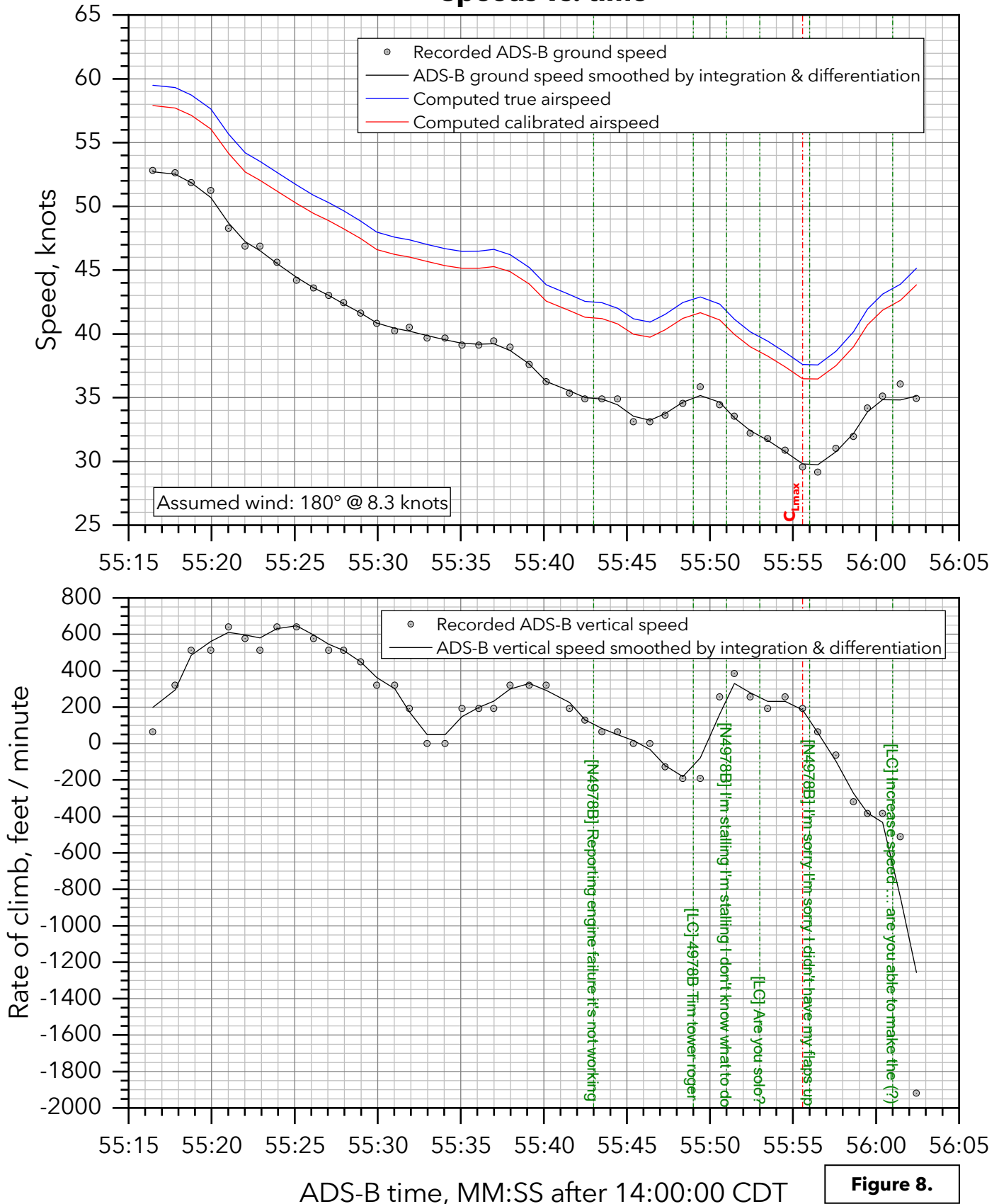
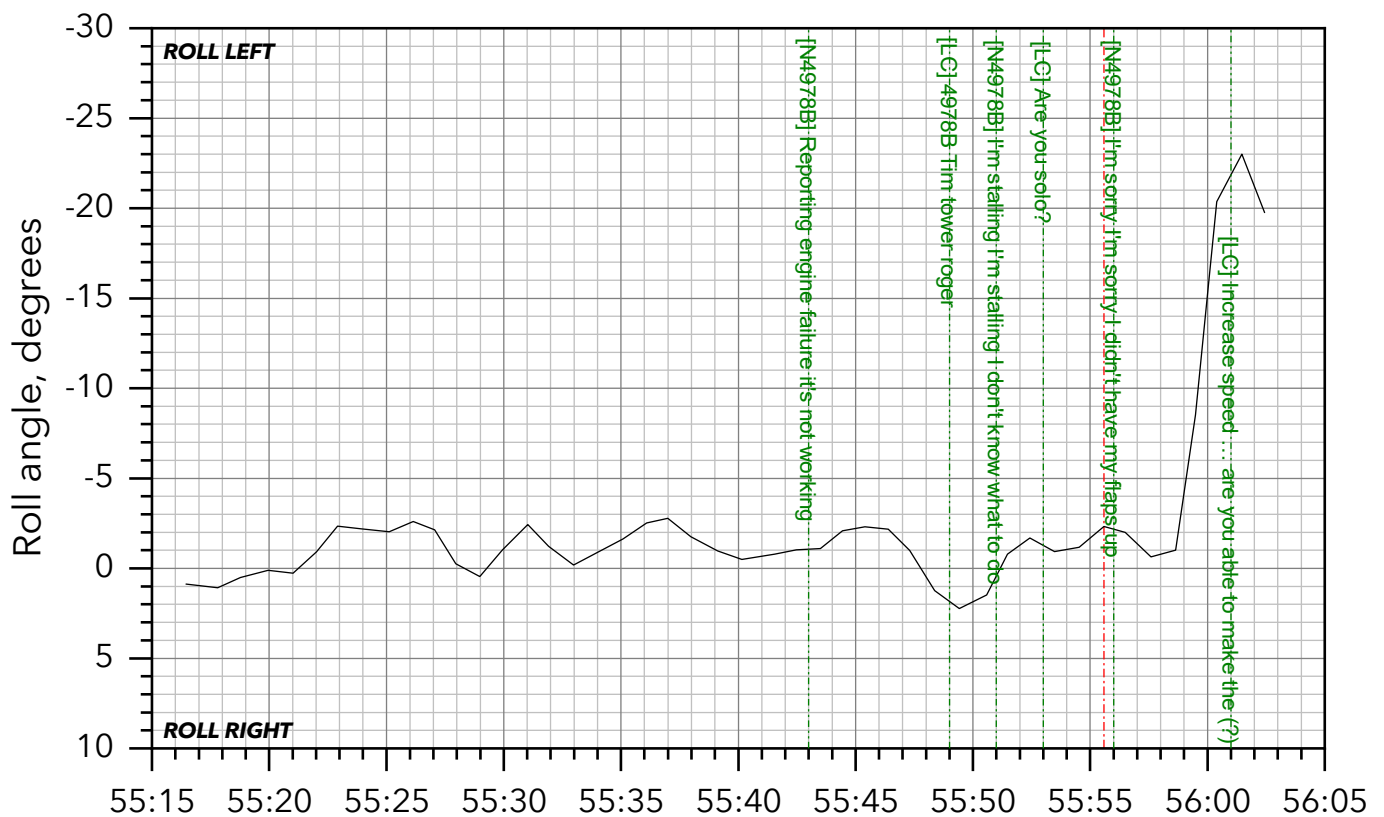
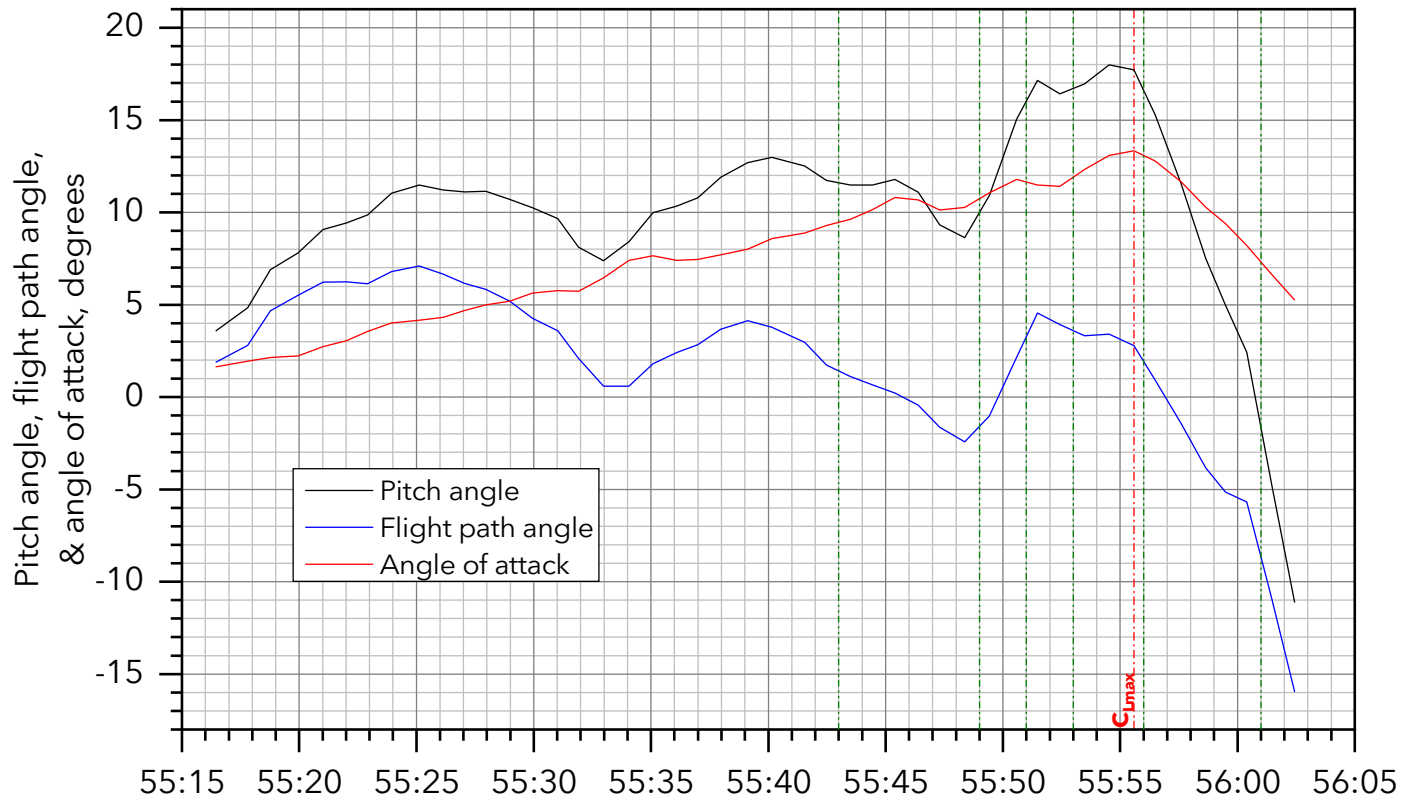


Figure 8.

CEN22FA214: Cessna 152, N4978B, Wauwatosa, WI 05/26/2022

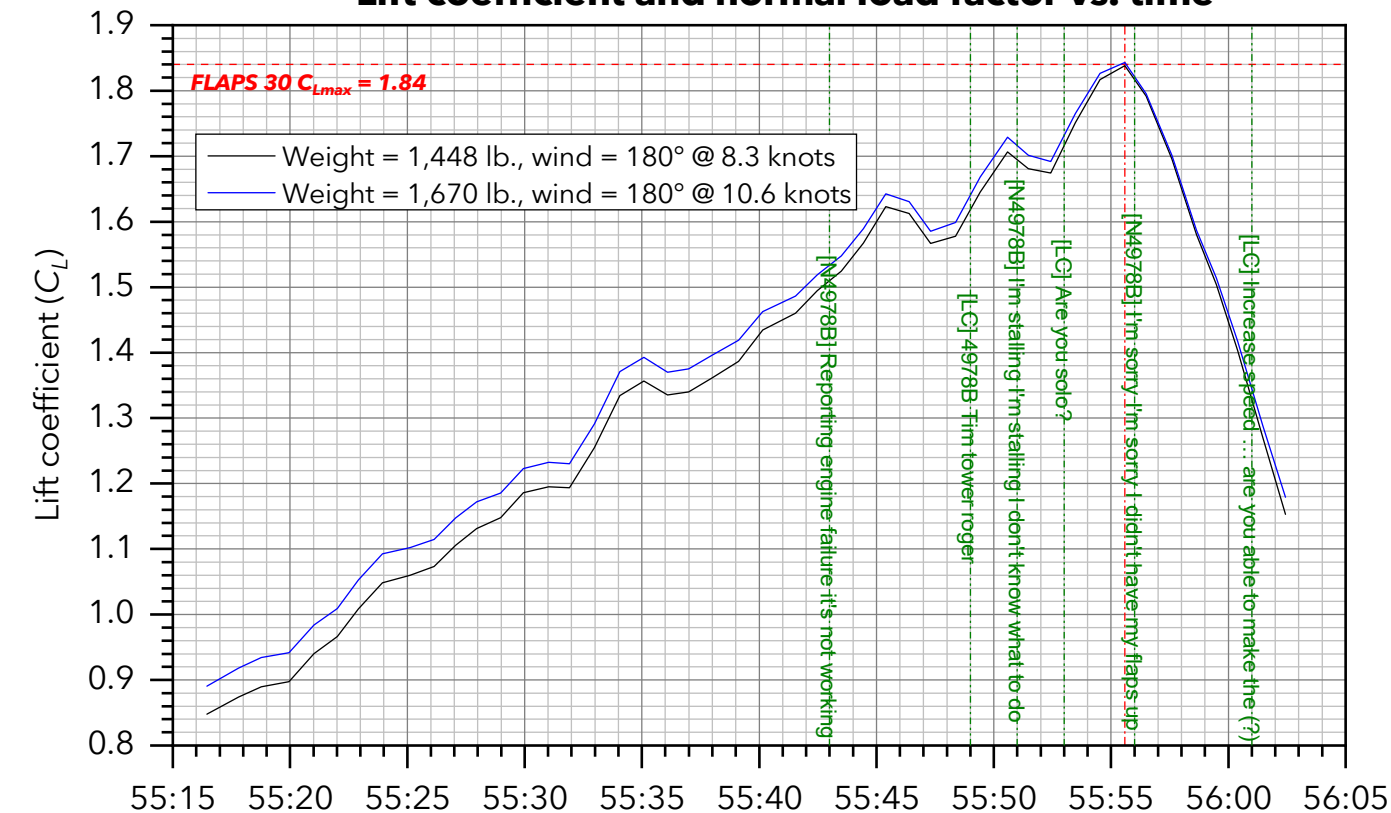
Computed flight angles vs. time



ADS-B time, MM:SS after 14:00:00 CDT

Figure 9.

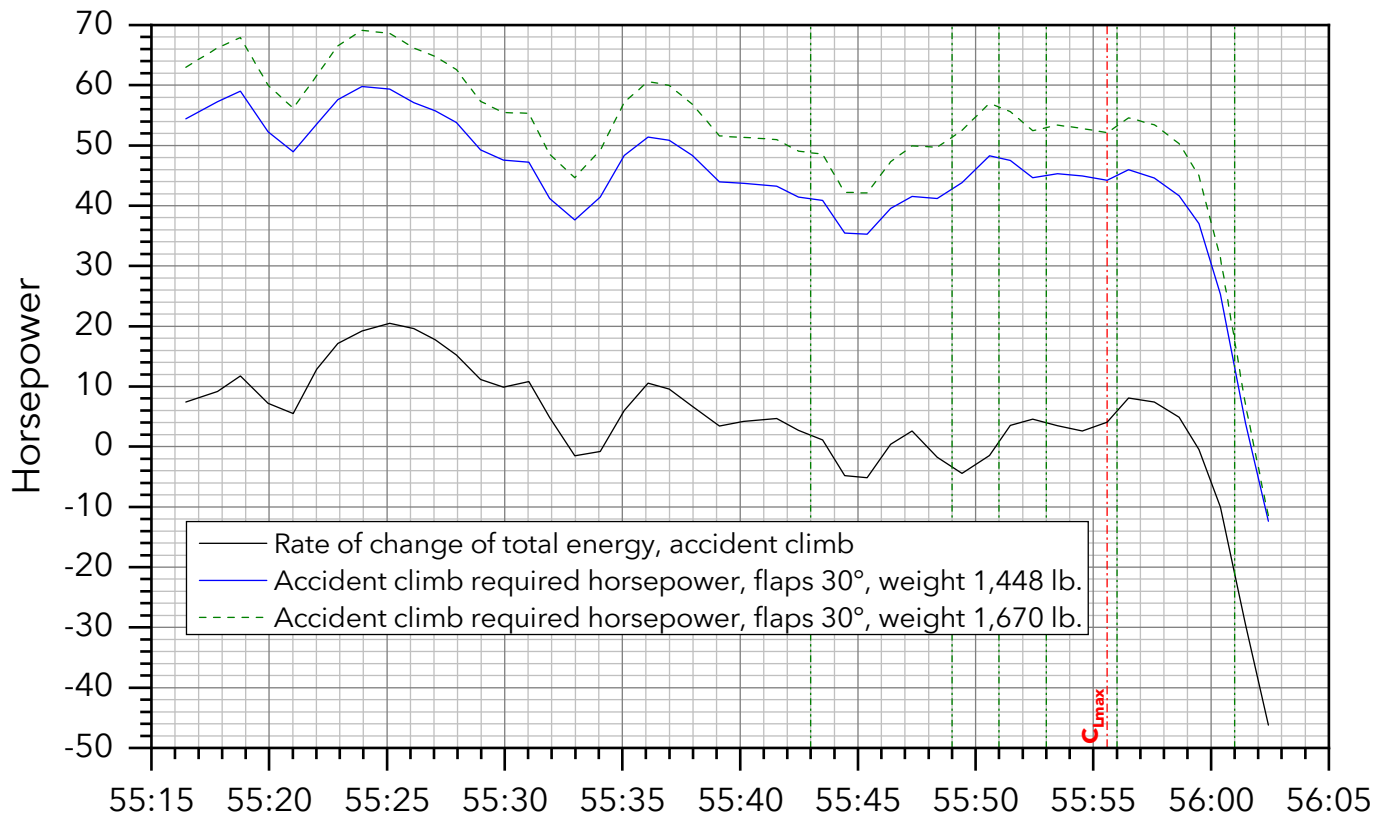
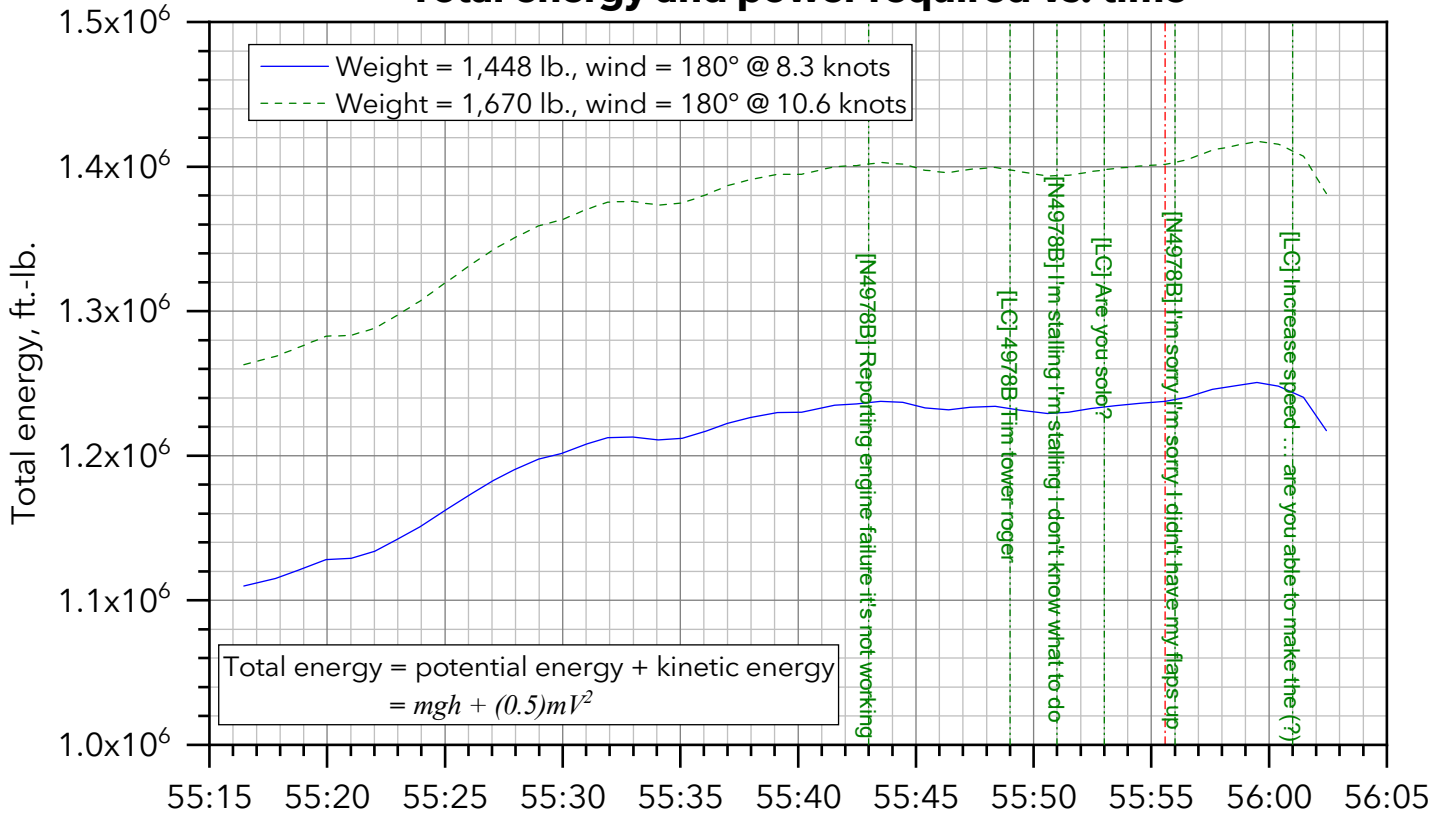
Lift coefficient and normal load factor vs. time



ADS-B time, MM:SS after 14:00:00 CDT

Figure 10.

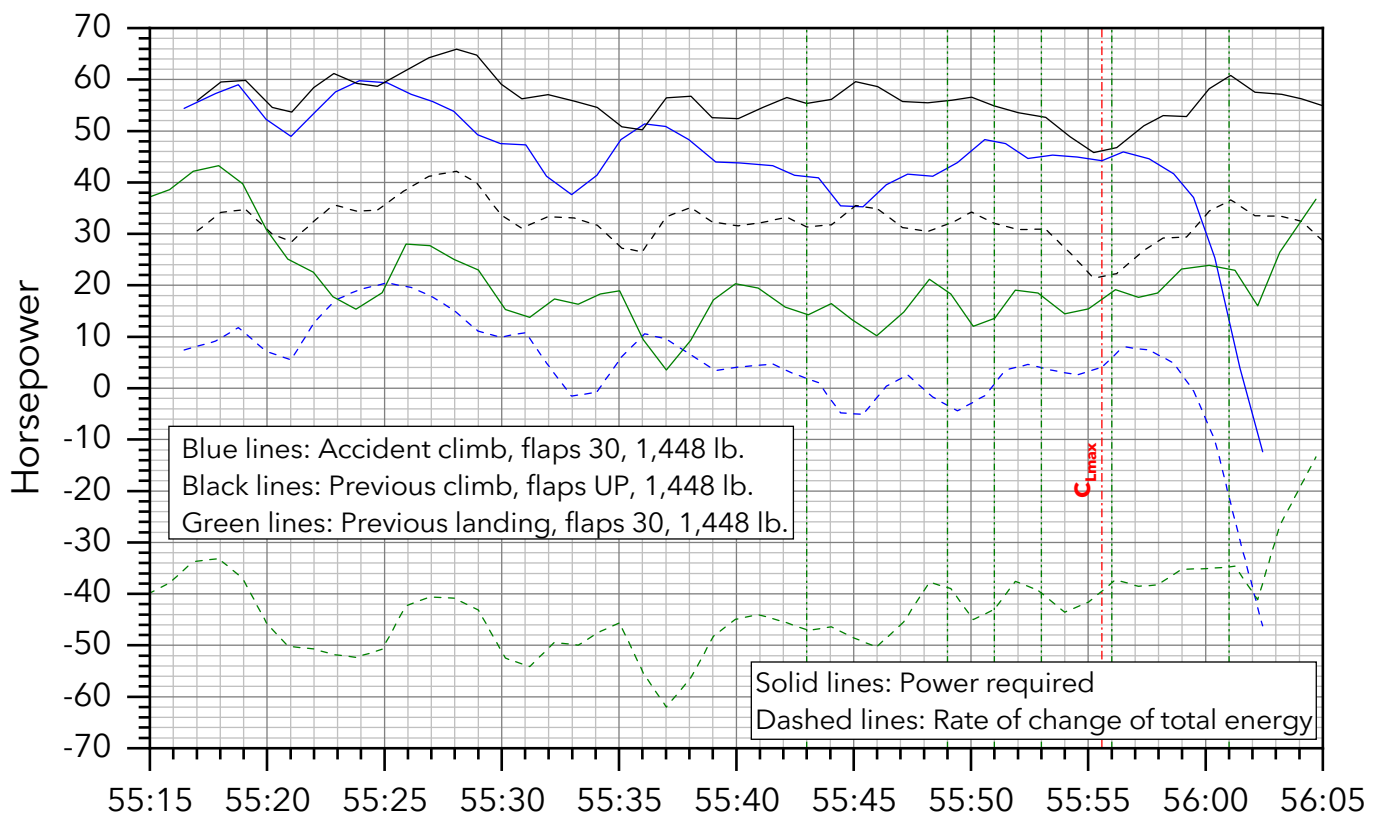
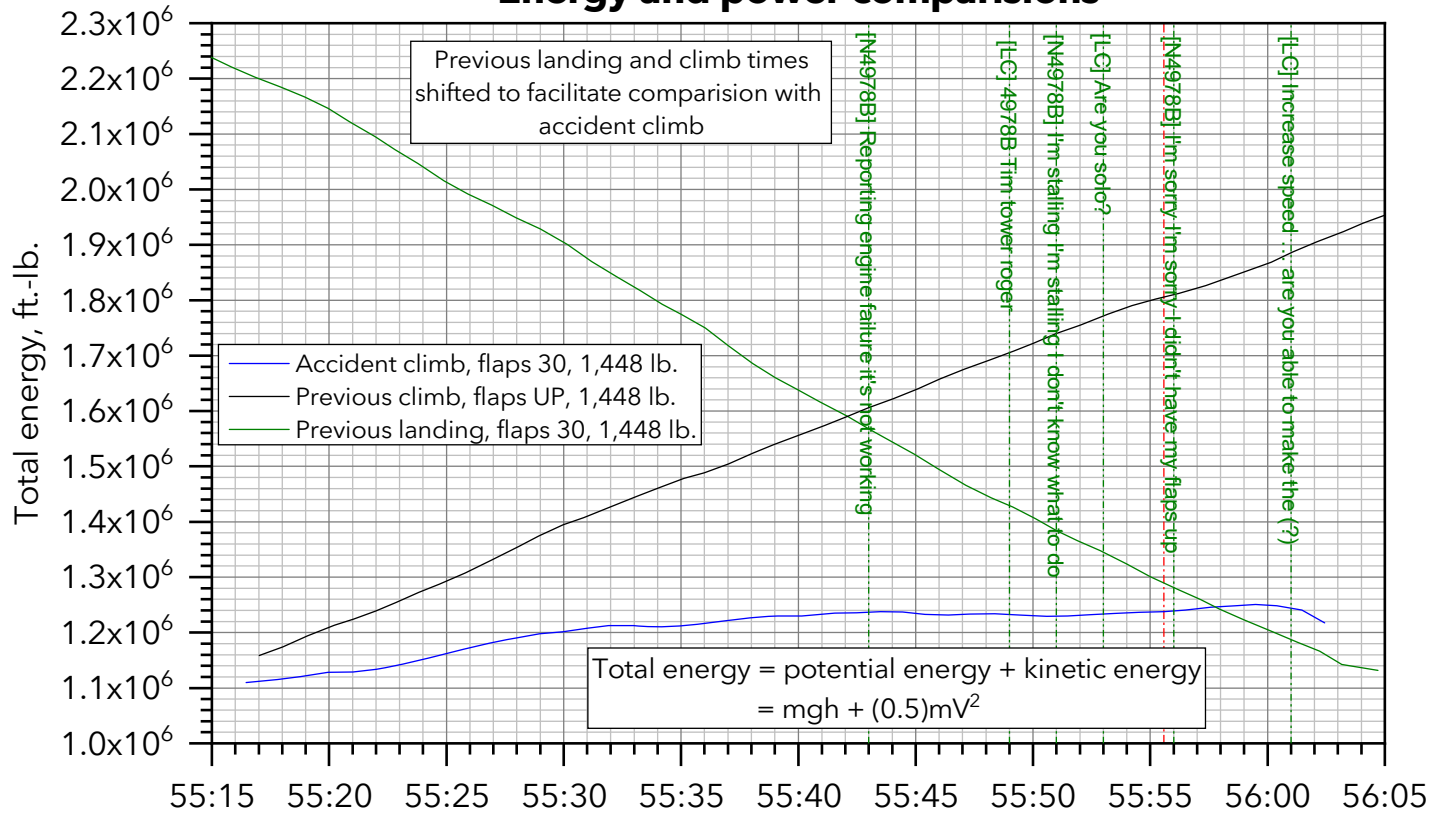
Total energy and power required vs. time



ADS-B time, MM:SS after 14:00:00 CDT

Figure 11.

Energy and power comparisons



ADS-B time, MM:SS after 14:00:00 CDT

Figure 12.

CEN22FA214: Cessna 152, N4978B, Wauwatosa, WI 05/26/2022

Power and rate of climb comparisons

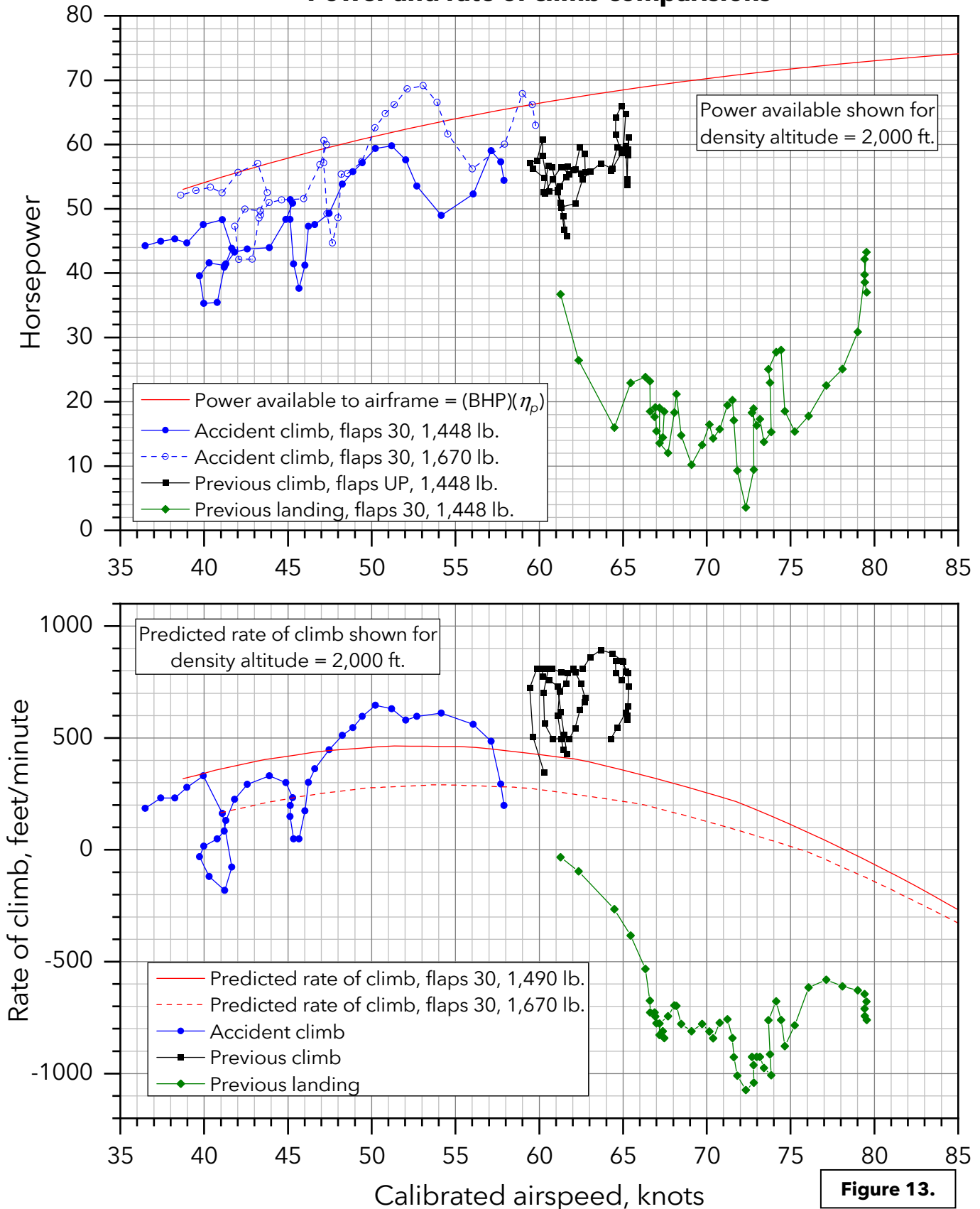


Figure 13.