INTRODUCING V_Z: BEST EFFICIENCY OF CLIMB SPEED FOR SMALL AIRPLANES

by

Norman E. Howell

A Graduate Capstone Project
Submitted to the Worldwide Campus
in Partial Fulfillment of the Requirements of the Degree of
Master of Aeronautical Science

Embry-Riddle Aeronautical University
Western Regional Office
Everett Campus
December 2012

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was prepared under the direction of the candidate's Research Committee Member,
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ACKNOWLEDGEMENTS

The researcher would like to thank Mr. Alfred Scott, Sequoia Aircraft Corporation, for the tireless work of developing the Benchmark software program. Without it, the project would not have been possible.

Thanks are also due to Dr. Brien Seeley and the all-volunteer members of the CAFE (Comparative Aircraft Flight Efficiency) Foundation. Dr. Seeley and the Foundation have been leading the way in general aviation research and application in the area of flight efficiency since 1980.

Finally, thanks to Scott Sellmeyer, William Mnich and Dixon Smith, the owners of the three Mooney airplanes that were used to fly the project tasks.

ABSTRACT

Researcher: Norman E. Howell

Title: Introducing V_Z: Best Efficiency of Climb Speed for Small Airplanes

Institution: Embry-Riddle Aeronautical University

Degree: Master of Aeronautical Science

Year: 2012

This project presents the results of an investigation into a proposed efficient climb speed for small airplanes. Federal Aviation Administration (FAA) approved climb speeds for general aviation (GA) airplanes are concerned primarily with maximum performance. However, obtaining maximum performance is not an overriding factor in the majority of GA climbs to cruise altitude. This project summarized the results of a literature study on efficient GA flight, and conducted a three-phased experiment into the determination of an efficient climb speed schedule for small airplanes, henceforth known as V_Z. The first phase of the study was a parametric evaluation of climb schedules using published and modeled performance data for a small GA airplane. The second phase generated a V_Z speed definition based on the phase one result that is in the format and structure of other FAA V-speeds. The third phase was flight test experiments, conducted in several Mooney M20 airplanes, each with a representative subject pilot. This phase gathered a subjective evaluation of the climb task, and provided a spot check of the parametric performance evaluation. Finally, a recommendation for further study and effort was made whose aim is to broaden the applicability and implementation of V_Z to all light GA airplanes through a variety of avenues.

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CHAPTER I

INTRODUCTION

Background of the Problem

Federal Aviation Administration (FAA) defined climb speeds for general aviation (GA) airplanes, as published in the respective FAA-approved Pilot Operating Handbooks (POHs) and Type Certificate Data Sheets (TCDSs), are concerned primarily with obtaining maximum performance. For example, two FAA-defined V-speeds associated with small airplanes are V_X; the best angle of climb (best climb per foot forward of travel), and V_Y; the best rate of climb (best climb per unit time). However, obtaining maximum performance is not an overriding factor in the majority of small GA airplane climbs to cruise altitude. With the increased emphasis on efficient, "green" operations of vehicles of all types in the present day, efficient GA flight operation in climb is desirable for environmental as well as economic stewardship.

Unfortunately, light GA has been one of the last adopters of vehicle efficiency improvements, for several reasons. First, light GA is a very small overall user of petroleum in the overall world context of transportation. Next, the GA market itself is very small, with little opportunity to use economies of scale for technological improvements. And finally, regulatory burdens tend to overwhelm any fiscal capability of the few manufacturers remaining in GA to develop and certificate such improvements.

Therefore the attention must turn to pilot operating technique. It may be possible to gain efficiency in climb operations solely by specification of climb technique. The technique specified should include aerodynamic as well as propulsion aspects. There have been a number of relevant papers published and other activities accomplished whose aim has been to increase understanding of the aerodynamic efficiencies of GA flight with respect to pilot operations. In addition, advanced knowledge and techniques for operating manually-controlled GA piston engines has emerged from the efforts and education of a number of online sources, including most notably the Advanced Pilot Seminars www.advancedpilot.com by Deakin, Braly, and Atkinson (n.d.). To this researcher's knowledge, no comprehensive connection between these recent aerodynamic and propulsion bodies of knowledge has ever been made in a relevant way to provide an integrated efficiency technique for climb.

Researcher's Work Setting and Role

The researcher is currently employed as a Senior Experimental Test Pilot for a major aerospace manufacturer in the State of Washington, USA. He holds an FAA Airline Transport Pilot (ATP) pilot certificate and a Certified Flight Instructor, Instrument Instructor, and Multi-Engine Instructor certificates. He has extensive experience in fixed wing general aviation, civil transport, military tactical and military transport flight operations. He has conducted the first flights of four different airplane types, these being the Cirrus ST-50 turboprop, the Cirrus SR-20, the Boeing/NASA/DARPA X-48B Blended Wing Body remotely piloted research airplane, and the Boeing P-8A *Poseidon.* He is an Associate Fellow in the Society of Experimental Test Pilots. In 1987, he won the FAI Bleriot Medal for a world record distance flight in a small single engine amateur-built airplane, and has amassed a number of other world aviation records and air race wins. In addition, he and his wife own two of the most efficient general aviation airplanes ever built, a Mooney M20J (201) single-engine airplane and a Ted Smith Aerostar 601P twin-engine airplane.

Statement of the Problem

Based upon the foregoing information, the problem facing the researcher is fairly simple. Is it possible to define a V-speed that describes a "best efficiency of climb" in the same manner that V_X and V_Y describe the best angle and best rate of climb speeds, respectively? Once that definition is synthesized, can the resulting task be accomplished to a relevant standard of performance in a GA airplane by a pilot of ordinary skill?

Significance of the Problem

Efficient GA flight is currently not a priority subject in flight instruction, nor have efficient speeds for GA airplane operations been required by FAA regulations for inclusion into Pilot Operating Handbooks. A technically rigorous, regulatory-compliant defined V-speed with parameters that are executable by a pilot of ordinary skill are the three requirements that must simultaneously be fulfilled to allow the idea of an efficient climb speed to gain traction in the GA community and in the FAA. Such an advance can possibly be attained with very few technological changes or up-front monetary investments to the current GA fleet, thus maximizing the return on the initiative.

Limitations

The planned parametric study will only be conducted on one type of airplane due to resource limitations. This airplane will have a normally aspirated fuel-injected engine and a controllable pitch propeller, and is inherently a low drag design. The study may only have a low correlation to airplanes of other configurations, such as turbo normalized or turbocharged engine induction, carburetor fuel distribution, fixed pitch propellers, and high airframe drag. The parametric study also is planned for sea-level standard day weather conditions at maximum certificated gross weight of the airplane, and no-wind conditions on the ground and at cruise altitude. The computational model used to predict airplane performance, although robust, may not account for certain small alterations in performance for conditions not accounted for. In addition, due to resource constraints, only a very small pilot sample will be used to conduct the subjective evaluation of the climb task. While every effort will be made to obtain subjects of varying abilities, a small sample size of up to 5 subjects will probably be insufficient to draw any definitive conclusions about the population as a whole with respect to the in-flight work load of the task. However, even a small sample size for a subjective evaluation such as this can be useful to identify an initial trend.

Assumptions

It is assumed that the performance data that will be used to generate the parametric study are reasonably accurate. In addition, the subjects chosen for the flights are assumed to be current and qualified in the category and class (Airplane, Single Engine Land) and endorsements (complex airplane) required to pilot the subject airplane. It is also assumed that the presence of the researcher as pilot in command and certified flight instructor will not affect the subjective evaluations of the climb task.

Acronyms

AIAA – American Institute of Aeronautics and Astronautics

AOPA – Aircraft Owners and Pilots Association

ATP – Airline Transport Pilot FAA – Federal Aviation Administration

CAFE – Comparative Aircraft Flight Efficiency

DARPA – Defense Advanced Research Projects Agency

EGT – Exhaust Gas Temperature

FAI – Federation Aeronautique Internationale

GA – General Aviation

GAMI – General Aviation Modifications, Incorporated

GCP - Graduate Capstone Project

GPH – Gallons Per Hour

LOP – Lean of Peak

L/D – lift to drag ratio

MPG – Miles Per Gallon

NASA – National Aeronautics and Space Administration

POH – Pilot’s Operating Handbook

ROP – Rich of Peak

TCDS – Type Certificate Data Sheet

WOT – Wide Open Throttle

V – velocity

CHAPTER II

REVIEW OF RELEVANT LITERATURE AND RESEARCH

Introduction

A review of relevant literature in the academic press and in public documents was undertaken to fully understand the current level of knowledge and operating integration for the conduct of efficient climbs in small general aviation (GA) airplanes. The review starts with a seminal paper on vehicular efficiency, progresses through several small-airplane-specific papers and studies on the subject, and ends with a review of studies on advanced GA piston engine operating techniques. The aggregate information is then used to formulate the hypothesis for the establishment of a technically rigorous efficient climb speed.

Vehicular Efficiency

The first paper reviewed is “What price speed?” (Gabrielli & von Karman, 1950). This paper, though published over 60 years ago, is still the seminal paper for vehicular efficiency. This researcher found reference to “What price speed” in nearly every article, journal entry, online wiki and book relating to vehicular efficiency. It is therefore illustrative to review this paper as the initial step in the process.

The abstract of the paper (Gabrielli & von Karman, 1950) was not formally separated as is common practice for more modern forms, therefore a key passage of the introduction will be presented instead.

> In this short study, the problem of comparative merits of various means of locomotion is considered merely from an engineering point of view. The power required for transportation of unit weight is used as a measure for the comparison. Evidently for a definite system of locomotion, the minimum of power necessary

> for transportation of unit weight is determined by the physical laws of the resistance of the medium, the efficiency of the method of propulsion, the unit weight and fuel consumption of the particular type of power plant, and many other factors. Nevertheless, it appears that if one throws all data together, a general trend, almost a kind of universal law, can be found for the power required per unit gross weight of the vehicle as a function of maximum speed. The demonstration of this general trend is the subject of the present contribution. One has to realize that the material is necessarily approximate and incomplete, and the conclusions are of rather tentative nature. (p. 1)

Gabrielli and von Karman conducted a study of nearly all forms of locomotion, including nearly every type of vehicle and several living beings (human walking or cycling, and horses). The study focused on resolving a parameter that could be compared across all of these disparate platforms to show the limits of feasibility of power to weight ratio versus speed of motion. Interestingly, a logarithmic graph of a dimensionless parameter ε, defined as $\varepsilon = P/WV$, where P is the maximum power of the vehicle, W is its gross weight and V is its velocity, gives great insight to the efficiency of the vehicle or being. ε is called **specific tractive force** or **specific resistance.** An updated version of the graph is shown on the following page.

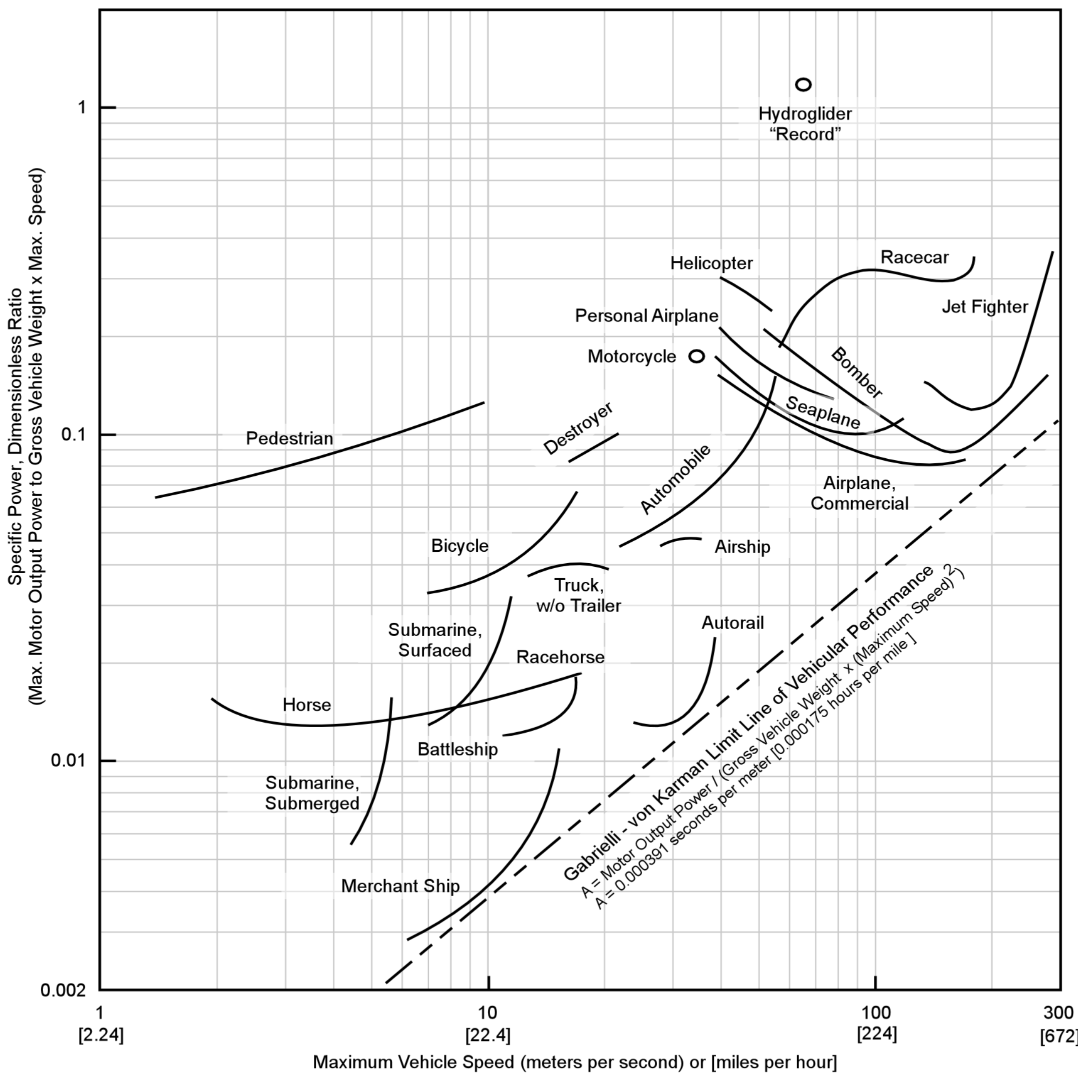

Figure 1. Specific resistance of single vehicles available in 1950. Diagonal is G-K limit line of vehicular performance. Adapted from original work by Gabrielli and von Karman (1950), updating with modern SI units. *Note:* From "Speed costs power" (Radtke, 2010. Reprinted with permission.)

Of interest is the Gabrielli-von Karman limit of vehicular performance (**G-K limit)**, a parameter whose demarcation represented the best available performance of a range of vehicles at the time. Also of interest is the shape of the curves of various vehicle types. The point of closest approach of ε to the limit line represents the best speed for the power to weight ratio of that class of vehicle, and hence its efficiency.

Sixty years of technological advances in all forms of transport have moved some of the curves of the various vehicle types beyond the G-K limit (Hatano, Hillmansen, Smith and Yong, 2005). Unfortunately for now, personal airplanes have not enjoyed such an improvement. The basic engine technology used in these airplanes, today as then, is a horizontally-opposed air-cooled 4-cycle gasoline engine, with either float bowl carburetion or constant-flow fuel injection, and fixed timing low energy (magneto) ignition. Use of the G-K limit as a measure of merit, though developed so long ago, still has validity today for general aviation for that reason. Technological improvements have the potential to bring the personal airplane curve closer to the G-K limit, but the cost of implementing these improvements and regulatory obstacles has been prohibitive in the past. Operation of the existing technology in a more efficient manner while preserving the speed benefit has the potential of deriving benefits for a far lower cost investment than a technological advance. It is with these thoughts that B.H. Carson then wrote his work (1980) that drew upon the principles first stated by Gabrielli and von Karman.

Small Airplane Efficiency

The next paper is AIAA-80-1847, "Fuel efficiency of small aircraft" (Carson, 1980). This paper, though published over 30 years ago, is still cited from time to time in the popular general aviation press. The most recent such citing was in the December 2010 issue of AOPA (Aircraft Owners and Pilots Association) *AOPA Pilot*.

The abstract of the paper (Carson, 1980) is as follows:

> There is a basic mismatch between the amount of power installed in small propeller-driven aircraft and that required for efficient cruising, which results from climb performance requirements. It is shown in this paper that there is a way of using excess power for most efficient cruise, the resulting airspeed coming

> closest to the Gabrielli-von Karman limit line of vehicular performance. A survey of 111 light aircraft was conducted, and it is found that many are operated at this optimum, while many more are not. A figure of merit is developed that measures cruise performance. Rationale is presented that is directly applicable to design for cruise efficiency. (p. 1)

Carson limited his study to propeller-driven light civil airplanes of 8000 lb. maximum takeoff weight or less, with a maximum of two reciprocating engines. He used information developed in "What price speed" (1950) to develop a measure of merit for airplane efficiency. This measure of merit uses the empirical limit published by Gabrielli and von Karman (the G-K limit) as an ideal from which to judge efficiency.

The overall development of the theory looked carefully at a standard design characteristic for airplanes, namely the lift to drag ratio (L/D), and the primary differentiator of airplane transportation from all other modes, namely speed (V). The difficulty in airplane design is that high L/D, while efficient from a fuel use standpoint, tends to produce airplanes with low maximum V. There are two parameters of airplane design that tend to work against one another to produce this difficulty: b, which is wingspan; and f, which is effective flat plat drag area. A low product $f*b^2$ gives high speed, but a low ratio of f and b^2 gives high L/D, thus the dilemma. Through a fairly complex set of mathematical manipulations, Carson determined that the speed of an airplane from a plot of L/D versus V whose point of closest approach to the G-K line represents an ideal speed for cruise efficiency. This speed, sometimes called **Carson's Speed**, is approximately 1.32 times the speed for the highest L/D ratio. Carson then goes on to establish a design criterion for an airplane that would cruise at this speed at high altitude. Not surprisingly to this researcher, his design specification of a 4900 lb. twin engine airplane with two turbo 300hp engines, a wing span of only 32.3 feet and cruise of 250 knots at 25,000 feet at 65% power is matched almost precisely by the Ted Smith Aerostar 601P, as shown below:

Figure 2. The researcher's Aerostar 601P airplane.

Although Carson's aim was to influence the design of airplanes, his legacy was the postulation of an operating technique instead. He showed an efficient cruising speed for light airplanes, this speed being approximately 1.32 times the speed at which the ratio of lift to drag is maximized. In terms of speeds stipulated by regulation, L/D max occurs at V_Y (the FAA-defined speed for best rate of climb) and so Carson's speed is $\boldsymbol{1.32*V_Y}$.

Several obstacles to the widespread adaptation of Carson's speed can be discerned by a close look at his assumptions coupled with personal knowledge of light airplane piston engine characteristics learned from a lifetime of flying. For instance, Carson assumed the specific fuel consumption of airplane piston engines is relatively constant for most power settings. However, the cruise speed he postulated results in power settings well below 65% for most installations. Specific fuel consumption rises at these power settings unless the power is limited by flight at high altitude. Such altitudes then result in the requirement for breathing oxygen for human metabolism.

A second obstacle can be found in regulatory and fiscal reality. In the paper, Carson (1980) wrote:

> It is the author's belief that this work has immediate application. As a start, manufacturers (who know the physical and aerodynamic parameters of their products better than anyone else) might consider supplementing their operational data with the information needed by pilots to operate at the cruise optimum developed in this paper. (p. 7)

Unfortunately, fiscal reality means manufacturers will only place operational data in their pilot operating handbooks to the extent those data are required by Federal Airworthiness Regulations. Therefore, unless such a speed for efficient cruise is defined by regulation, its import may never be communicated to a large percentage of the target audience.

Carson’s speed does have the potential for acceptance in general aviation. Instead of cruise, special attention should be placed upon the climb portion of a general aviation flight with respect to the aerodynamic and propulsive principles outlined in his paper. Such synthesis may eventually prove to realize Carson’s vision of more efficient flight.

Efficiency in Climb

In the book *Flying high performance singles and twins* (1994), Dr. John C. Eckalbar, PhD, discusses the concept of cruise climb as it pertains to high performance piston airplane operations. He presents a chart showing several climb speeds and resulting performance, and gives several examples of recommended cruise climbs from manufacturers of between 10 to 20 percent above V_Y. However, the primary reasons for the cruise climb according to Eckalbar are lowered deck angle, visibility, passenger comfort and engine cooling. He does mention that trip time and trip fuel may be lessened by use of a cruise climb, but does not offer rigorous analysis of these assertions.

In the book *The logic of flight* (2007), author and aerospace engineer Jack Norris develops the idea of a maximum speed per pound of drag as being the ideal speed for efficient flight. Although the development of the theory is quite different than Carson's derivations of lift to drag ratio versus the G-K limit, the resulting ideal speed turned out to be the same for both approaches. In each case, the most efficient speed turned out to be about 1.32 times the speed for max L/D, or $1.32*V_Y$. Norris also discussed climbing at this same speed as an efficient climb and advocated maintaining that speed until the airplane could no longer climb, and then cruise at the same power and speed (2007).

Although the reasons for Norris's climb schedule are technically sound, from an operational standpoint there are some additional considerations. First, it is difficult from an airspace perspective to maintain a low rate of climb. Depending on the level of air traffic control, such low climb rates at higher altitudes tend to pose problems for air traffic controllers trying to maintain traffic separation. This is because controllers primarily use altitude differential to separate traffic. A slowly climbing airplane requires a very large lateral area for separation from other cruising airplanes at level altitudes.

A secondary consideration is, again, physiological. For an unpressurized high-performance airplane, climbing until the airplane can no longer climb at $1.32*V_Y$ will typically result in a cruise altitude requiring supplemental breathing oxygen for the crew and passengers. Other considerations: The slow climb rate may be objectionable from a pilot operating perspective, and there is little reserve power to maintain altitude in descending air masses once the absolute maximum has been reached. Therefore, it may be prudent to stipulate a climb rate limit that is reasonably easy to fly with nearly any type of ordinarily available instrumentation in the small airplane cockpit, and that would be harmonious with the need for traffic separation by Air Traffic Control.

Despite a lengthy and rigorous search of the relevant literature, no other reference to an efficient general aviation climb speed in any publication could be found.

Auto-Constraining Formulae for Aircraft Efficiency

The Comparative Aircraft Flight Efficiency Foundation (CAFE Foundation, www.cafefoundation.org) in Santa Rosa, CA, is a small, nonprofit aeronautical research organization. The group has been conducting research, efficiency air races, and symposia for over 30 years. The founder of CAFE, Brien Seeley, published a paper for NASA as preparation for the conduct of a technology contest for Personal Air Vehicles in 2007 and 2008 (http://cafefoundation.org/v2/pav_general_goals.php). In the paper entitled *Auto-constraining scoring formulae for aircraft efficiency* (2007), Seeley discusses the factors for scoring airplane flight efficiency. He starts with three key quantities, namely V (true airspeed), W_p (weight of payload), and MPG (miles per gallon, or V/gph (gallons per hour of fuel flow). The parameter V^n/gph was optimized for a number of different values of n, and the results are shown in the table on the following page.

Table 1

CAFE Scoring Development

n	***V^n/gph***	**Corresponding V-speed**	**Definition**
0	*1/gph*	V_X	**Best Angle of Climb**
1	*V/gph*	V_Y	**Best Rate of Climb**
2	*V^2/gph*	***TBD***	**Carson's Speed**
2.3	***$V^{2.3}$/gph***	**V_{BC}**	**Best CAFE Speed**
3	***V^3/gph***	**V_{MAX}**	**Max Level Flight Speed**

Note: From Seeley, B. (2007). *Auto-constraining scoring formulae for aircraft efficiency.*

It is important to note the speeds in column 2 are true airspeeds, and the V-speeds in column 3 are calibrated airspeeds. Also, the CAFE Foundation did specify a no-wind best efficiency **cruise** speed different from Carson's speed, called V_{BC} in the paper. The exponent *n=2.3* was empirically derived from a decade of efficiency air racing results of hundreds of different airplanes and tends to optimize cruise at about 65% power. The expression $V^{2.3}/gph$ can also be expressed as $V_{MG}^{1.3}*MPG$ (Velocity Made Good and Miles Per Gallon, respectively) to evaluate the overall efficiency of a segment or segments of flight with varying fuel flows (Seeley, 2007). This expression $V_{MG}^{1.3}*MPG$ may also be referred to as the "CAFE Parameter". The optimization curves are shown in the following figure.

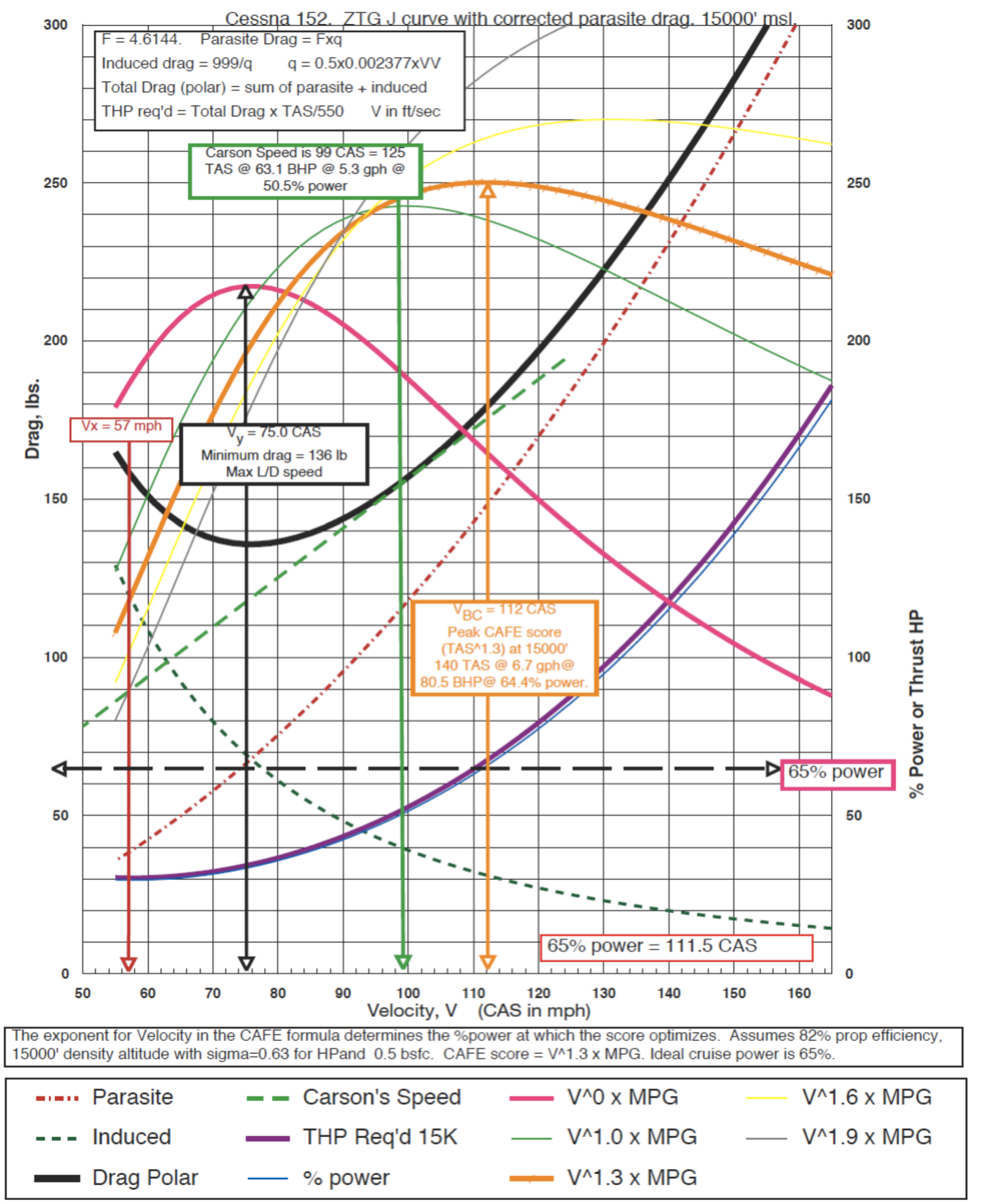

Figure 3: CAFE scores, drag polar and fuel flows. *Note:* from *Auto-constraining scoring formulae for aircraft efficiency*, by Dr. Brien Seeley (2007). Retrieved from http://cafefoundation.org/v2/pdf_pav/PAV.CAFE.Formula.Deriv.7.7.pdf . Used with permission.

The selection of 65% power is not a coincidence. As previously stated, Carson assumed constant specific fuel consumption with changes in power for the derivation of his efficiency speed. However, this is not the case. The next publication shows the actual variance of specific fuel consumption with percent power from typical GA piston engines, and will show the importance of 65% power in the context of efficiency and current GA propulsion technology.

Efficient GA Piston Engine Operations

The advent of the Internet and wide low-cost distribution of educational content is in the process of transforming the GA pilot population's understanding of piston engine operations. The "lost lessons" of efficient piston engine airplane power management, implemented during the waning era of propeller airliners, were rediscovered, updated and distributed by a few experts whose efforts have gained considerable traction. The three instructors of the Advanced Pilot Seminars (www.advancedpilot.com) have published scores of columns and articles, conducted research into piston engine fuel management, built a state of the art engine test cell, and founded a successful businesses called General Aviation Modifications, Inc (GAMI). John Deakin, one of the aforementioned instructors, in an online article on AvWeb called *Pelican's perch #65: Where should I run my engine? (part 3 – cruise)* (2003) discussed engine cruise power management and published charts with very important landmarks to understanding airplane piston engine mixture management. As the following chart shows, the specific fuel consumption of most GA piston engines is at its best value when the mixture control is adjusted to an exhaust gas temperature (EGT) of 25 degrees Fahrenheit lean of peak (25^{o}F LOP).

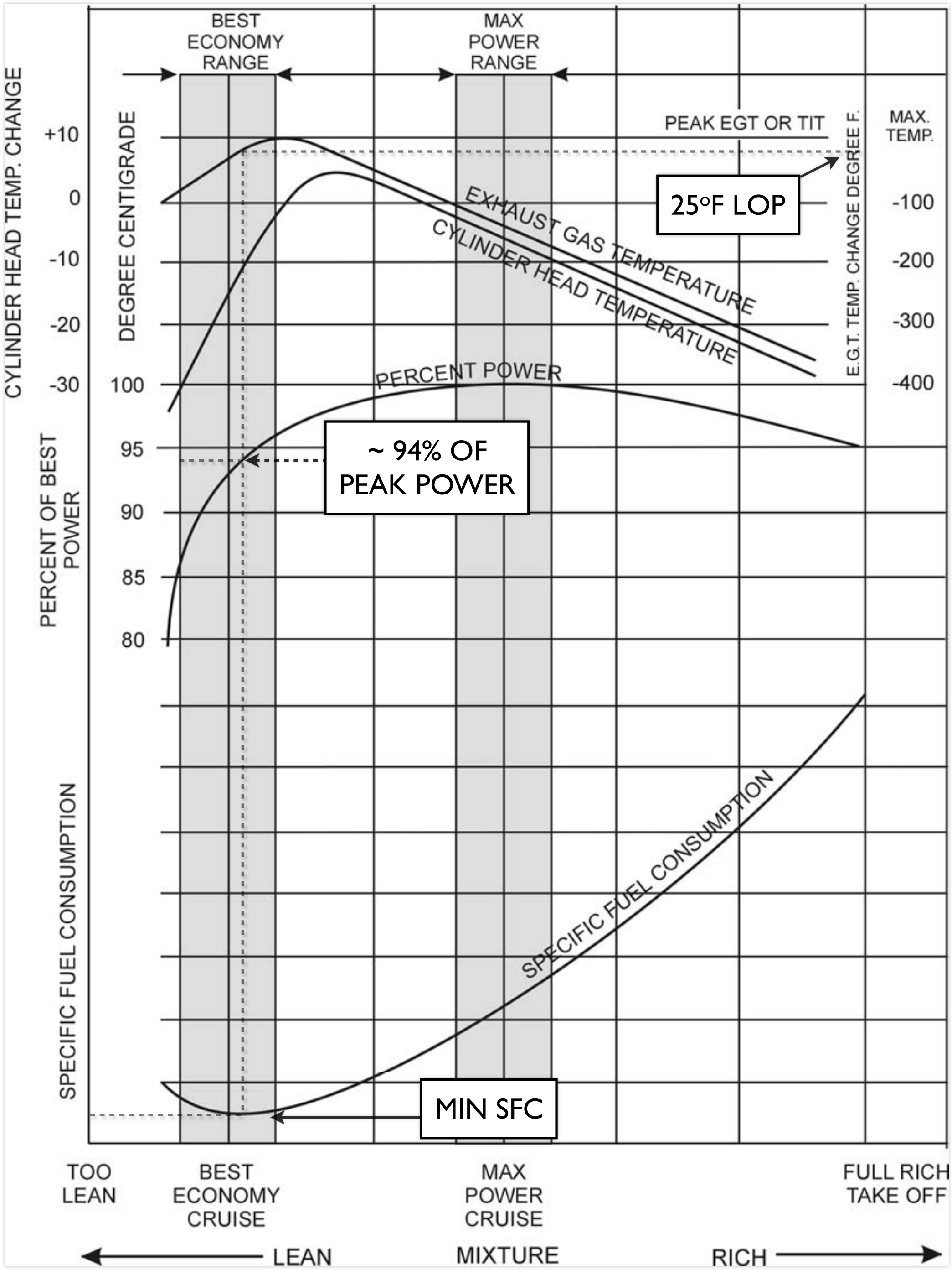

Figure 4: Piston engine power, temperatures and specific fuel consumption with varying mixture settings. *Note:* From *Lycoming O, HO, IO, HIO, TIO-360 series operator's manual* (2007). Additional annotations added by author. Used with permission.

However, a very important additional factor comes into play. When the mixture is adjusted near peak value at high power settings, it is possible to trigger an anomalous combustion event called detonation. A trace of inter-cylinder pressures during normal and detonating combustion events is shown below.

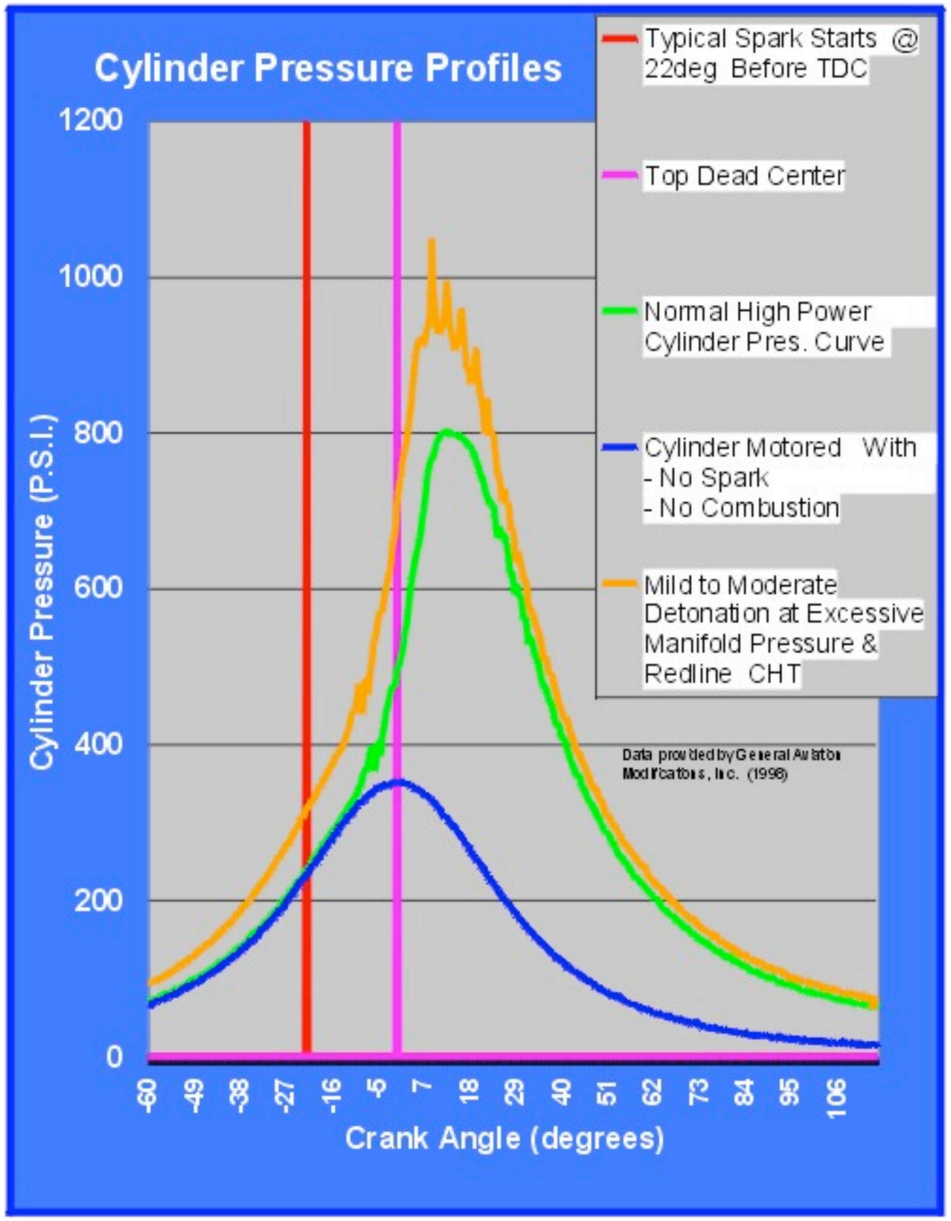

Figure 5: Inter-cylinder pressure profiles during normal combustion and detonation. From *Pelican's perch #18: mixture magic,* by John Deakin (1999). Retrieved from http://www.advancedpilot.com/downloads/prep.pdf , p. 27. Used with permission.

Detonation can occur anytime cylinder head temperatures and power output are high. For this reason, GA piston engines are typically run at mixtures well rich of peak (ROP) at high power settings to provide adequate detonation margin. Atkinson, Braly and Deakin (2003) found that there was a relationship between power and allowable mixture settings (with respect to peak EGT), both ROP and LOP, that allowed operation with sufficient margins. Conversely, there were certain combinations of power and mixture settings that did not provide adequate detonation margin. This area of operation to avoid was dubbed **the red box.**

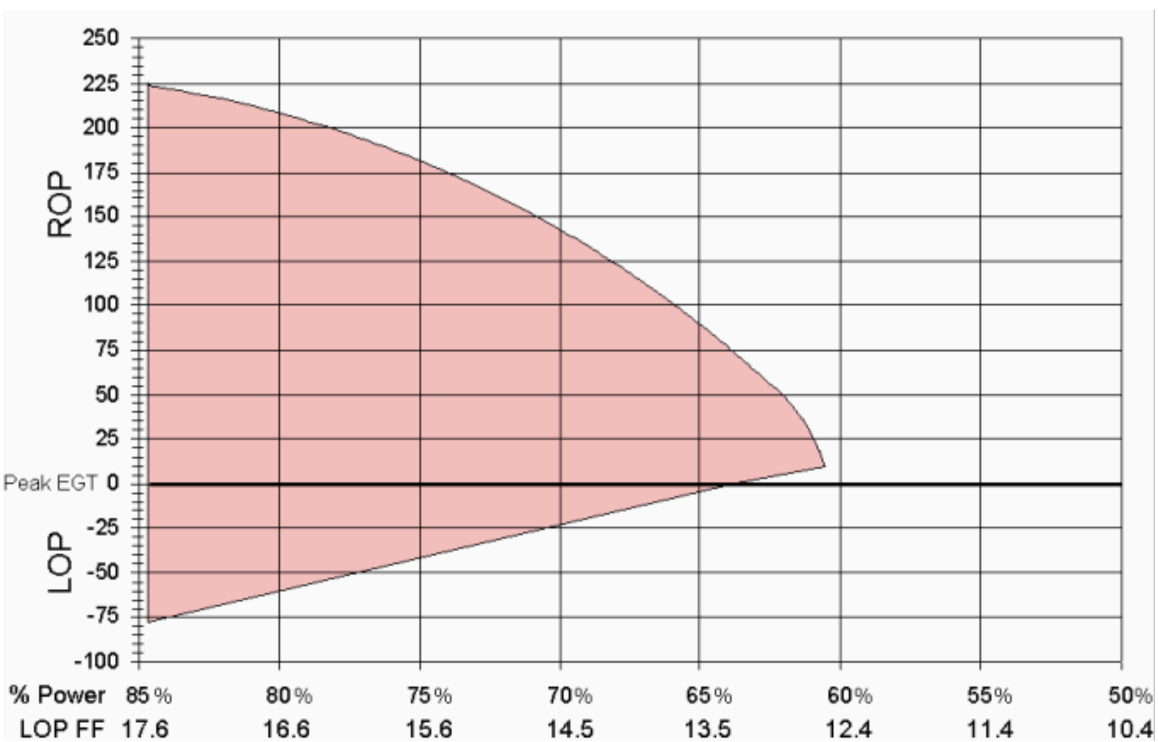

Figure 6: Mixture settings to avoid for adequate detonation margin, or "the red box". From *LOP Engine management – Operational Procedures* by G.A. Feingold. Adapted from Deakin et al, (1999), retrieved from http://daniel-at.com/site/aviation/n567ab/LOP%20Operations.pdf . Used with permission.

From the foregoing graph, it is clear that 25°F LOP can be achieved at 65% power, with some amount of distance away from the red box. Therefore, the maximum power attainable from a GA piston engine at the mixture setting that results in the best specific fuel consumption while maintaining a reasonable operating margin from detonation happens at around 65% power.

Next, the idea of a nominal target altitude to climb can be discerned from an examination of available engine power from a normally aspirated GA piston engine at wide open throttle (WOT) as altitude is increased. As shown in the graph below, the red box gets smaller as the altitude increases. At about 8000' altitude, the red box is not a factor for mixture settings. Therefore, under standard day conditions, about 8000' altitude is the minimum altitude at which 65% power can be attained with wide open throttle.

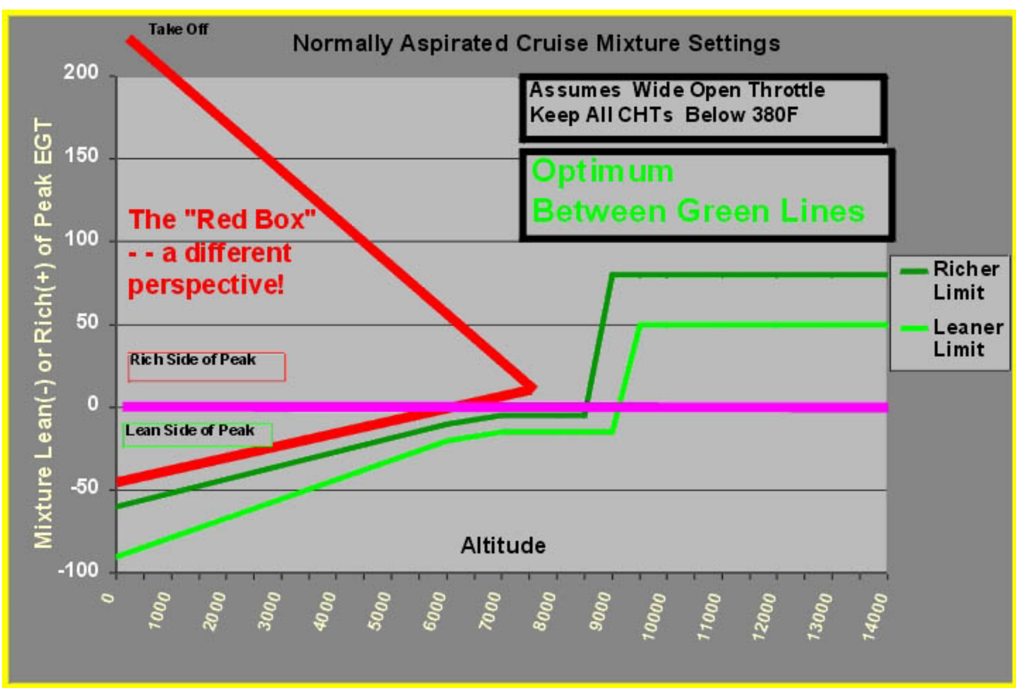

Figure 7: The red box, a different perspective. *Note:* From *Pelican's Perch #65 Where Should I Run My Engine?(Part 3 -- Cruise)*, by John Deakin (2003). Retrieved from http://www.avweb.com/news/pelican/182583-1.html . Used with permission.

Finally, an efficient means of mixture control for climb for normally aspirated GA piston engines will be explored. Most pilot operating handbooks specify a full rich mixture and maximum continuous power for climb. This is to provide a very wide margin for detonation, as previously explained. However, since the intake charge on normally aspirated engines is not boosted, manifold pressure (and hence maximum power available) slowly decreases as altitude increases. The mixture setting is predicated on a fixed intake charge density, so if the density decreases, the mixture ratio becomes more rich. Deakin et al (2005) suggest a more efficient method is called the "Target EGT" method of mixture control for a climb. The following chart portrays the different methods.

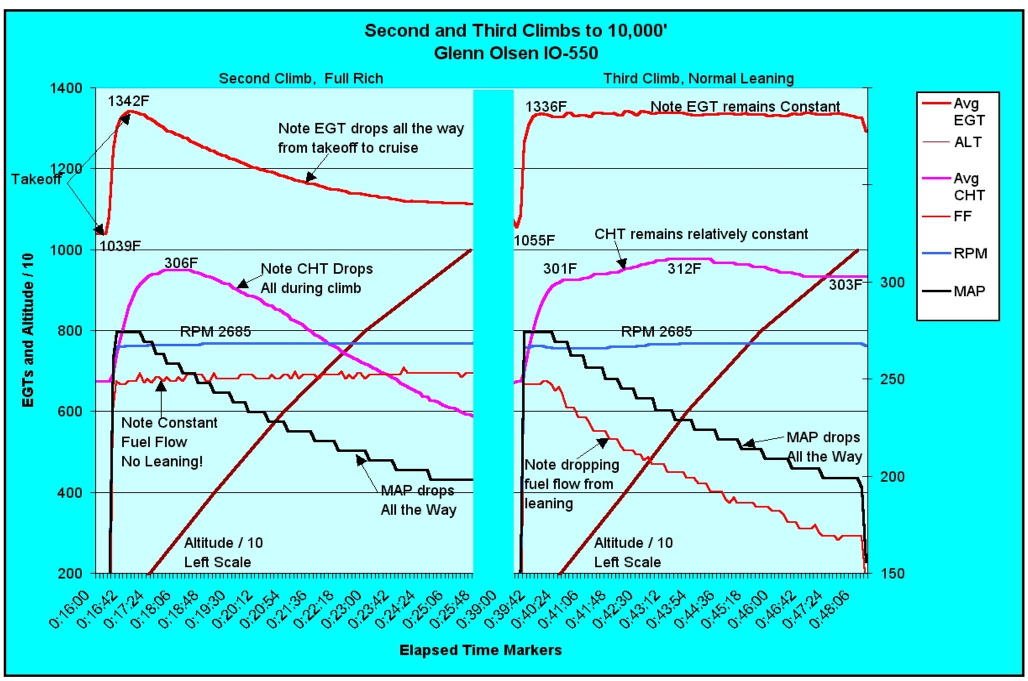

Figure 8: Full rich climb versus "target EGT" data traces. *Note:* From *Target EGT,* by Deakin, Braly and Atkinson (2005). Retrieved from http://www.advancedpilot.com/downloads/targetegt.pps.zip Used with permission.

It is clear from the chart that the Target EGT method provides several advantages. Fuel used to climb is less, power available at altitude is slightly better and the climb rate is better. Therefore, a more efficient climb can be obtained for normally aspirated GA piston engine airplanes using this method.

Summary

The basis for formulating and evaluating an efficient climb speed profile for general aviation airplanes is now summarized. Several aerodynamic analyses have pointed to the velocity $1.32*V_{Y}$, or Carson's Speed, is the most efficient speed to fly given simplifying assumptions for power. During a climb, excess power not required for forward motion is used to provide climb rate. At some point during that climb, the power available from a normally aspirated GA piston engine will not provide enough excess power to produce an acceptable real-world rate due to pilot and air traffic control factors. For the purposes of evaluating cruise efficiency based upon the actual variances of specific fuel consumption and detonation margin, maximizing the expression $V_{MG}^{1.3}*MPG$ ("CAFE Parameter")is a more valid measure of merit than Carson's speed to determine the overall efficiency of a climb task or a combined climb-cruise task. From a propulsion standpoint during climb, the most efficient results for a normally aspirated GA piston engine will be realized using the Target EGT method of mixture management. Also from a propulsion standpoint, absent significant headwinds or tailwinds, the most efficient cruise operations will result from operating the normally aspirated GA piston engine at about 65% power, WOT, 25^{o}F LOP. The minimum altitude for which that power can be attained at WOT without having to consider red box cautions with respect to detonation is nominally 8000 feet.

Statement of the Research Question

A postulation of the definition of efficient climb speed, based upon the foregoing discussion, can now be made. In keeping with the FAA V-speed nomenclature, and mindful of the defined climb V-speeds V_X (best angle) and V_Y (best rate), the currently unassigned V-speed V_Z is chosen to represent *best efficiency of climb*. V_Z is postulated to be defined as follows:

For all GA piston engine airplanes, V_Z (best efficiency of climb) = $1.32*V_Y$, at maximum continuous rated power. When climb performance decreases to 500 feet per minute climb rate at V_Z , maintain a constant 500 fpm climb until speed decreases to V_Y.

During a V_Z climb, for normally aspirated GA piston engine airplanes (or for boosted engines above critical altitude), use the target EGT method of mixture management for most efficient operation.

If equipped, adjust cowl flaps during the climb to the minimum opening required to maintain a maximum cylinder head temperature (CHT) of about 380 ^oF.

Note: Best efficiency is judged by maximizing the value of the ideal ratio of velocity made good and fuel used, as shown:

$$V_{MG}^{1.3}*MPG,$$

This value is also known as the “CAFE Parameter”.

CHAPTER III

RESEARCH METHODOLOGY

Research Model

The purpose of this experimental study was to test the hypothesis that a (targeted EGT) V_Z climb will be more efficient to top of climb than currently published or postulated V_Y climb-cruise methods. The method of study was the extraction of performance data from an airplane manufacturer's published POH for a particular type, as well as modeled data from the Benchmark modeling program for the same type. In addition, a qualitative experimental evaluation of the difficulty of flying the climb task was accomplished using a pilot subject, representing pilots of ordinary skill, flying the task in a representative GA airplane.

Survey Population

The population for this experiment was the worldwide set of licensed pilots, who own and/or operate light general aviation airplanes. Due to resource limitations, three subjects were flown in the qualitative experimental evaluation. The subjects had a variety of experience, with one having only the minimum qualifications for the test airplane, that is a Private Pilot rating with a complex airplane endorsement. Even though the sample size was small, the researcher believes his own experience level provided a sufficient upper boundary on the sampled pilots who have performed the task, and sufficient qualitative data to identify an initial trend with respect to the ease of the task were found.

Sources of Data

The primary source of the quantitative data was an FAA-approved pilot's operating handbook for the subject airplane, a 1977 Mooney 201. A secondary source of quantitative data was a computational model of the same airplane in the "Benchmark" computer program that computed performance for a variety of conditions not published in the POH. The primary source of the qualitative data was the result of the Cooper-Harper rating and pilot comments from the subject who flew the task in the same type of airplane.

The Data Collection Device

The quantitative data collection device for the non-published performance data was the Benchmark-based model of the drag and power characteristics of the Mooney M20J airplane. Several input parameters were specified and varied as necessary to gather the performance data for those conditions not found in the POH.

The qualitative data collection device was the Cooper-Harper rating scale. This rating scale of pilot workload and acceptability of an in flight task is the standard data collection device in the flight test profession worldwide. The scale is shown on the following page.

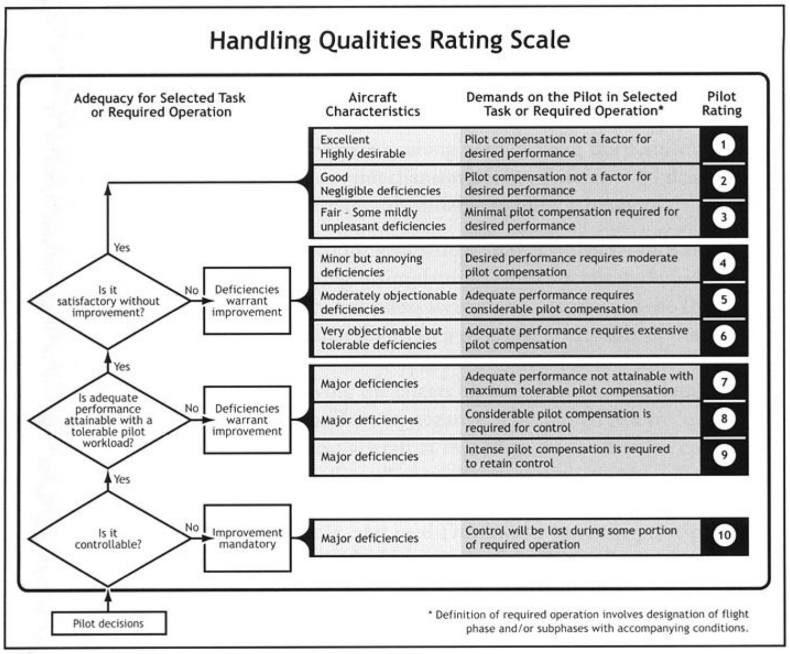

Figure 9: Cooper-Harper rating scale. *Note:* From *The use of pilot rating in the evaluation of aircraft handling qualities* (AGARD Report 567), by G. Cooper and R. Harper. London: Technical Editing and Reproduction Ltd.; April 1969. Retrieved from http://www.eurocontrol.int/eatmp/hifa/hifa/HIFAdata_tools_ratingscales.html . Used with permission.

Instrument Pretest and Validity

The Benchmark performance model was pretested and validated by inputting a number of initial conditions that are the same as those in the POH. The resulting performance data from the model were compared to the published data to show the validity of the model. See Appendix C for detailed results.

Procedures

The quantitative aspect of the study showed V_Z provides a more efficient method of climb than published or postulated V_Y methods. Efficiency was measured by computing the value of $V_{MG}^{1.3}*MPG$ found at the downrange distance for V_Z top of climb for the following data matrix, under standard day, no-wind conditions at maximum certificated gross weight.

Table 2

Data Matrix for Quantitative Study

Climb Speed	Altitude Band	Climb Mixture	65% Cruise Segment Power
V_Y	0-8000’	Full Rich	Best Power
V_Y	0-8000’	Full Rich	Best Economy
V_Y	0-8000’	Full Rich	25^{o}F LOP
V_Y	0-8000’	Target EGT	25^{o}F LOP
1.15*V_Y (Eckelbar)	0-8000’	Target EGT	25^{o}F LOP
V_Z	**0-8000’**	**Target EGT**	**N/A**
V_Y	0-10000’	Full Rich	Best Power
V_Y	0-10000’	Full Rich	Best Economy
V_Y	0-10000’	Full Rich	25^{o}F LOP
V_Y	0-10000’	Target EGT	25^{o}F LOP
1.15*V_Y (Eckelbar)	0-10000’	Target EGT	25^{o}F LOP
V_Z	**0-10000’**	**Target EGT**	**N/A**

Data were extracted from the Mooney 201 POH or from Benchmark as necessary to find the time, fuel and distance to climb. For the V_Y data lines, a cruise (from V_Y top-of-climb to V_Z top-of-climb distance) true airspeed and fuel flow were extracted/modeled, and using distance and fuel used, an aggregate Velocity Made Good and MPG were calculated to compare efficiency.

For the qualitative data, a climb task was written and a pilot flight data card was generated to perform the task in the airplane. The flight data card is shown on the following page.

V_Z MISSION CARD		DATE	5-31-12	SCHED TAKEOFF	1200L	
CALL SIGN	CREW		AIRBORNE		BLOCK	MSN FREQS
N11MH	S SELLMEYER	LND	:	IN	:	
	N HOWELL	TO	:	OUT	:	
		TOT	:	TOT	:	

SET UP G696, G530, JPI 700, SONY CAM	
STND GND OPS	
ALT SETTING 29.92, NOTE SAT & WINDS	
TAKEOFF PER POH, NOTE EGT FOR TGT V_Y CLIMB 88 KIAS (86 KCAS)	
FLY ROUTE	
KAAO-IAAO-DEYEK-HUKAM-IAAO/001/18.0-IAAO/001/24.0-IAAO/001/30.0-IAAO/001/36.0-IAAO/001/42.0-HUKAM	
V_Z CLIMB TASK:	
AT 2000' PA, MAINTAIN WOT/2700	
-ACCEL TO AND MAINTAIN 115 KIAS (113 KCAS)	
-CLIMB TO 8000' PA, CONSTANT 115 IAS	
-LEAN TO TGT EGT APPROX EA 1000'	
-USE COWL FLAPS FOR CHT <380 DEG F	
-IF CLIMB = 500 FPM, MAINTAIN 500 FPM	
UNTIL SPEED = V_Y, THEN MAINTAIN V_Y	
-LEVEL AT 8000' PA, NOTE DIST TO WPT	
DES PERF: AIRSPEED 115 KIAS +/- 5	
ADEQUATE PERF: 115 KIAS +10/-5, PER	
PVT. PILOT PTS (ADDING COMPLEX)	
ALTERNATE TASK: AT 2000' PA, MAINTAIN WOT/2700, FULL RICH MAINTAIN V_Y CLIMB (88-83 KIAS) TO 8000' FOR BASELINE PERFORMANCE	
RECORD C-H RATING AND COMMENTS	

ALTITUDE TIME	SAT	FF	VVI	COWL FLAP
2000				
3000				
4000				
5000				
6000				
7000				
8000				
C-H SCORE				
COMMENTS				

Figure 10: Pilot flight data card for V_Z qualitative evaluation.

CHAPTER IV

RESULTS

The results of the first phase, a quantitative study of climb speeds from the M20J POH and Benchmark, respectively, and the calculated CAFE parameters for the input conditions of Table 2 are summarized below.

Table 3

0-8000' Climb Quantitative Results, 1977 Mooney M20J

Climb Speed	Climb Mixture	65% Cruise Segment Mixture	Time (Minutes)	Fuel (Gallons)	Distance (Naut Miles)	Velocity Made Good (knots)	NMPG	CAFE Parameter $V_{MG}^{1.3}$*NMPG
V_Z	**Target EGT**	**N/A**	**12.8**	**3.4**	**25.5**	**119.5**	**7.6**	**3812.1**
V_Y (POH)	Full Rich		10.0	2.7	14			
	+65% Cruise	Best Power	4.4	0.8	11.5	106.3	7.3	3132.9
V_Y	Full Rich		10.0	2.9	15.4			
	+65% Cruise	Best Power	3.9	0.7	10.1	110.3	7.1	3190.9
V_Y	Full Rich		10.0	2.9	15.4			
	+65% Cruise	Best Economy	3.9	0.6	10.1	110.2	7.3	3284.4
V_Y	Full Rich		10.0	2.9	15.4			
	+65% Cruise	25^{o}F LOP	3.9	0.6	10.1	110.2	7.4	3326.0
V_Y	Target EGT		9.8	2.7	14			
	+65% Cruise	25^{o}F LOP	4.4	0.6	11.5	107.6	7.6	3342.3
1.15*V_Y (Eckelbar)	Target EGT		10.5	2.8	18.2			
	+65% Cruise	25^{o}F LOP	2.8	0.4	7.3	115.1	7.9	3764.0

Table 4

0-10000' Climb Quantitative Results, 1977 Mooney M20J

Climb Speed	Climb Mixture	65% Cruise Segment Mixture	Time (Minutes)	Fuel (Gallons)	Distance (Naut Miles)	Velocity Made Good (knots)	NMPG	CAFE Parameter $V_{MG}^{1.3}$*NMPG
V_Z	**Target EGT**	**N/A**	**16.8**	**4.2**	**32.8**	**116.9**	**7.8**	**3795.6**
V_Y (POH)	Full Rich		13.5	3.5	19.0			
	+65% Cruise	Best Power	5.2	0.9	13.8	105.4	7.4	3140.3
V_Y	Full Rich		13.6	3.8	21.1			
	+65% Cruise	Best Power	4.4	0.8	11.7	109.3	7.1	3163.8
V_Y	Full Rich		13.6	3.8	21.1			
	+65% Cruise	Best Economy	4.5	0.7	11.7	109.2	7.3	3244.6
V_Y	Full Rich		13.6	3.8	21.1			
	+65% Cruise	25°F LOP	4.5	0.6	11.7	109.2	7.4	3289.8
V_Y	Target EGT		13.5	3.5	21.1			
	+65% Cruise	25°F LOP	4.5	0.6	11.7	109.6	7.9	3561.8
1.15*V_Y (Eckelbar)	Target EGT		14.5	3.8	25.7			
	+65% Cruise	25°F LOP	2.7	0.4	7.1	114.5	7.9	3757.0

As mentioned, the first two data lines for each table were generated from the M20J POH, the remainder were modeled data from the Benchmark program. Appendix C contains detailed screenshots of the POH page(s) used and the results from various inputs into the Benchmark model.

The results clearly show the V_Z profile is more efficient in terms of maximizing the CAFE parameter than any other published or postulated V_Y method. Therefore, the data support the assertion of efficiency of the profile.

The second phase of the project was to synthesize the definition of V_Z, based on the phase one results, in language that will foment incorporation into FAA training manuals and manufacturer pilot guides, as shown in the following paragraph:

- For all GA piston engine airplanes, V_Z (best efficiency of climb) = 1.32*$V_{Y,\ SL,\ STND,\ MGW*}$ at maximum continuous rated power. When climb performance decreases to 500 feet per minute climb rate at V_Z , maintain a constant 500 fpm climb until speed decreases to V_Y.

- During a V_Z climb, for normally aspirated GA piston engine airplanes (or for boosted engines above critical altitude), use the target EGT method of mixture management for most efficient operation.

- If equipped, adjust cowl flaps during the climb to the minimum opening required to maintain a maximum cylinder head temperature (CHT) of about 380 ^{o}F.

** Note: The manufacturer's published sea level, standard day, maximum gross weight V_Y value is used to compute V_Z, and the resulting indicated airspeed is held constant during the climb until the climb performance limit is reached.*

Note: Best efficiency is judged by maximizing the value of the ideal ratio of velocity made good and fuel economy, as shown:

$$V_{MG}^{1.3} * MPG$$

This value is also known as the "CAFE Parameter".

The third phase of the project was to evaluate the in-flight work load of the V_Z profile as flown by a pilot of ordinary skill. Three test days and 6 flights comprised the inflight program, in a variety of Mooney M20 airplanes. The first and second flights were accomplished on May 31, 2012, in a 1977 Mooney M20J, from the James Jabara Airport in Wichita, Kansas. The airplane type was the same make, model and year as the airplane data used in the Benchmark modeling program, with the exception of the installed propeller. This propeller change in no way affects the handling qualities of the airplane. The flight data card as shown in Figure 10, above, was used to conduct the evaluation. The Cooper-Harper task as specified for the make and model airplane, clarifying details, desired criteria, and adequate criteria are as follows:

V_Z Climb Task: At 2000 feet PA (Pressure Altitude), maintain WOT/2700 (Wide Open Throttle, 2700 RPM, aka maximum continuous rated power). Accelerate to and maintain 115 KIAS (113 KCAS) (knots indicated airspeed and knots calibrated airspeed, respectively). Climb to 8000' PA (pressure altitude), maintain constant 115 knots IAS. Lean to target EGT approximately each 1000 feet of altitude gain. Use cowl flaps as necessary to maintain highest CHT (cylinder head temperature) to less than 380 DEG F. If rate of climb decreases to 500 FPM (feet per minute), maintain a constant 500 FPM until speed = V_Y, then maintain V_Y. Level at 8000 feet PA.

Desired Performance: Maintain airspeed 115 KIAS +/- 5 knots

Adequate Performance: Maintain airspeed 115 KIAS +10/-5 knots (this pilot performance criterion reflects the required performance of the Federal Aviation Administration (FAA) Practical Test Standards for private pilot applicants for a climb task, and represents the minimum FAA-acceptable performance by the lowest skill level pilot with respect to the task.

The subject pilot #1 was a 39 year-old male with a Private Pilot, Airplane Single Engine Land, Instrument Airplane rating, with complex airplane and high performance airplane endorsements. With respect to the flying task, his ratings represent a minimum level of skill expected to be able to demonstrate a climb in an airplane with a constant-speed propeller. The subject was able to fly the task specified to the Desired Performance level, within +/- 5 knots. His Cooper-Harper rating was 3, indicating “Fair - Some Mildly Unpleasant Deficiencies - Minimal Pilot Compensation Required for Desired Performance”. A Cooper-Harper rating of 5 or below would indicate Adequate (as opposed to Desirable) performance was obtainable only with considerable pilot compensation or worse, and would indicate a negative outcome to the evaluation of pilot accomplishment of the V_Z task by a pilot of ordinary and expected skill. The subject’s comments were “No harder to fly than a V_Y climb, it was easy to see when to transition to the 500 foot-per-minute climb, and less rudder was needed to counteract P-factor [sidewash].”

The third and fourth flights were accomplished on August 27th, 2012, in a 1998 Mooney M20K “Encore”, from the Bremerton airport in Bremerton (Seattle), Washington. Due to the different published V_Y speed for this model airplane, the V_Y task was flown at 96 KIAS and the V_Z task was flown at 127 KIAS. The subject pilot #2 was a 54 year-old male with an Airline Transport Pilot rating, and was a Flight Test Engineer graduate of the US Navy Test Pilot School. This individual currently serves as a production test pilot for a large aerospace firm, in a variety of transport category airplanes. This subject was able to fly the task to the Desired Performance level and rated the task Cooper-Harper “3”. His comments were “V_Z task is somewhat demanding for a Private Pilot - Complex level aviator, but not overly so”. He also stated that after flying a V_Y task back to back with the V_Z task, that he would be “using the V_Z profile from the present time forward” in his personal airplane.

The fifth and sixth flights were accomplished on August 30th, 2012, in a 1979 Mooney M20K 231, from the Bremerton airport in Bremerton (Seattle), Washington. Due to the different published V_Y speed (in statute mph instead of knots) for this model airplane, the V_Y task was flown at 110 MPH IAS and the V_Z task was flown at 145 MPH IAS. The subject pilot #3 was a 62 year-old male with an Airline Transport Pilot rating, who currently serves as a production systems operator (flight engineer) for a large aerospace firm, in a variety of transport category airplanes. This subject was able to fly the task to the Desired Performance level and rated the task Cooper-Harper “3”. His comments were “Airplane is stable in pitch at V_Z, I could hold speed within 2 mph, task should be no problem for a Private Pilot. The published V_Y is harder to fly, the airplane is not as stable in pitch, there is more rudder for sidewash needed, and my oil temps and cylinder head temps are much hotter. Also, forward visibility is poor during the V_Y climb and is much better using V_Z.”

This researcher has been flying the V_Z profile for well over a year, in a 1977 Mooney M20J airplane as well as a 1977 Smith Aerostar piston twin (see figure 2). Pilot qualifications represent the other end of the scale from the lowest qualified subject pilot #1 listed above - FAA ATP Rating, Certified Flight Instructor (Airplane and Glider), Certified Instrument Flight Instructor, Multi-Engine Instructor, and 20 years of experience as an credentialed experimental test pilot. This researcher has found the V_Z profile to be as easy or easier to fly than any published V_Y climb speed or profile, and also finds the Cooper-Harper rating of the task as 3, as flown on a number of occasions in the time period. Therefore, the initial trend of the suitable in-flight work load of V_Z is found to be positive.

CHAPTER V

DISCUSSION

Phase One - Benchmark

As shown in the previous section, the proposed V_Z climb profile was found to be more efficient than any published or postulated V_Y speed or profile. The essential element that enabled the assertion of this statement with rigor was the Benchmark program (specifically, the climb modeling), which was developed and enhanced due to the impetus of the research done for this project. The ability to *accurately model* the climb performance of a light general aviation airplane for other than manufacturer-published performance data was a capability that did not exist in the industry until the present. The program was available at the time of this project's publication at the following web address: http://www.seqair.com/benchmark/index.html. In addition, Benchmark was in Open Beta test at publication time, therefore it was available as a free trial.

The Benchmark program builds a mathematical model of a general aviation airplane from a number of different modules. The basic airplane is modeled in the opening page of the program, as shown on the following page.

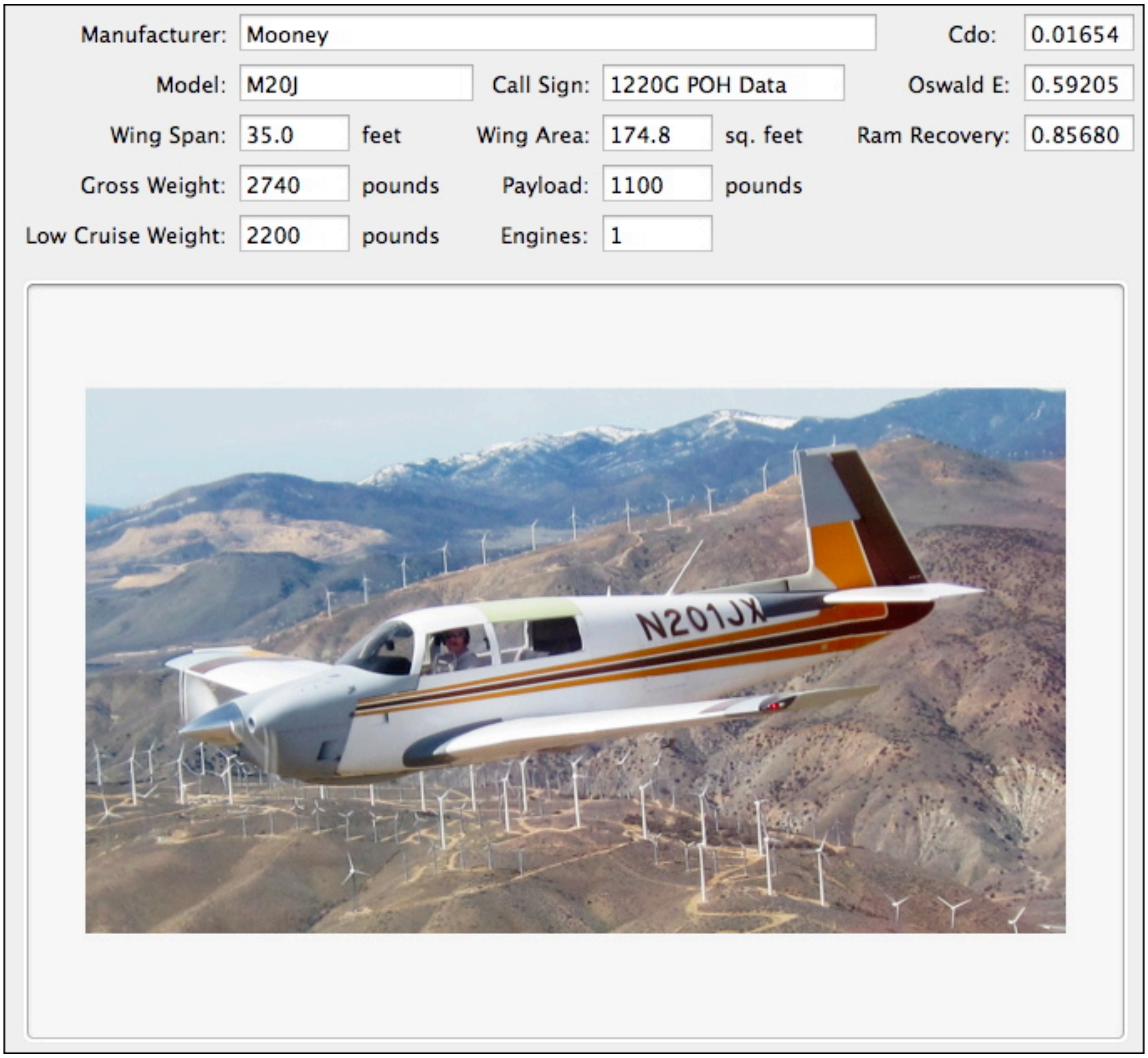

Figure 11: Benchmark basic airplane data entry page. C_{DO}, Oswald E, and Ram Recovery are Benchmark-modeled values based upon down path program data entry, all other values are basic airplane parameters. The airplane shown was a 1977 Mooney M20J, owned and flown by the researcher.

Next, the engine as installed in the airplane is modeled through data entry in a number of Benchmark pages. For brevity, only the Fuel Flow page for Best Power is shown on the following page.

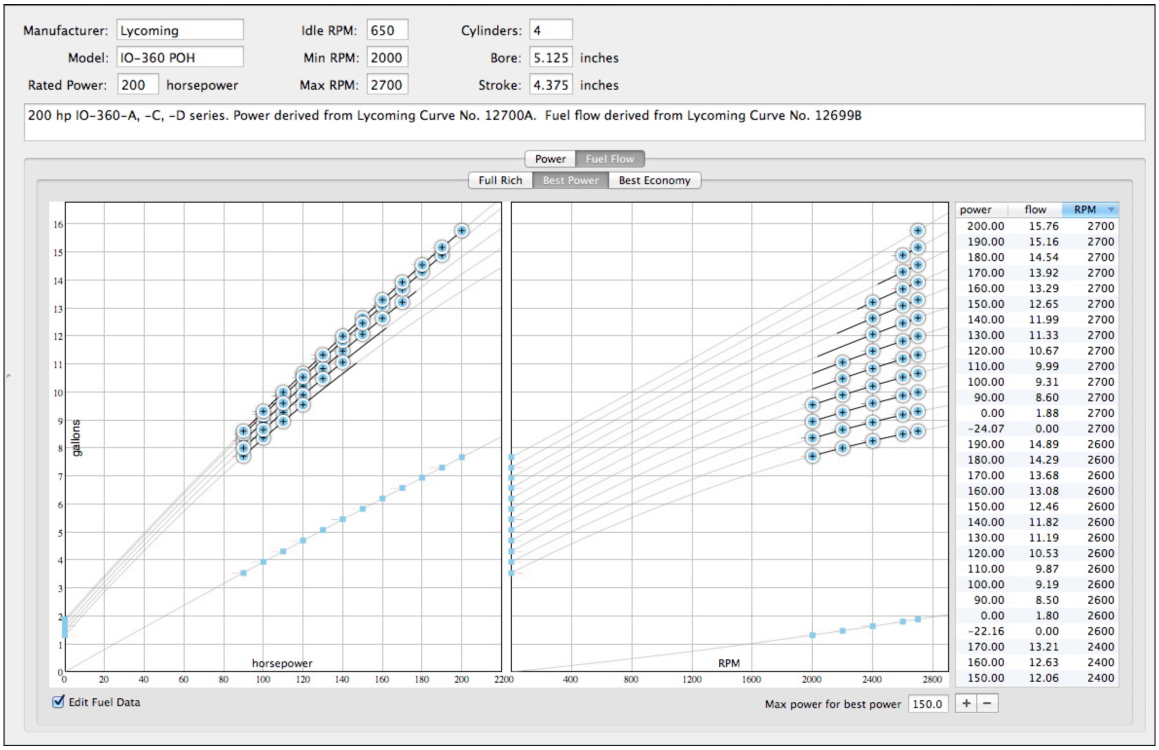

Figure 12: Benchmark fuel flow page, best power. The circles are entered data points, and the families of curves are the modeled engine data derived from the data points and the Perry power equation as used by the program.

A computational model of aviation piston engine power and fuel flow is unique to Benchmark. Such models do not exist anywhere else, *not even at the general aviation engine manufacturers.*

The next module is the propeller model. An entire paper could be written solely about the extensive work undertaken to mathematically represent the empirical data and hand-drawn charts of the Boeing General Propeller Chart, from which the Benchmark propeller modeling algorithm is derived. However, it may be more illustrative to compare the output of the program to results from the manufacturers. Unlike piston engine manufacturers, prop manufacturers have a larger production and economic base due to the installed population of aviation props on turboprop airplanes. For this reason, the prop manufacturers have been able to invest in more robust tools, such as computational fluid dynamics (CFD) models and algorithms to predict the performance of their products. Therefore, this researcher was able to perform a comparison using identical input conditions for a propeller type and observe calculated results from Benchmark and the manufacturer's state-of-the-art proprietary CFD algorithm. It should be noted that while the manufacturer's CFD modeling algorithm was proprietary, the resulting output was not. Benchmark predicts propeller performance within only a few pounds of thrust as compared to the CFD model. See Appendix C for a detailed presentation of the validation.

One of the surprising results of the climb performance quantitative study was the powerful effect of the climb speed upon the resulting CAFE parameter. Since the measure of efficiency $\boldsymbol{V_{MG}^{1.3} * MPG}$ is optimized for a 65% power LOP cruise, one would think that climbing to altitude at best rate and target EGT, and then cruising for the maximum amount of time at the optimized cruise condition to the down path evaluation point would result in the highest score. However, V_Z wound up providing the highest score, even though the time spent at a cruise condition optimized for the measure of efficiency was zero. It is illustrative to examine the propeller efficiency output from Benchmark with this in mind.

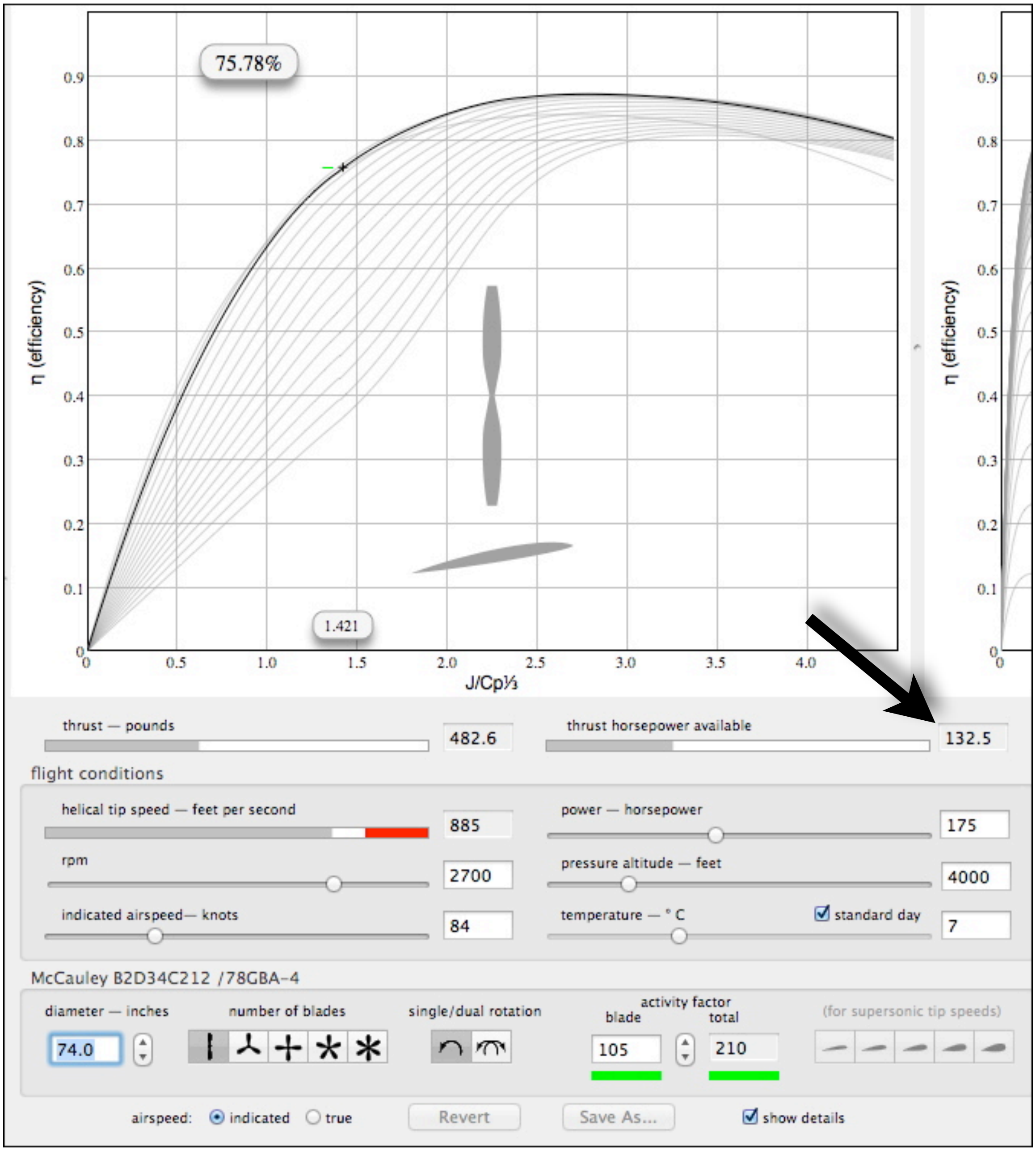

Figure 13: Benchmark output for Mooney M20J propeller, at published V_Y speed.

At 4000 feet during a climb (halfway to altitude for a nominal 8000'), notice the thrust horsepower available from the propeller, at 132.5 hp. Making no other changes, the indicated airspeed is now increased to V_Z in the model, for the M20J that is from 84 KCAS to 113 KCAS for the given conditions.

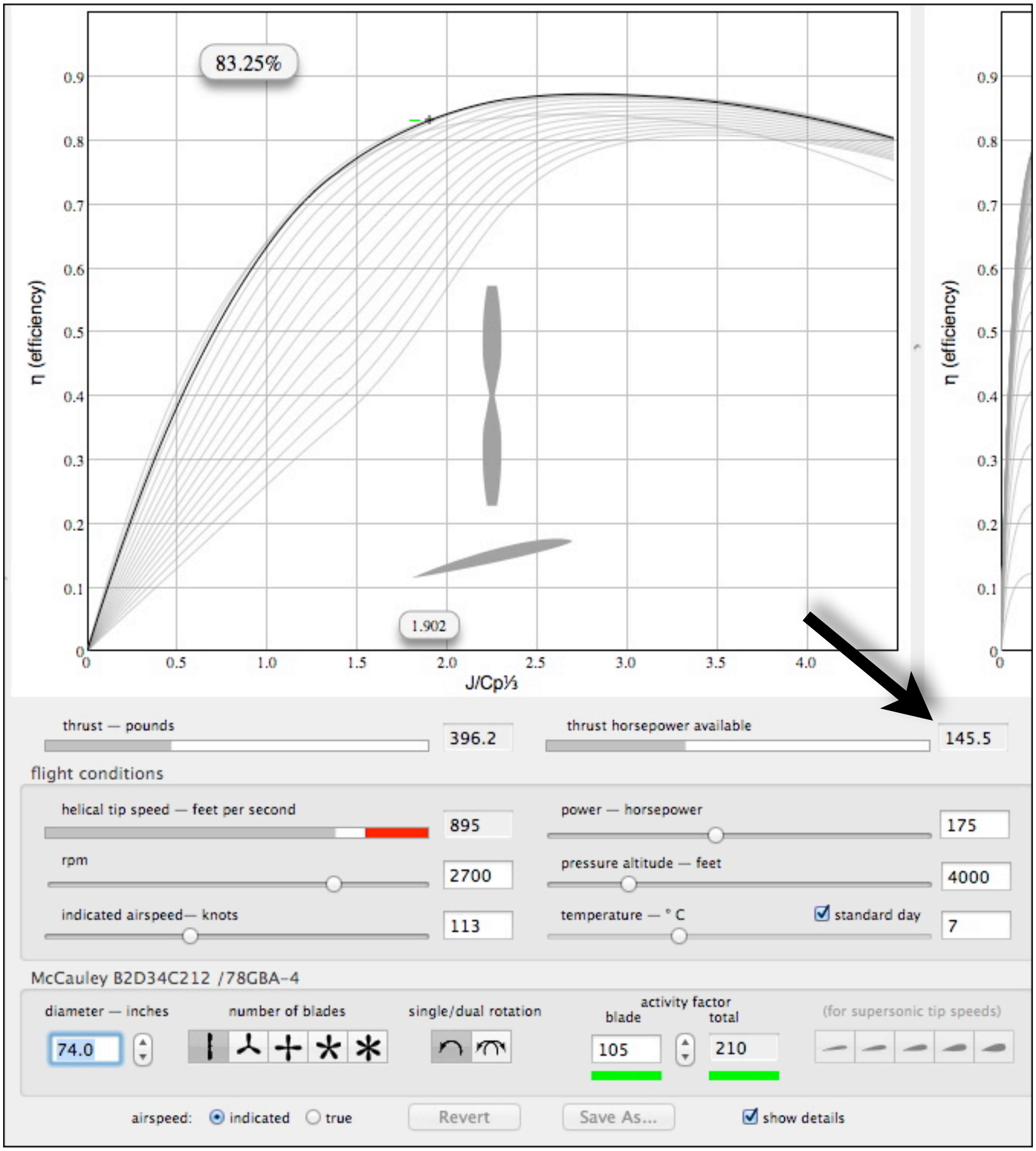

Figure 14: Benchmark output for Mooney M20J propeller, at V_Z speed.

Notice the increase in thrust horsepower available, from 132.5 to 145.5 hp. The 13 hp increase represents a 7.5% increase *from the same available engine horsepower. This increase in efficiency results solely from a change in pilot technique, and is one factor, but not the only factor, in making the* V_Z *profile so efficient.* This is but one of the many engineering observations that can be made from the Benchmark model, and it is important to note that such precise insight into small airplane performance ***has never been possible before*** in general aviation.

The airframe drag is then calculated from a series of speed-power flight tests on the airplane of choice. Although Benchmark was originally designed to model experimental amateur-built airplane performance from actual flight test, this researcher synthesized a method to input published certificated airplane performance data from FAA approved Airplane Flight Manuals (AFM) and Pilot Operating Handbooks (POH). This "off-label" first-use of the program was a critical discovery in the course of research, and allows a robust modeling of any number of (constant speed prop) general aviation airplanes using data that have already been conformed and published.

The following chart shows the results of the input of the *entire set* of published Best Power cruise data (over 200 data points) from the Mooney M20J POH into Benchmark. Each altitude and weight produces a discrete set of drag data, from which the C_{DO} (zero lift drag coefficient) and Oswald E (Oswald efficiency number) is calculated by the program. As shown, the published data for 6000 feet, Best Power, and 2740 lb gross weight represent the best line fit to the aggregate set of data.

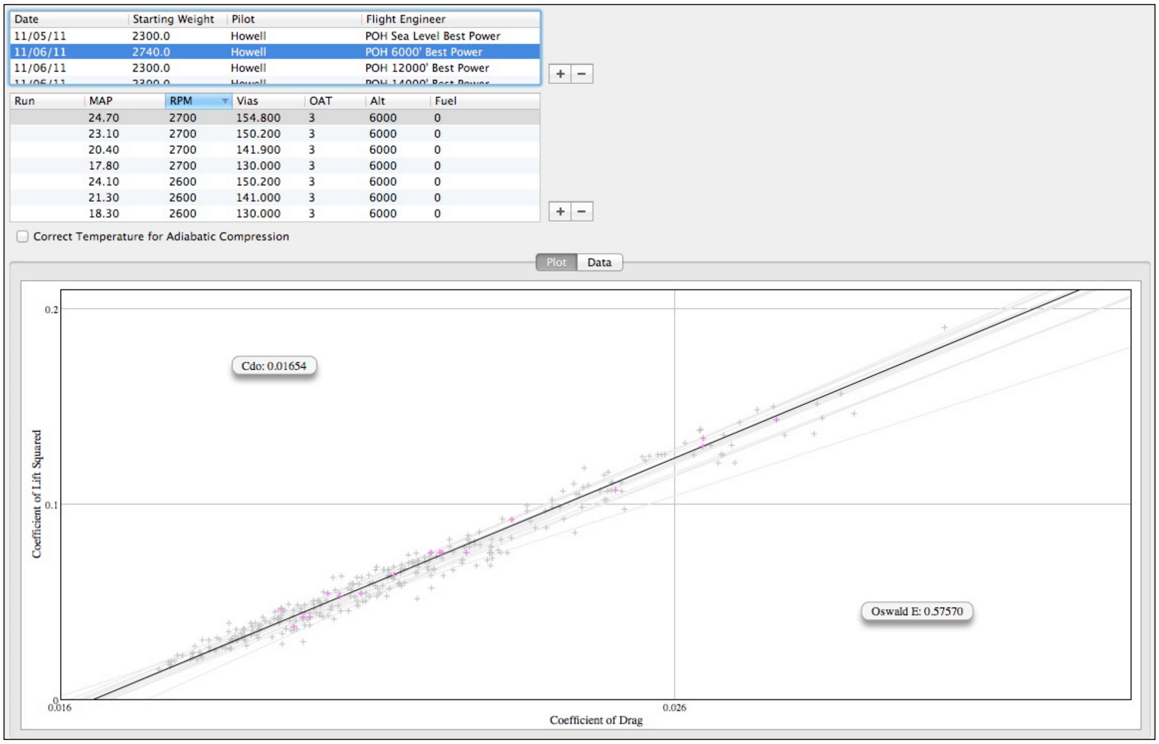

Figure 15: Benchmark calculated drag polar for Mooney M20J, from POH data.

Next, the three modules for the engine, propeller and airframe are utilized to calculate and display an airplane speed chart. The charts elements include a series of input sliders and controls on the bottom of the screen, where the left set represents horsepower (throttle) and the right side represents RPM (prop control). Located above the sliders are graphic representations of the engine model for power and RPM. Those models feed into the propeller model curves for specific advance ratio and power factor, and the results are used to calculate the airplane performance, shown in the graph located in the upper center of the page..

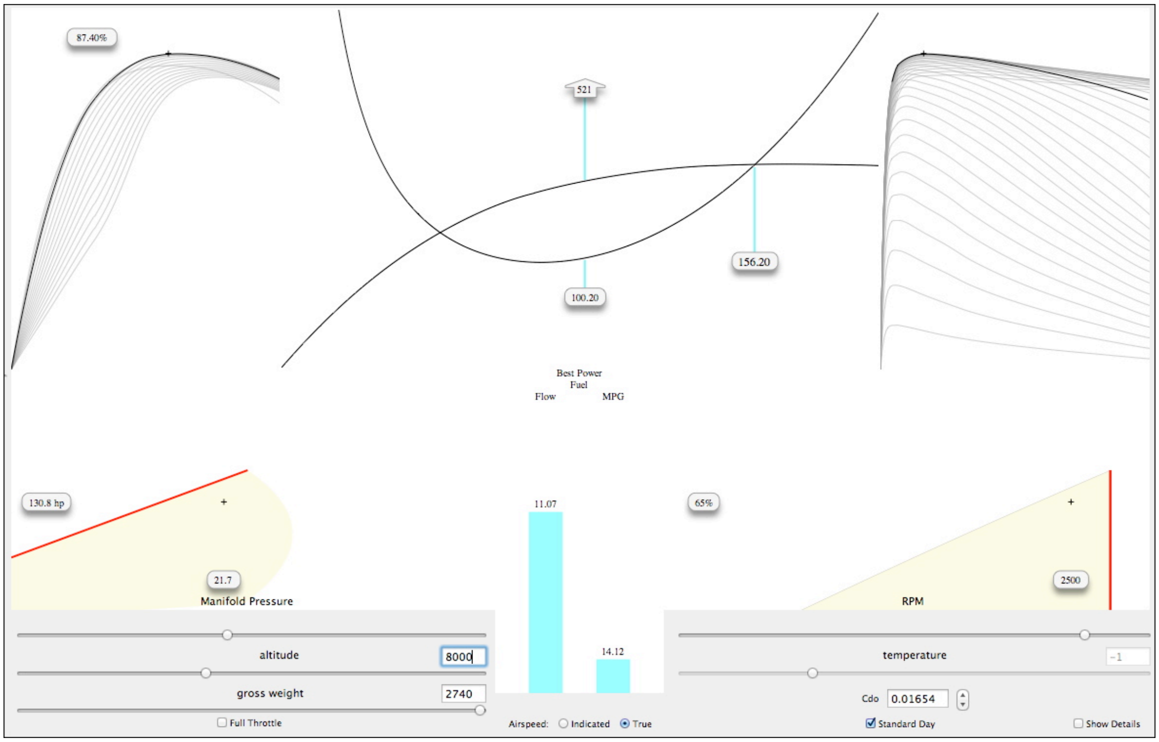

Figure 16: Benchmark airplane speed chart. Condition shown is a 65% power, best power mixture, cruise at 8000' pressure altitude, standard day for the Mooney M20J. Modeled true airspeed 156.2 knots (POH is 157 knots) and fuel flow is 11.08 gallons per hour (POH is 11.1 gallons per hour). These data were utilized for the values in Table 3, above.

The final product from Benchmark is the climb chart. Benchmark iterates the entire airplane model at 20 foot increments to determine rate of climb at a chosen velocity, true airspeed at that condition, fuel flow at that condition, and accumulates time, distance and fuel used. So, for a climb from sea level to 8000 feet, the model is iterated 400 times.

The conditions shown on the following pages are representations of a Mooney M20J V_Y climb to 8000', comparison of time to climb curves from Benchmark and the POH for identical conditions, and a V_Z climb at 6000' during the climb.

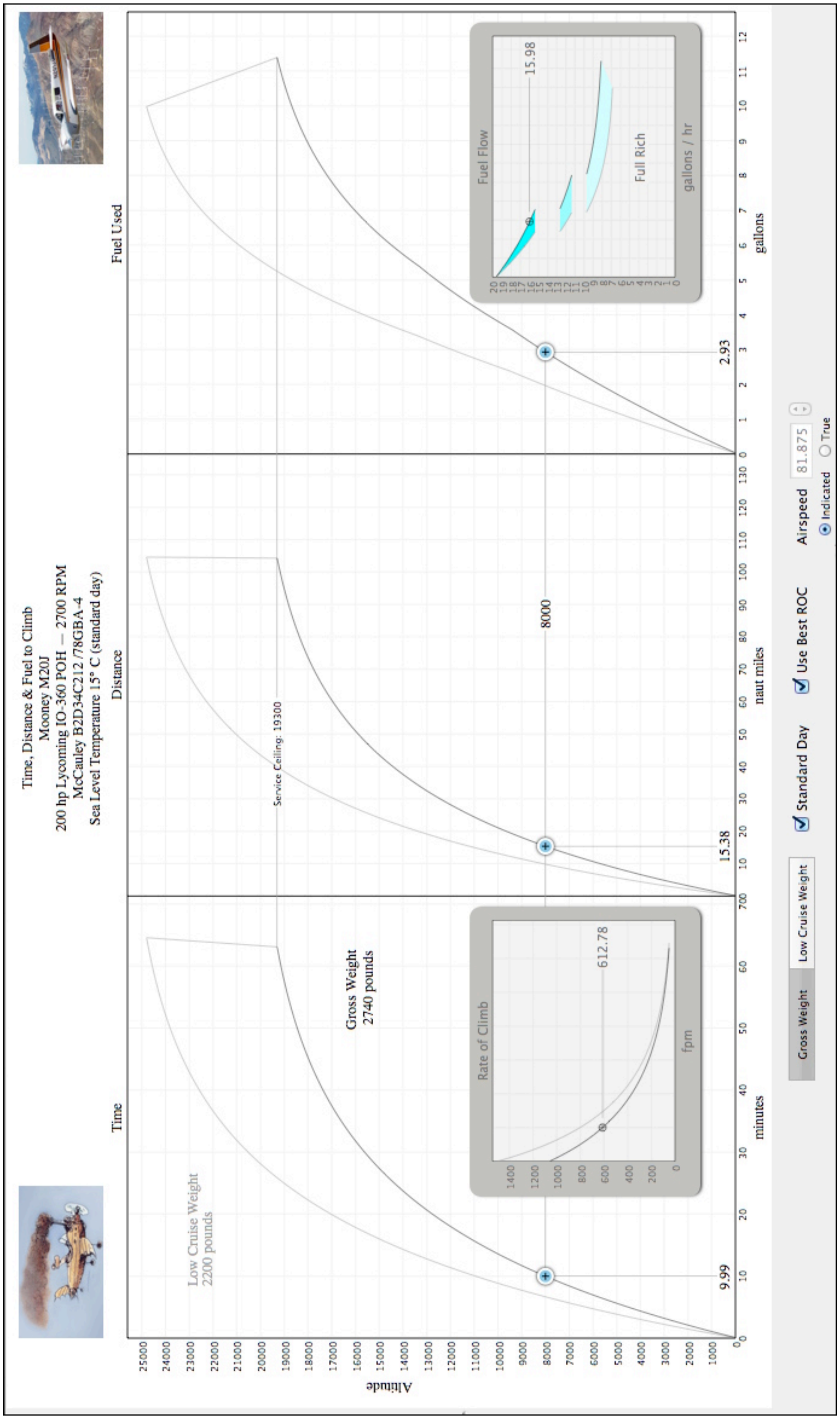

Figure 17: Benchmark climb chart for Mooney M20J. Values shown were used in table 3.

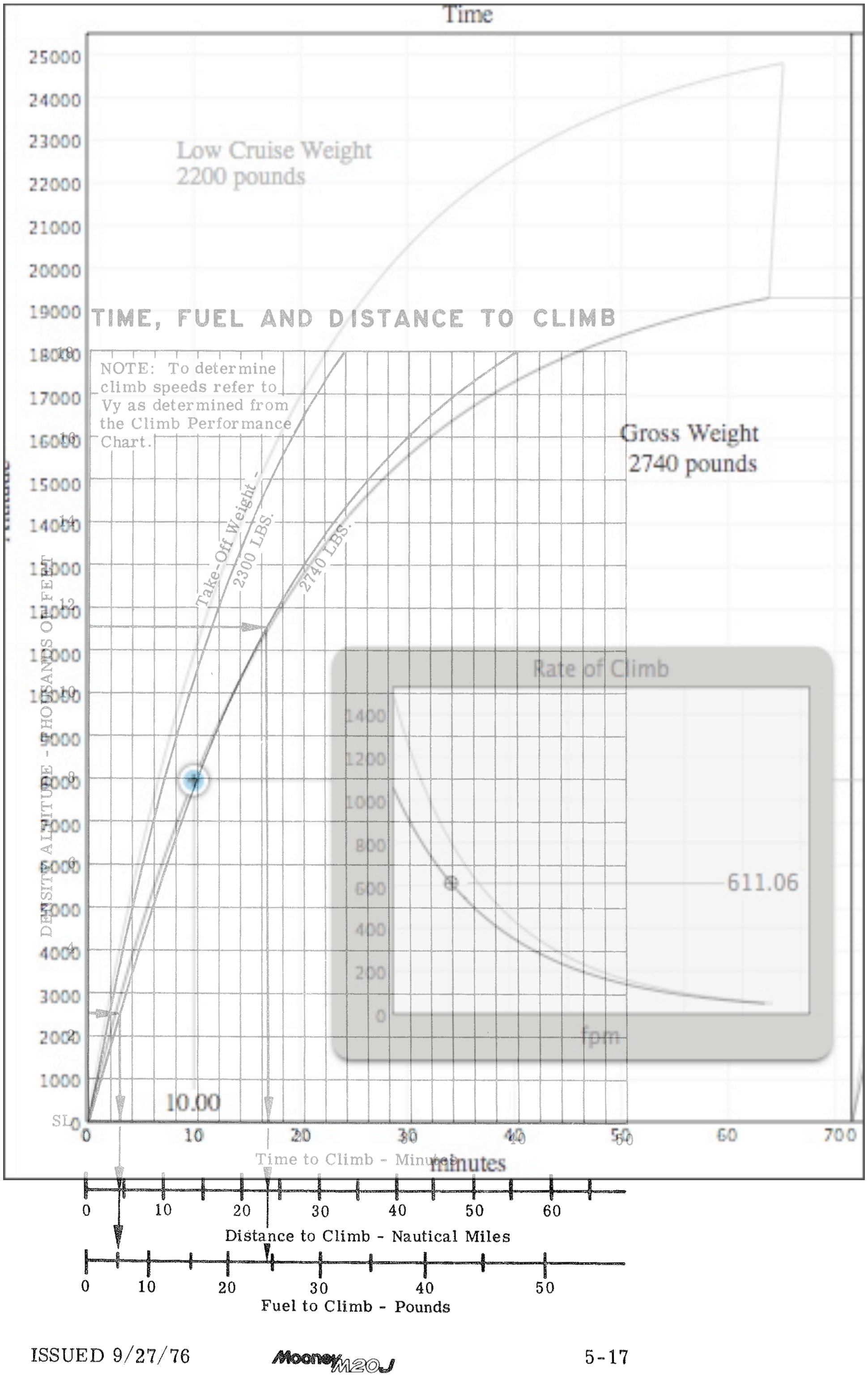

Figure 18: Superposition of Benchmark time to climb data on Mooney M20J POH chart. *Note:* From *Pilot's operating handbook and FAA approved airplane flight manual, Mooney M20J* (p. 77), by Mooney Aircraft Corporation, 1984, Kerrville, TX. Copyright 2005 by Mooney Airplane Company. Reprinted with permission.

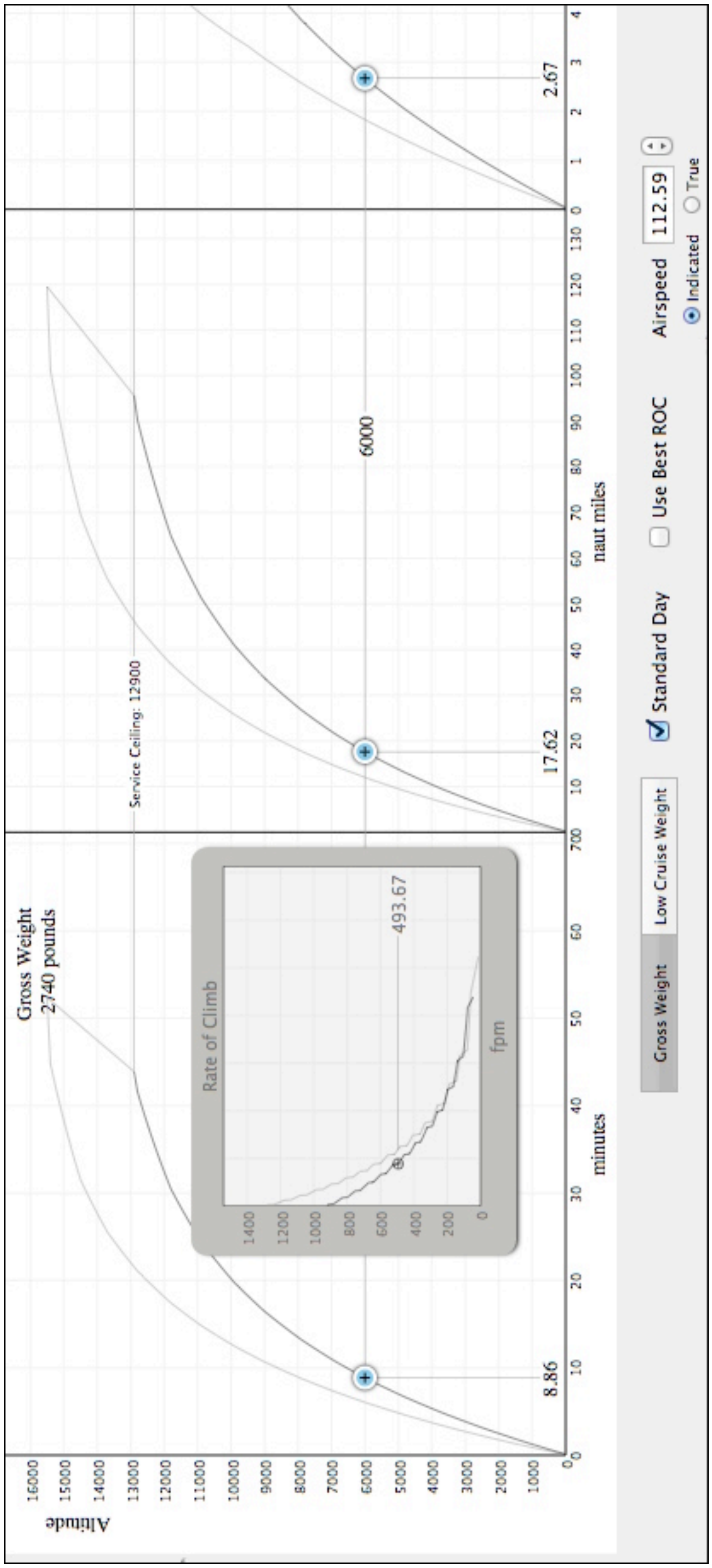

Figure 19: Benchmark climb chart, showing V_Z performance transition, 6000' PA.

In figure 19, the predicted rate of climb at V_Z has decreased to 500 fpm during the climb from 5900' to 6000', and represents the altitude at which a pilot would transition from the constant indicated airspeed climb to a constant VVI climb in accordance with the V_Z profile.

The ability to dynamically manipulate a number of input parameters in Benchmark was the key factor in the ability to predict the performance of the Mooney M20J for conditions other than those published in the POH. Since Benchmark can be used to model any GA airplane with a spark-ignition piston engine and constant speed propeller, the potential for insight into the performance of these airplanes may be greatly increased.

Phase 3 - Performance and Suitable In-Flight Work Load

As outlined in Chapter IV, above, all subject pilots gave a Cooper-Harper rating of 3 to the V_Z climb task. Although the primary data product for this phase was the C-H rating, a large set of ancillary performance data was collected that provides additional validation to the proposed climb profile. After the V_Z profile was completed, the subject pilots and the researcher returned to the airport for landing, quickly refueled to the same level as the V_Z flight, then departed again to fly the alternate task as shown on the flight card at Figure 10. This allowed a back to back performance and work load comparison of the baseline V_Y climb task and V_Z, under identical aircraft weight, configuration, wind and weather conditions, and route of flight. The researcher took handwritten notes during the six flights, and the scanned flight cards , weather and weight and balance are shown in Appendix E. Using a handheld aviation GPS with differential capability, GPS data were recorded in the form of GPS tracks and GPS receiver screenshots during the climbs. An overview of the first two flights with the tops-of-climb for each climb profile are shown below. The tracks shown are from radar data recorded from Wichita Terminal Radar Approach Control Facility (TRACON), available on any number of flight tracking web sites, such as www.flightaware.com. The tracks are keyed to the subject airplane N-number, N11MH, and the flight date, May 31, 2012.

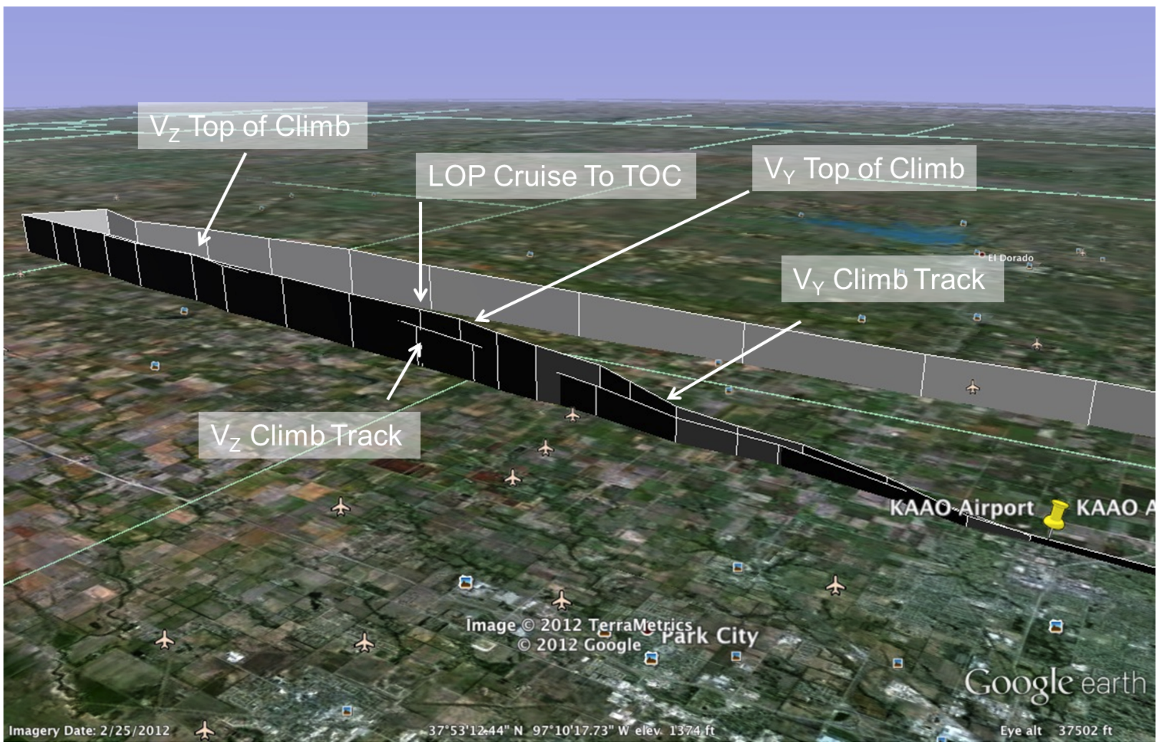

Figure 20: V_Z and V_Y climb tracks from radar data, Mooney M20J. *Note:* Retrieved from http://flightaware.com/live/flight/N11MH/history/20120531/1700Z/KAAO/KAAO. Additional image annotations by the researcher.

The next series of images show closer views of the two climb tracks, this time from GPS data. The two tracks were created from GPS recorded position, time and altitude data and loaded into the Google Earth online application.

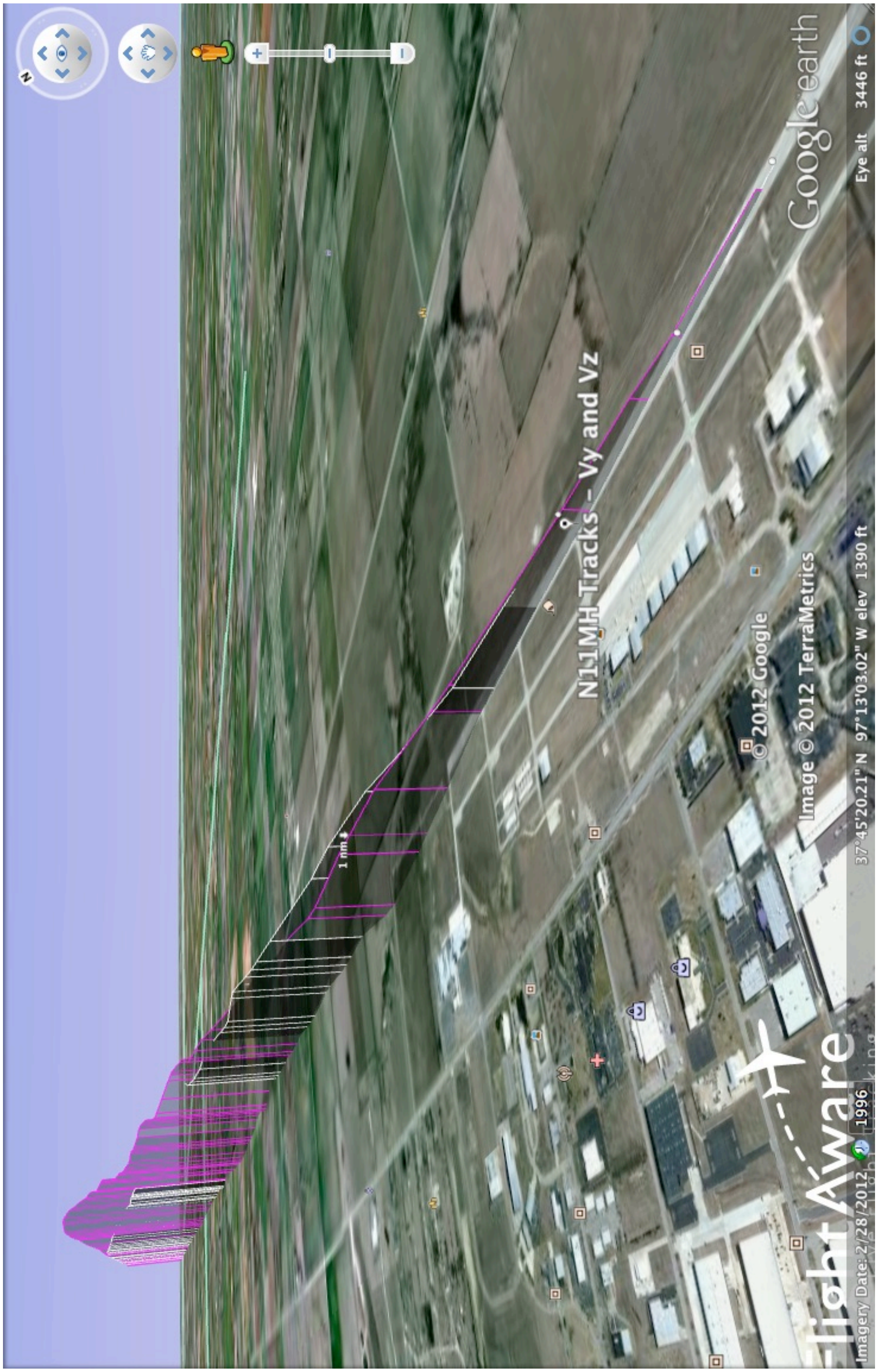

Figure 21: GPS tracks, V_Z (in white) and V_Y (in magenta) for Mooney M20J under identical field conditions. Flight test data, May 31, 2012, Wichita, KS.

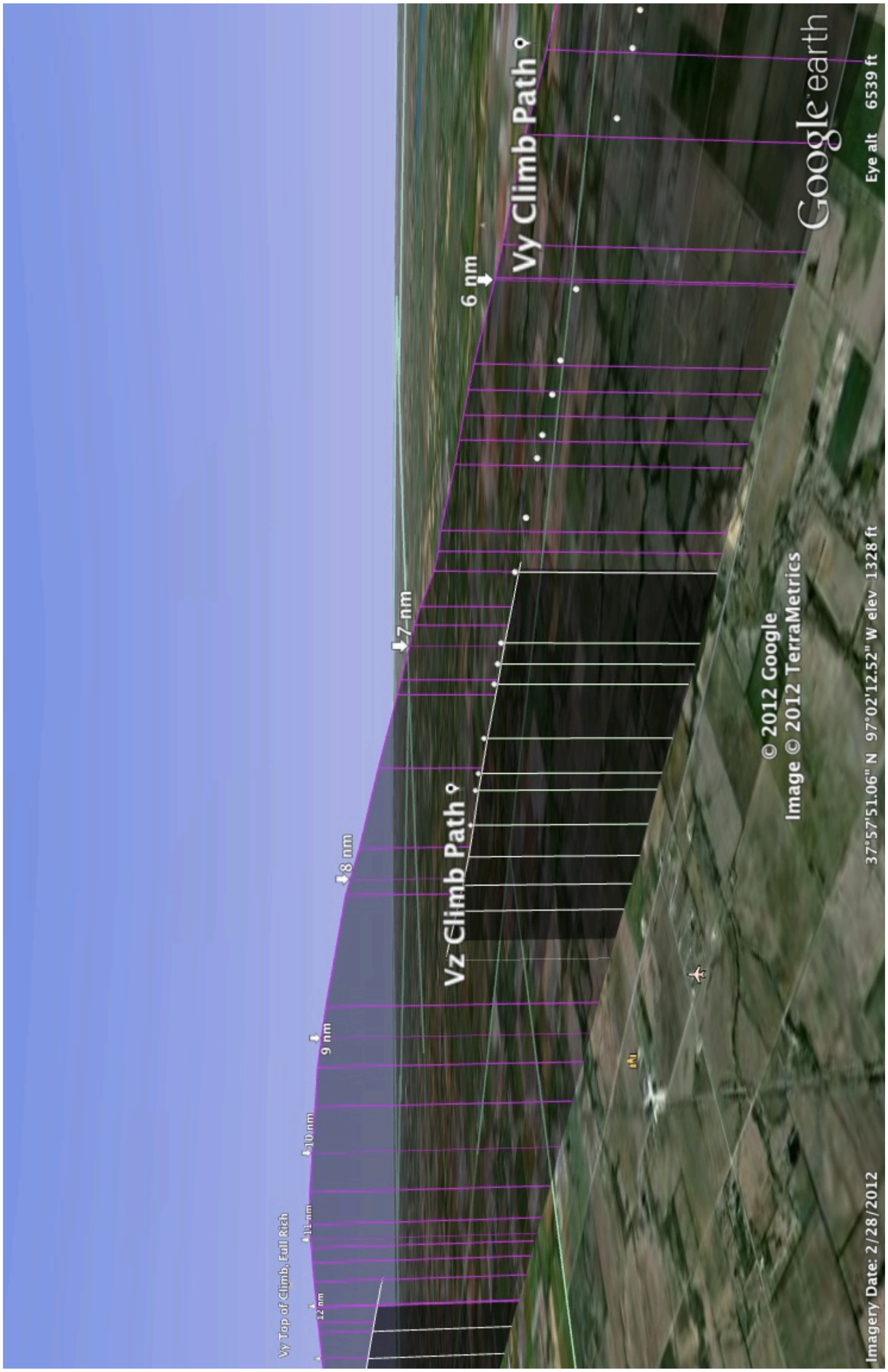

Figure 22: V_Z climb path versus V_Y climb path, Mooney M20J, May 31, 2012., Wichita, KS. Note V_Y top of climb at 12 nautical miles down path, center left of image.

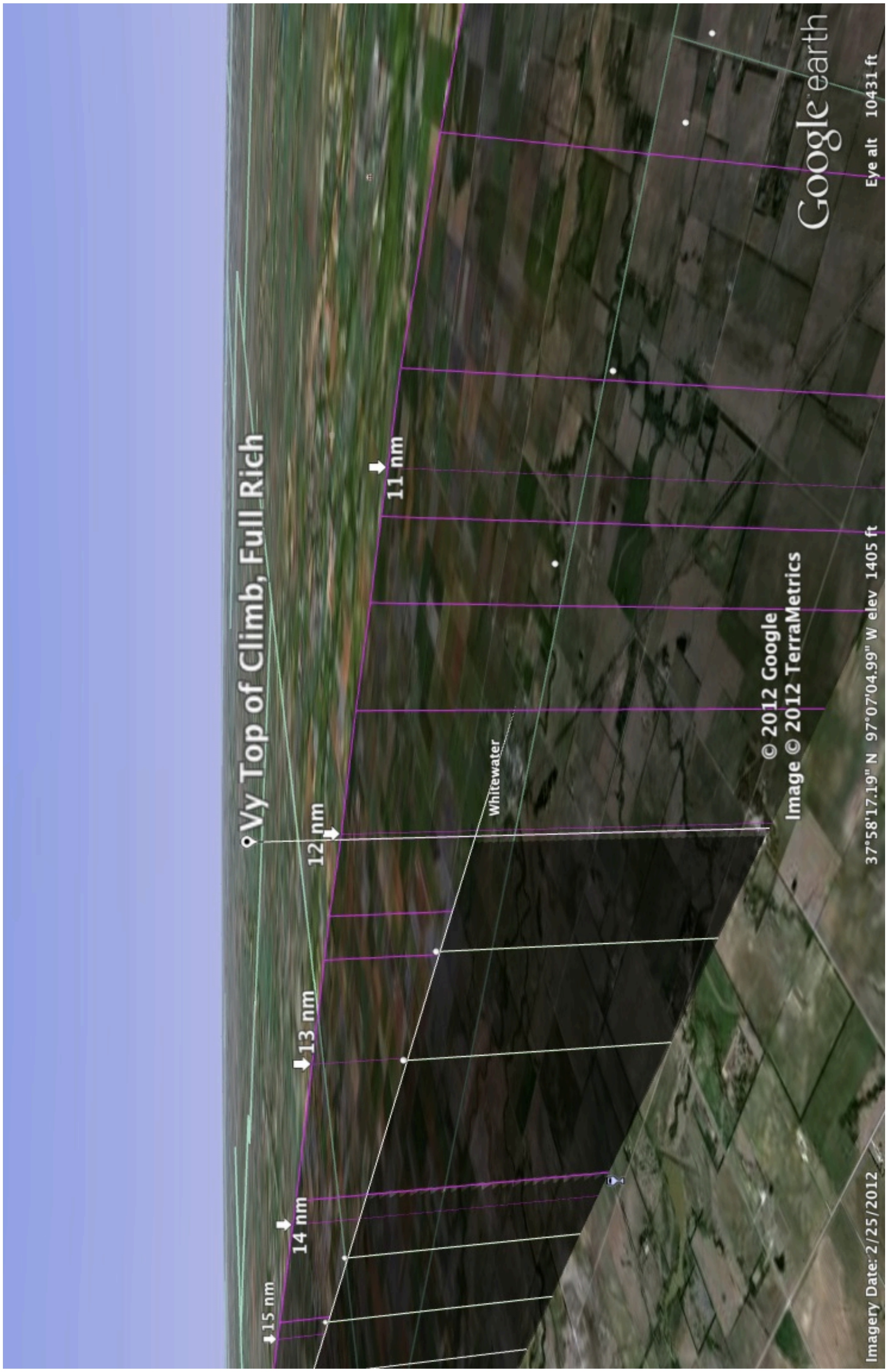

Figure 23: V_Y top of climb, Mooney M20J. Flight test data, May 31, 2012, Wichita, KS.

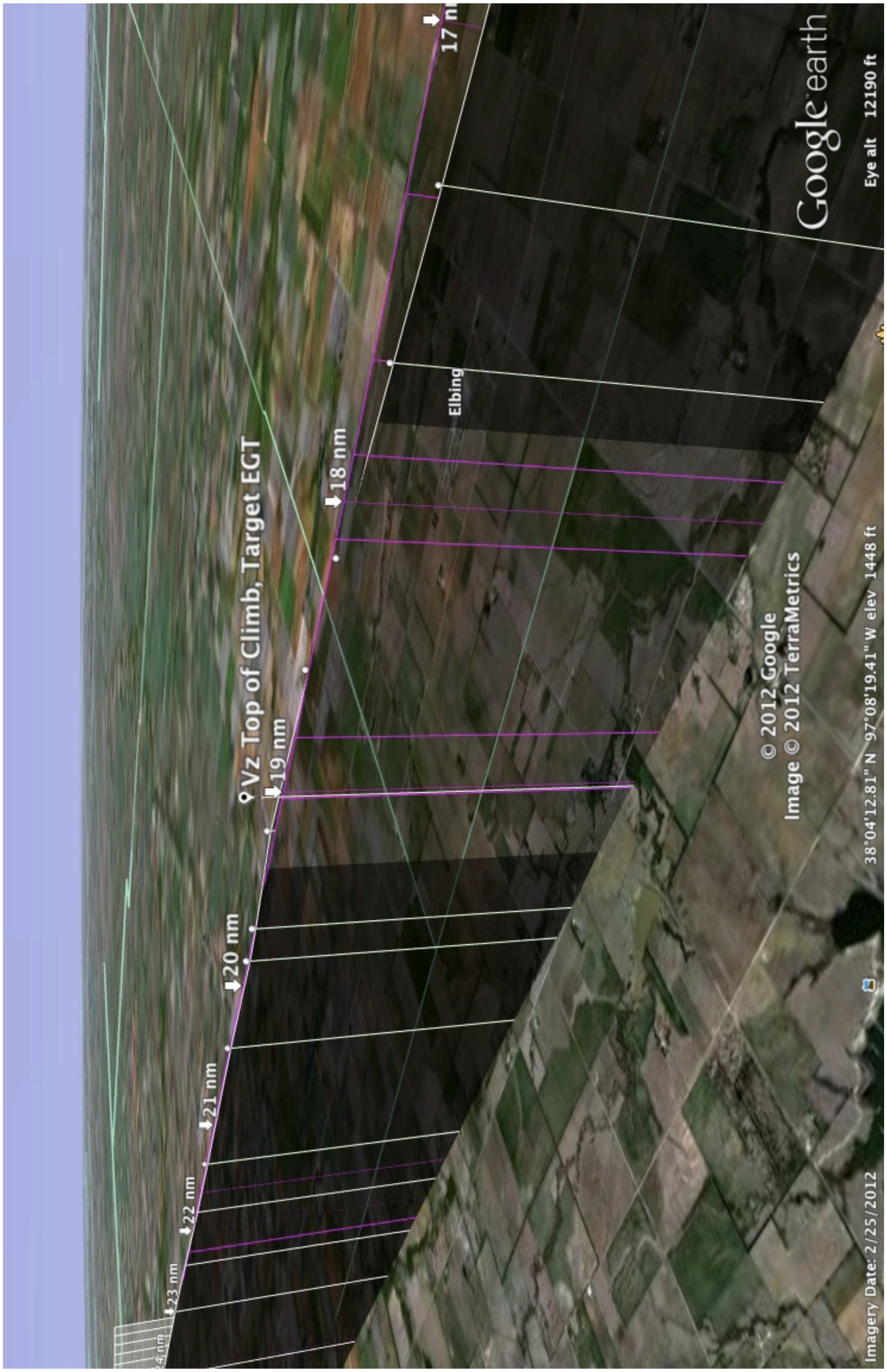

Figure 24: V_Z top of climb, Mooney M20J. Flight test data, May 31, 2012, Wichita, KS.

It is possible with the gathered data to perform a test day condition evaluation of the V_Y climb and V_Z climb from the six flights in the same manner as table 3, above. Even though the conditions of airplane weight, cg, weather, winds and altitude band are not standardized, a direct comparison of the resulting CAFE parameter from each flight will show the applicability and validity of the technique under real world conditions and a variety of airplane models. Note that a 25 knot average headwind for both flights reduced the resulting V_{MG} values considerably from the no-wind conditions in the earlier tables.

Table 5

0-8000' Climb Quantitative Results, Test Day Conditions, 1977 M20J N11MH

Climb Speed	Climb Mixture	65% Cruise Segment Mixture	Time (Minutes)	Fuel (Gallons)	Distance (Naut Miles)	Velocity Made Good (knots)	NMPG	CAFE Parameter $V_{MG}^{1.3}$*NMPG
V_Z	**Target EGT**	**N/A**	**12.0**	**4.1**	**19**	**95.0**	**4.6**	**1725.9**
V_Y	Full Rich		11.0	3.5	11.5			
	+65% Cruise	25°F LOP	3.9	0.6	7.5	76.3	4.7	1308.1

More tables are shown on the following page.

Table 6

0-8000' Climb Quantitative Results, Test Day Conditions, 1998 M20K N91618

Climb Speed	Climb Mixture	65% Cruise Segment Mixture	Time (Minutes)	Fuel (Gallons)	Distance (Naut Miles)	Velocity Made Good (knots)	NMPG	CAFE Parameter $V_{MG}^{1.3}$*NMPG
V_Z	**Full Rich**	**N/A**	**10.1**	**3.7**	**16**	**95.0**	**4.3**	**1611.6**
V_Y	Full Rich		8.5	3.0	12			
	+65% Cruise	25°F LOP	2.0	0.7	4.0	91.4	4.3	1532.2

Table7

0-8000' Climb Quantitative Results, Test Day Conditions, 1979 M20K N231HG

Climb Speed	Climb Mixture	65% Cruise Segment Mixture	Time (Minutes)	Fuel (Gallons)	Distance (Naut Miles)	Velocity Made Good (knots)	NMPG	CAFE Parameter $V_{MG}^{1.3}$*NMPG
V_Z	**Full Rich**	**N/A**	**9.9**	**3.7**	**19**	**115.0**	**5.1**	**2472.1**
V_Y	Full Rich		7.7	2.8	11			
	+65% Cruise	25°F LOP	3.3	0.7	8.0	103.2	5.4	2250.6

It is clear that the validity of the V_Z profile in terms of efficiency can be shown from the real world results above.

There are also additional insights on flight work load from the alternate task flown as part of the evaluation. The first subject pilot evaluated the V_Y full rich climb that was flown immediately after the V_Z climb to provide a back to back comparison of the task, and to observe and comment on any differences in the task that may have not been addressed in the original test plan. He gave the baseline V_Y flying task a Cooper-Harper rating of 3, the same as the V_Z task. He also noted that the V_Z profile was no harder to fly than the V_Y profile.

The pilot further commented that the V_Z task was actually slightly easier to fly than the V_Y task with respect to flight controls, because the amount of rudder required to counteract sidewash was less. Although there was some added workload involved in observing the climb performance limit and changing the climb control parameter from airspeed to VVI, the subject found that the workload of the task element to be about equal to the same task element during a V_Y climb. A V_Y climb flown accurately involves flying a slightly decreasing indicated airspeed as the altitude increases.

In addition, there was an additional V_Z task element of adjusting cowl flaps as necessary to maintain a cylinder head temperature of about 380°F or less during the V_Z climb. The engine data in figure 25 on the following page show the effect of cowl flap movement on cylinder head temperature during the V_Z climb. Even though the cowl flap adjustments were made approximately every 90 seconds for a portion of the climb, the subject did not feel the task element was difficult or distracting from the primary flight task.

Adjusting cowl flaps as necessary during the V_Z climb as discussed does result in an additional efficiency advantage - a reduction in cooling drag. The high drag cooling capability of full open cowl flaps is not necessary due to the higher climb speed, and in this case, adjusting cowl flaps from part open to closed gave satisfactory results.

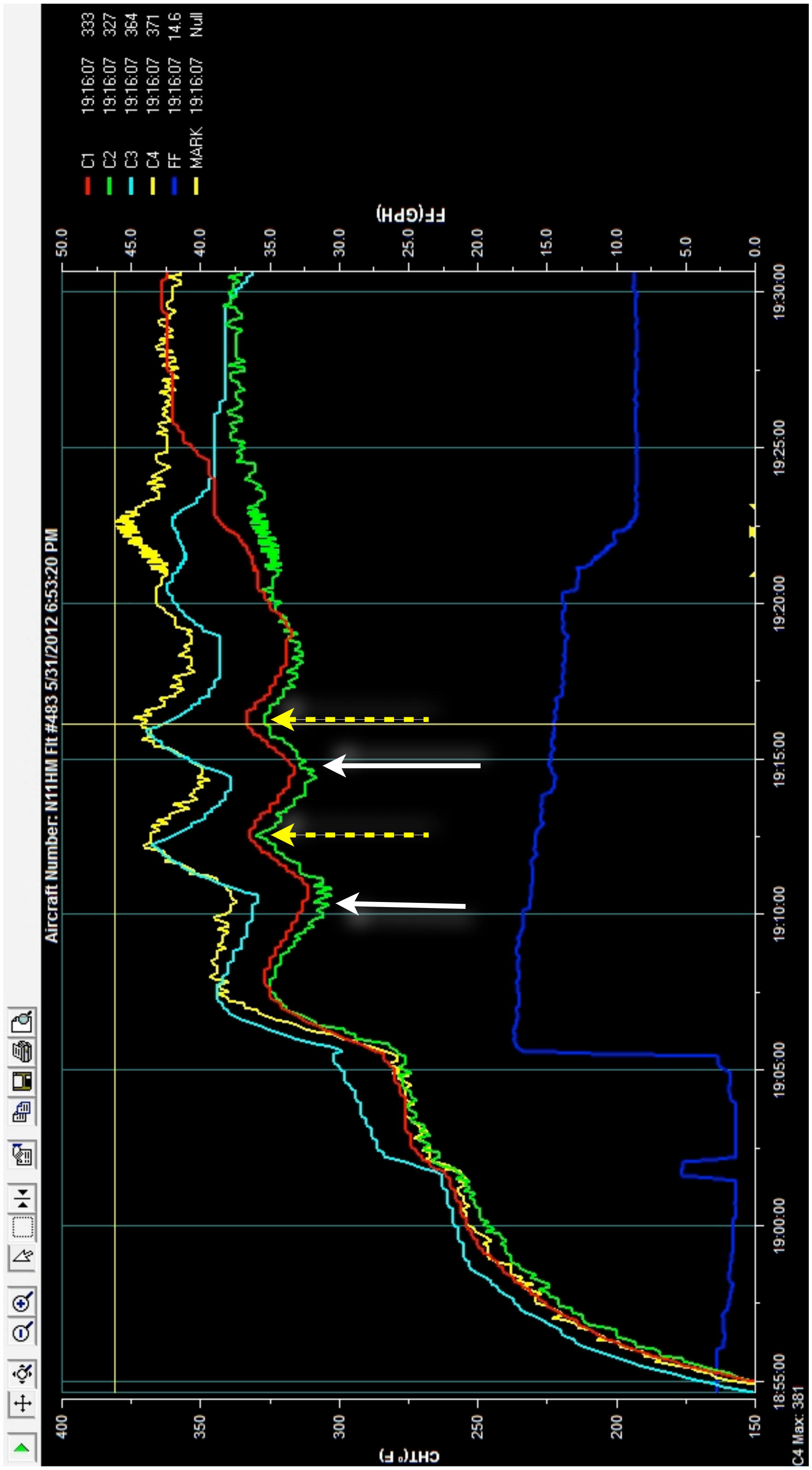

Figure 25: V_Z climb data, M20J cylinder head temperature. White arrows indicate cowl flaps closed, yellow dotted arrows indicate cowl flaps partly opened (trail position).

The final flight work load detail for the V_Z climb is the specification of the Target EGT method of mixture control as outlined in Chapter II, figure 8 and the associated paragraphs. The POH method of mixture control for a V_Y climb specifies full rich mixture, with leaning only as necessary for smooth operation, not economy (Mooney, 1984). The target EGT method involves slightly more pilot workload, as the mixture control is adjusted more often during the climb. The engine data plots, below, show the effects of the target EGT method on EGT and fuel flow during the V_Z climb, and a full rich mixture (POH) method on the same parameters during the V_Y climb, respectively. The data were gathered back-to-back during the project test flights on May 31, 2012 in Wichita, KS. The apparatus used was a JP Instruments EDM-700 engine analyzer, and the data were processed and plotted using EZTrends software.

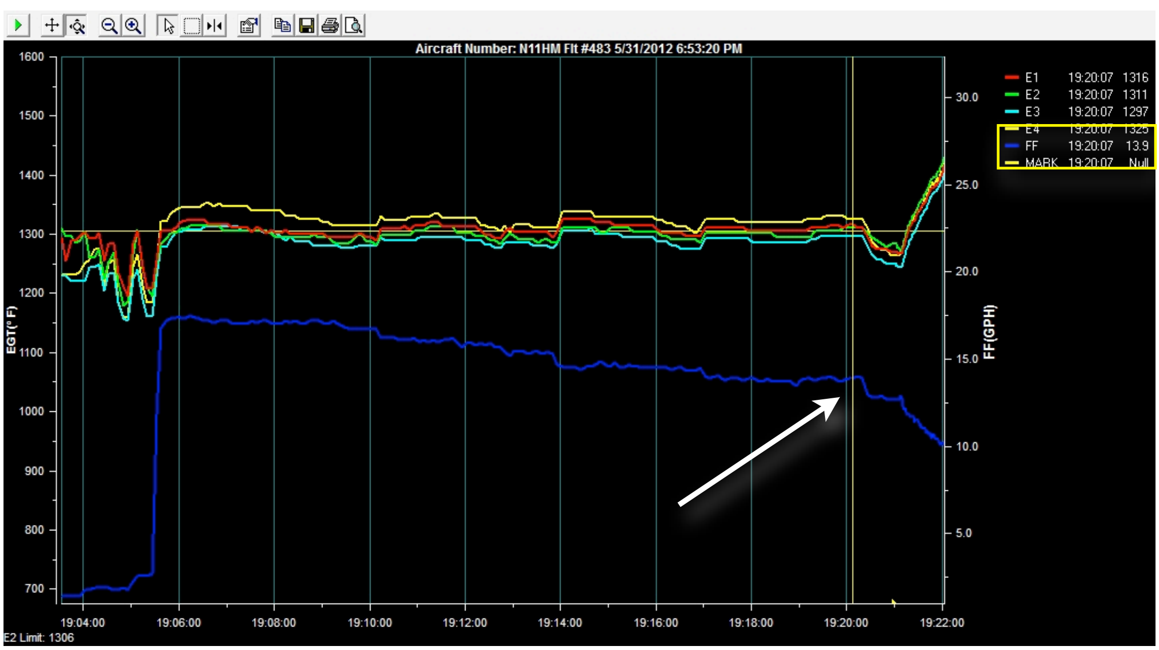

Figure 26: V_Z climb flight test data, M20J EGT and fuel flow, May 31, 2012. Target EGT method of mixture control. White arrow indicates fuel flow at V_Z top of climb, yellow box encloses fuel flow value (13.9 gallons per hour).

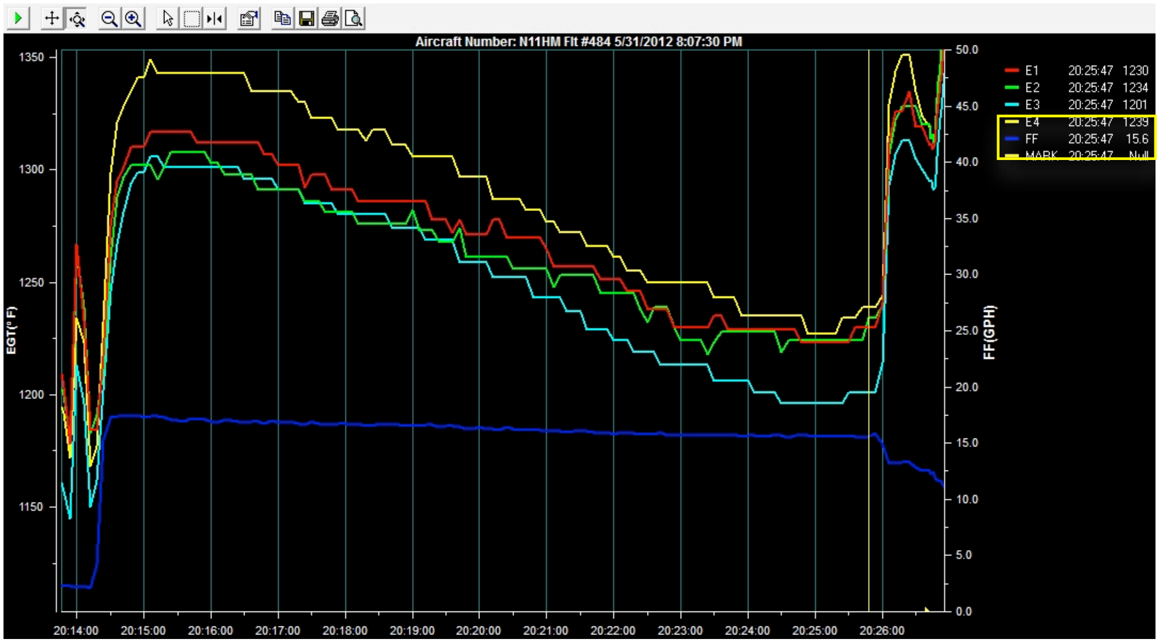

Figure 27: V_Y climb flight test data, M20J EGT and fuel flow, May 31, 2012. Full rich EGT as per Mooney M20J POH (1984). Yellow vertical line indicates fuel flow at V_Y top of climb, yellow box encloses fuel flow value (15.6 gallons per hour).

Note the similarity of the flight test data to figure 8. Clearly, the target EGT method is easily repeatable under field conditions as shown above. Although the method does involve a slightly higher workload than the baseline Full Rich method, the subject felt that the entire V_Z climb task was no more difficult overall than the baseline V_Y climb as shown in the Mooney POH.

One final statement may be made about the sensitivity of attained efficiency with respect to the adequate criteria of -5 knots. In tables 3 and 4, the CAFE parameters obtained for Eckelbar's method (1994) are well above any of the V_Y methods and are quite close to the values shown for V_Z. Since the speed for Eckelbar's method (about 1.15*V_Y, or roughly 99 KCAS) is below the adequate threshold for V_Z, even a poorly flown V_Z profile can still obtain efficient results.

CHAPTER VI

CONCLUSIONS

The research into V_Z covered three areas of investigation. The first was to model a climb profile that resulted in the most efficient climb, where the measure of merit of efficiency was the CAFE parameter $\boldsymbol{V_{MG}^{1.3} * MPG}$. The data extracted from the Mooney POH, the modeled data from the Benchmark program, and a spot check of comparative performance obtained in field trial all support the hypothesis of the proposed V_Z profile as providing best efficiency of climb.

Modeling the aircraft performance in the Benchmark program from the published conformed performance data in the airplane's POH was a somewhat time consuming task, but could be done at virtually no cost. Such modeling could be increased to a number of different airplane types without a large economic impact to industry or owner groups.

The second area of investigation was to formulate a definition of V_Z that would be suitable for inclusion in FAA training manuals and manufacturer operating guidelines. The definition listed in Chapter IV meets this objective. It may be possible to socialize the definition among the active pilot population through a number of other media such as magazine articles (both general aviation and specific type clubs) and the various online type club forums, such as Mooneyspace or Beechtalk. This effort might disseminate the idea more rapidly than through the FAA or manufacturer channels.

The third area investigated the flight work load of the task. Even though the sample size (airplane type and pilot) was small due to resource constraints, the objective of identifying an initial trend as to the suitability of the flight work load of the task was met. In particular, the back-to-back comparison of the proposed method to the current FAA approved climb method, giving identical C-H scores and comments, lends support to the assertion of Vz as a suitable flight task for the target pilot population.

CHAPTER VII

RECOMMENDATIONS

The V_Z profile holds promise to increase the efficiency of general aviation flight, with virtually no monetary investment as compared to other possibilities. In order to increase the acceptance and implementation of this idea into the general aviation population, the following recommendations are made:

1. *Increase the base of modeled airplane type designs in Benchmark.* The researcher's Aerostar 601P and the Embry-Riddle fleet of Piper Arrows and Diamond DA42 L360s are ideal for this recommendation. The ERAU Eagle Flight Research Center should obtain a copy of Benchmark and utilize it for this and other research.

2. *Use the increased number of type design models in Benchmark to predict V_Z for other airplanes, including twin engine airplanes, airplanes with turbocharged or turbonormalized engines, and fixed gear constant speed prop equipped high performance airplanes such as the Cirrus SR22 and Cessna 182.* Other than the researcher's twin turbonormalized Aerostar 601P mentioned above, this effort should be undertaken by the ERAU College of Engineering.

3. *Increase the sample size of pilots in each airplane type.* This researcher plans to conduct additional flight trials for in-flight work load in an instrumented Mooney M20J over the next two months. The Eagle Flight research center should consider the same process for its fleet of suitable airplanes.

4. Perform a thorough performance comparison of a Benchmark modeled airplane to actual airplane performance in flight test. This would be an ideal graduate project for a Piper Arrow airplane at the Eagle Flight Research Center.

*5. Increase the awareness of V_Z among the pilot population.*Such awareness can occur through research and popular press postings on airplane type club forums, magazine articles and presentations to appropriate groups. This researcher has done all three, and exemplars are found at Appendix F. Other research groups (ERAU, USAF Test Pilot School or National Test Pilot School, the CAFE Foundation and the Raspet Flight Research Laboratory at Mississippi State University) can create and share additional research on this idea as it is validated.

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APPENDIX A

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APPENDIX C

DATA COLLECTION DEVICE

Benchmark

The validation of the three modules (engine, propeller, and airframe) of Benchmark's performance algorithm will be shown in this Appendix.

Figure 28, below, is a copy of the Mooney M20J POH (1984) performance page for Cruise and Range at Economy Cruise, 8000', -1°C. Benchmark models the engine parameters shown on the page under %hp and fuel flow.

CRUISE & RANGE AT ECONOMY CRUISE
8000 FT, -1° C

MIXTURE SETTING:
Lean mixture in accordance with instructions in Section IV.

					TRUE AIRSPEED MPH/KNOTS		ENDURANCE	RANGE (NAUT MI)	
RPM	MAN PRES (IN. HG)	% BPH	FUEL (GAL/HR)	FUEL (LBS/HR)	2740 LBS	2300 LBS	(HR: MIN)	2740 LBS	2300 LBS
2700	23.6	75	10.8	64.7	195/169	197/171	5:00	835	850
	21.7	70	10.3	61.6	187/162	191/166	5:15	850	871
	20.4	65	9.7	58.0	181/157	185/161	5:37	881	904
	19.0	60	9.2	55.1	174/151	179/156	6:00	906	936
	17.8	55	8.6	51.5	167/145	173/150	6:27	928	961
	14.8	44	7.4	44.4	146/127	155/135	7:31	954	1014
2600	23.0	71	10.1	60.6	189/164	193/168	5:20	869	890
	21.2	65	9.4	56.6	181/157	185/161	5:48	910	933
	19.8	60	8.8	53.3	174/151	179/156	6:10	931	962
	18.6	55	8.3	50.1	167/145	173/150	6:37	952	985
	17.0	50	7.8	46.8	158/137	165/143	7:05	970	1012
	15.2	43	7.6	45.5	144/125	153/133	7:55	989	1053
2400	22.8	64	9.1	54.4	181/157	185/161	6:04	946	970
	21.3	60	8.6	51.6	174/151	179/156	6:21	958	990
	19.8	55	8.1	48.6	167/145	173/150	6:50	984	1018
	18.2	50	7.5	45.5	158/137	165/143	7:20	1004	1048
	15.5	42	6.7	40.0	141/122	151/131	8:20	1016	1091
2200	22.0	55	7.8	47.1	167/145	173/150	7:05	1020	1055
	20.0	50	7.3	44.1	158/137	165/143	7:40	1050	1096
	16.8	41	6.3	38.0	138/120	150/130	8:54	1068	1157
2000	20.3	45	6.5	39.0	148/129	156/136	8:35	1102	1167
	18.2	40	6.0	35.7	135/117	147/128	9:28	1110	1211

ISSUED 9/27/76 Mooney M20J 5-23

Figure 28: Cruise and Range at Economy Cruise, Mooney M20J POH, 8000', -1°C. *Note:* From *Pilot's operating handbook and FAA approved airplane flight manual, Mooney M20J* (p. 77), by Mooney Aircraft Corporation, 1984, Kerrville, TX. Copyright 2005 by Mooney Airplane Company. Reprinted with permission.

Table 6 and Figure 29, below, compare the best economy engine data from the POH with the data generated by Benchmark.

Table 8

POH vs. Benchmark, Lycoming IO-360-A3B6D as installed in M20J, 8000’, Best Econ

RPM	Man. Press. (In. Hg)	POH % BHP (Brake Horsepower)	Benchmark % BHP (Brake Horsepower)	POH Fuel Flow (Gal/ Hr)	Benchmark Fuel Flow (Gal/ Hr)
2700	23.6	75	--	10.8	--
	21.7	70	73	10.3	10.6
	20.4	65	68	9.7	10.1
	19	60	62	9.2	9.4
	17.8	55	58	8.6	8.9
	14.8	44	--	7.4	--
2600	23	71	--	10.1	--
	21.2	65	67	9.4	9.8
	19.8	60	62	8.8	9.3
	18.6	55	58	8.3	8.8
	17	50	52	7.8	8.1
	15.2	43	45	***7.6***	7.4
2400	22.8	64	65	9.1	9.3
	21.3	60	61	8.6	8.8
	19.8	55	56	8.1	8.3
	18.2	50	51	7.5	7.7
	15.5	42	42	6.7	6.7
2200	22	55	57	7.8	8.1
	20	50	51	7.3	7.5
	16.8	41	42	6.3	6.5
2000	20.3	45	46	6.5	6.7
	18.2	40	41	6.0	6.2

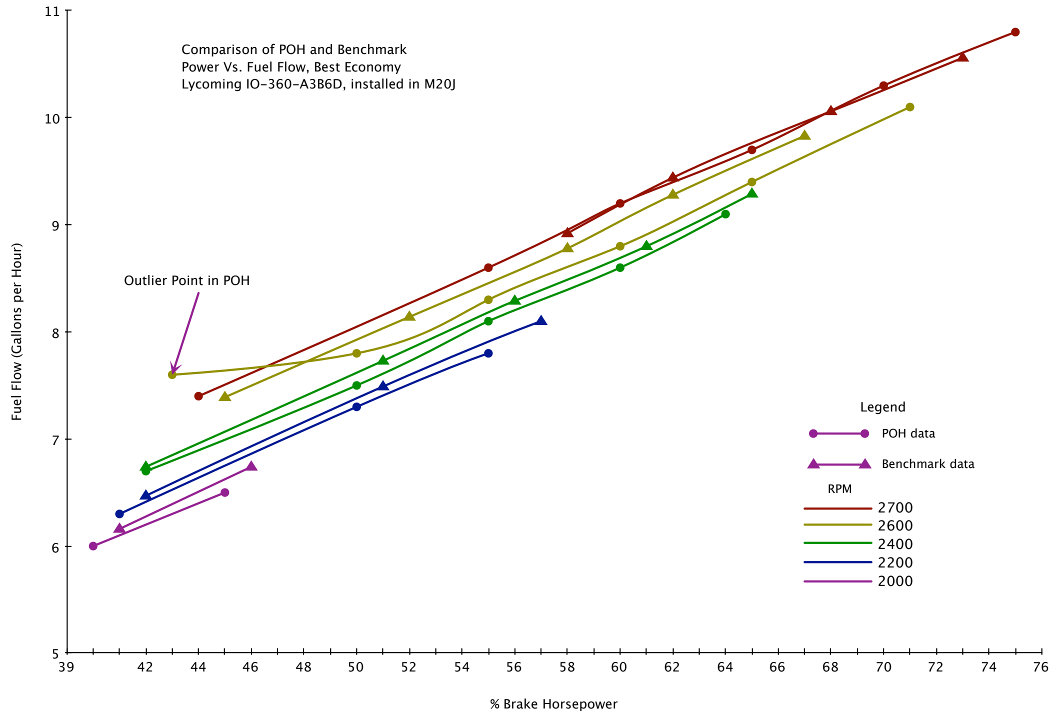


Figure 29: Comparison of Fuel Flow versus % BHP at various RPMs. Data shown are for a Lycoming IO-360-A3B6D as installed in Mooney M20J. Note outlier point in POH 2600 RPM data set.

The data show excellent correlation for % brake horsepower versus fuel flow at 2700 RPM, which is the RPM used for all climb data. Other RPMs show good correlation. There is an obvious outlier point in the FAA approved data (shaded in red on the table and indicated in Figure 29, above)- this point obviously does not follow the relatively linear characteristics of the remaining data for either the POH or Benchmark.

The next module for validation is the propeller model. The following data sets were run using input conditions for Benchmark and a CFD model (called PROP) used by Hartzell Propeller, Inc.

Table 9

Validation of Propeller Performance Module, Benchmark versus Hartzell PROP

Hartzell Propeller and Blade Data:

Hartzell Run Date/Time: 20120327 150621.4

BLADE FILE : 7497.dat METAL BLADES
SINGLE ENGINE RECIPROCATING

PROPELLER DIAMETER:	74.000 (in) (6.167 ft)
REFERENCE RADIUS:	30.000 (in)
NUMBER OF BLADES:	2
SPINNER DIAMETER:	14.000 (in)
BLADE ACTIVITY FACTOR:	95.
DESIGN COEFFICIENT CLi:	.517
BLADE POLAR MOMENT IP:	10.6 in.lb.sec**2
BLADE WEIGHT FROM STA. 3.5 :	14.6 (lb)
(RADIUS 3.500 (in))	

Test Case 1 (V_Z Climb, midpoint, WOT):

FLIGHT CONDITION: **119.8 KTAS @ 4000. FT ISA**
POWER: **175.0 HP @ 2700. RPM**
FLIGHT MACH NO.: 0.184
IDEAL EFFICIENCY FOR THIS CONDITION IS ETA = 0.881
AIR MASS DENSITY RHO = 0.2110958E-02 lb(sec.**2)/(ft**4)
AIR VISCOSITY Mu = 0.3654183E-06 lbsec/(ft**2)
SPEED OF SOUND Va = 1101.4 ft/sec

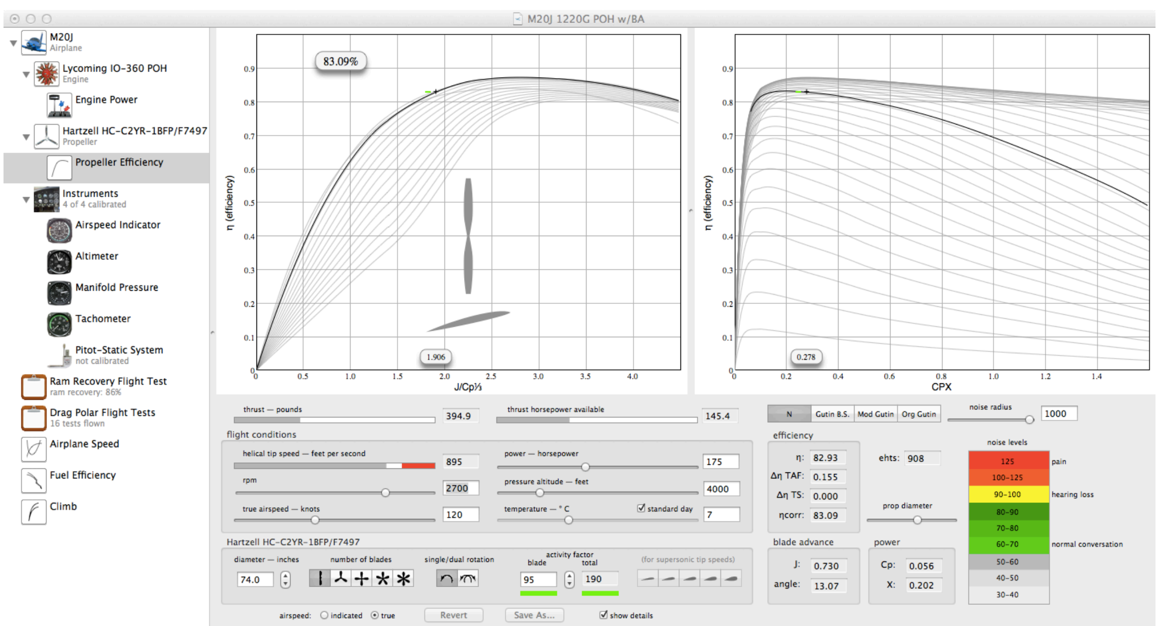
Model	J	Helical Tip Speed (fps)	THP	Thrust (lb)	ETA
PROP	0.729	895.4	143.0	389.0	0.817
Benchmark	0.730	895	145.4	394.9	0.831

Original PROP data, Test Case 1:

HELICAL TIP MACH NO. = 0.813
ADVANCE RATIO = 0.729

BETA	HP	CT	CP	THP/SHP	THRUST (lb)	EQUIV. EFFY (Ct/Cp*J)	THRUST (lb)
18.813	175.0	0.063	0.056	0.817	389.	0.877	417.

Benchmark Screen Shot, Test Case 1:



Test Case 2 (Low Altitude, Level, WOT 90% Power):

FLIGHT CONDITION: **175.5 KTAS @ 3000. FT ISA**
POWER: **180.0 HP @ 2700. RPM**
FLIGHT MACH NO.: 0.268
IDEAL EFFICIENCY FOR THIS CONDITION IS ETA = 0.937
AIR MASS DENSITY RHO = 0.2175193E-02 lb(sec.**2)/(ft**4)
AIR VISCOSITY Mu = 0.3673811E-06 lbsec/(ft**2)
SPEED OF SOUND Va = 1105.3 ft/sec

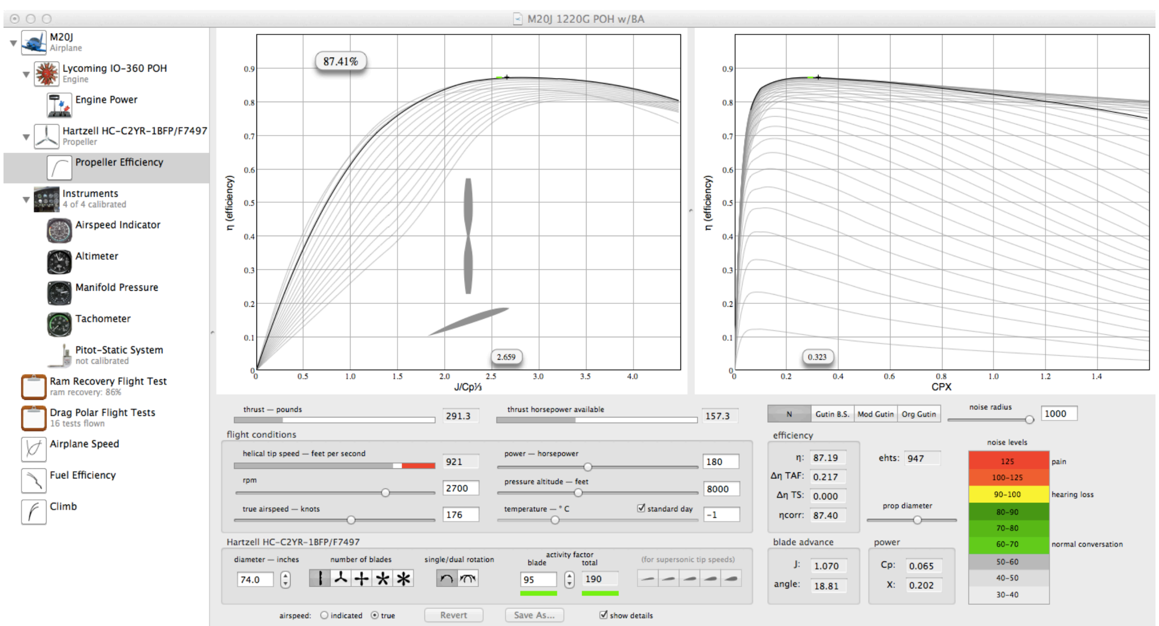
Model	**J**	**Helical Tip Speed (fps)**	**THP**	**Thrust (lb)**	ETA
PROP	1.068	920.7	155.3	288.0	0.863
Benchmark	1.070	921	157.3	291.3	0.874

Original PROP data, Test Case 2:

HELICAL TIP MACH NO. = 0.833
ADVANCE RATIO = 1.068

BETA	HP	CT	CP	THP/SHP	THRUST (lb)	EQUIV. EFFY (Ct/Cp*J)	THRUST (lb)
23.141	180.0	0.045	0.056	0.863	288.	0.921	307.

Benchmark Screen Shot, Test Case 2:



Test Case 3 (Hi Power 8000' Cruise, Level, WOT 75% Power):

FLIGHT CONDITION: **169.9 KTAS @ 8000. FT ISA**
POWER: **151.0 HP @ 2700. RPM**
FLIGHT MACH NO.: 0.264
IDEAL EFFICIENCY FOR THIS CONDITION IS ETA = 0.935
AIR MASS DENSITY RHO = 0.1868401E-02 lb(sec.**2)/(ft**4)
AIR VISCOSITY Mu = 0.3575337E-06 lbsec/(ft**2)
SPEED OF SOUND Va = 1085.7 ft/sec

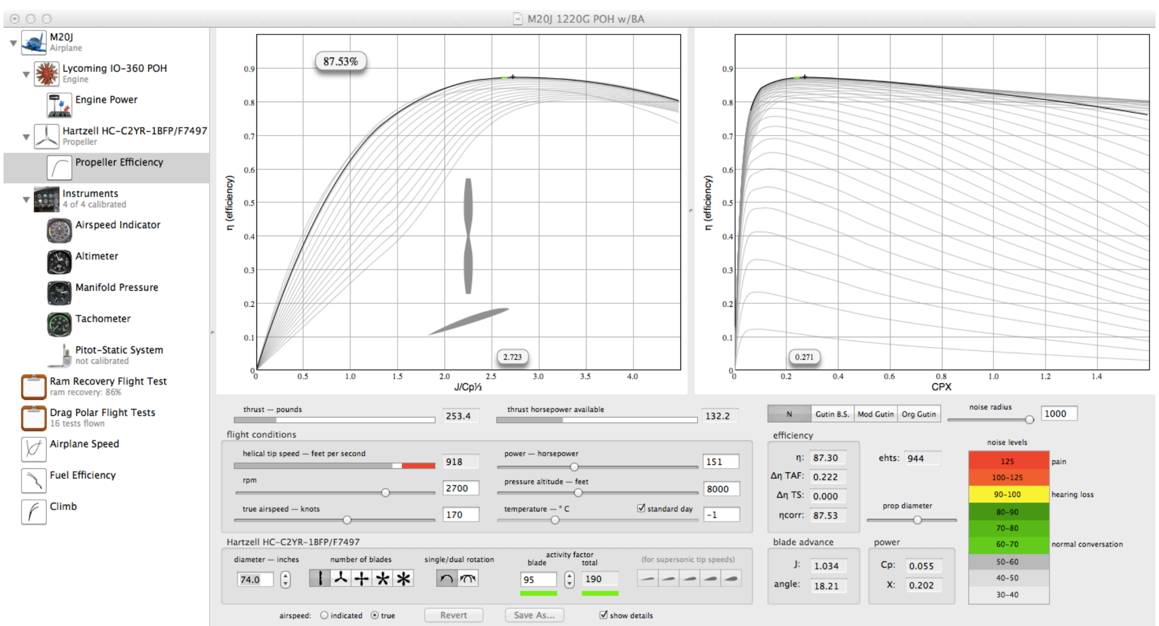
Model	J	Helical Tip Speed (fps)	THP	Thrust (lb)	ETA
PROP	1.034	917.4	130.0	249.0	0.861
Benchmark	1.034	918	132.2	253.4	0.875

Original PROP data, Test Case 3:

HELICAL TIP MACH NO. = 0.845
ADVANCE RATIO = 1.034

BETA	HP	CT	CP	THP/SHP	THRUST (lb)	EQUIV. EFFY (Ct/Cp*J)	THRUST (lb)
22.493	151.0	0.046	0.055	0.861	249.	0.918	266.

Benchmark Screen Shot, Test Case 3:



Test Case 4 (Econo 8000' Cruise, Level, WOT 65% Power):

FLIGHT CONDITION: **157.6 KTAS @ 8000. FT ISA**
POWER: **130.0 HP @ 2500. RPM**
FLIGHT MACH NO.: 0.245
IDEAL EFFICIENCY FOR THIS CONDITION IS ETA = 0.931
AIR MASS DENSITY RHO = 0.1868401E-02 lb(sec.**2)/(ft**4)
AIR VISCOSITY Mu = 0.3575337E-06 lbsec/(ft**2)
SPEED OF SOUND Va = 1085.7 ft/sec

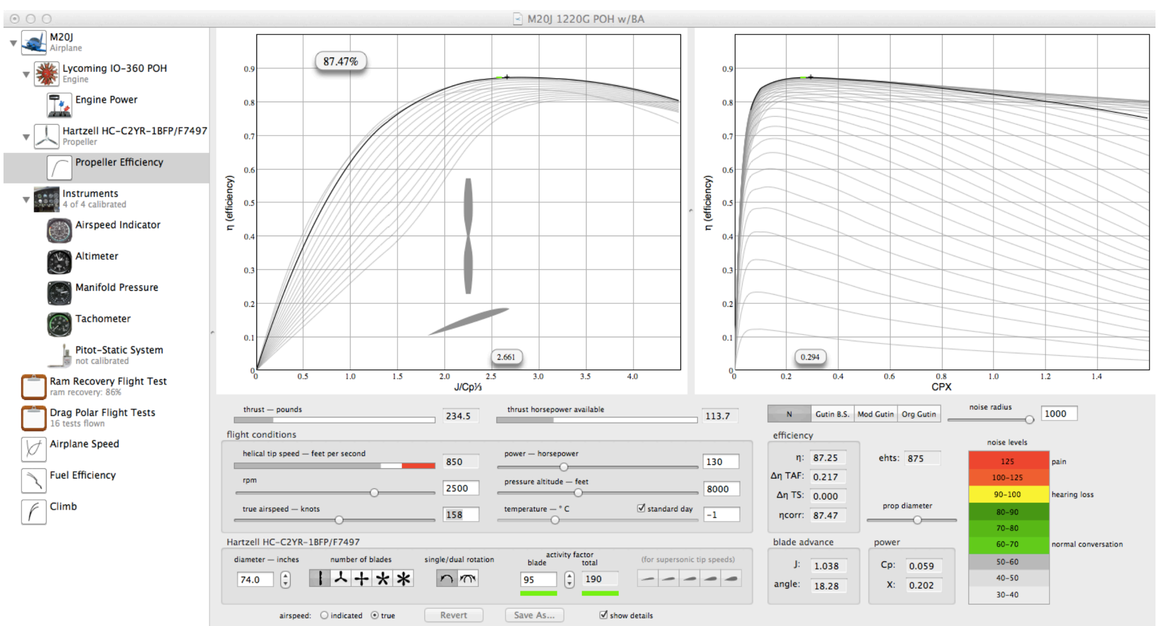
Model	**J**	**Helical Tip Speed (fps)**	**THP**	**Thrust (lb)**	ETA
PROP	1.036	850.1	112.2	232.0	0.863
Benchmark	1.038	850	113.7	234.7	0.875

Original PROP data, Test Case 4:

HELICAL TIP MACH NO. = 0.783
ADVANCE RATIO = 1.036

BETA	HP	CT	CP	THP/SHP	THRUST (lb)	EQUIV. EFFY (Ct/Cp*J)	THRUST (lb)
23.226	130.0	0.049	0.059	0.863	232.	0.922	248.

Benchmark Screen Shot, Test Case 4:



Note: End of Table 9.

The propeller data from Benchmark are slightly optimistic as compared to the output from Hartzell for the set of evaluated input conditions. Conditions 1 and 4 are most relevant to the V_z task, and the predicted thrust horsepower for these points is 1.7% and 1.3% optimistic, respectively. For the purposes of the relative comparisons of performance from the same model algorithm, the module is valid. The reason is that the improvement in thrust horsepower percentage due to the V_Z profile is about a half order of magnitude above the baseline. However, for absolute determination of performance there may be some improvements to be made in this area.

The final validation of Benchmark will be made using a Best Economy cruise data point from figure 28, above.

Table 10

Comparison of POH vs. Benchmark cruise data, 8000', Best Economy

	RPM	**Man. Press. (In. Hg)**	**% BHP (Brake Horsepower)**	**Fuel Flow (Gal/Hr)**	**True Airspeed 2740 lb GW**	**True Airspeed 2300 lb GW**
POH	**2700**	20.4	65	9.7	157.0	161.0
Benchmark	**2700**	19.6	65	9.72	155.3	159.8

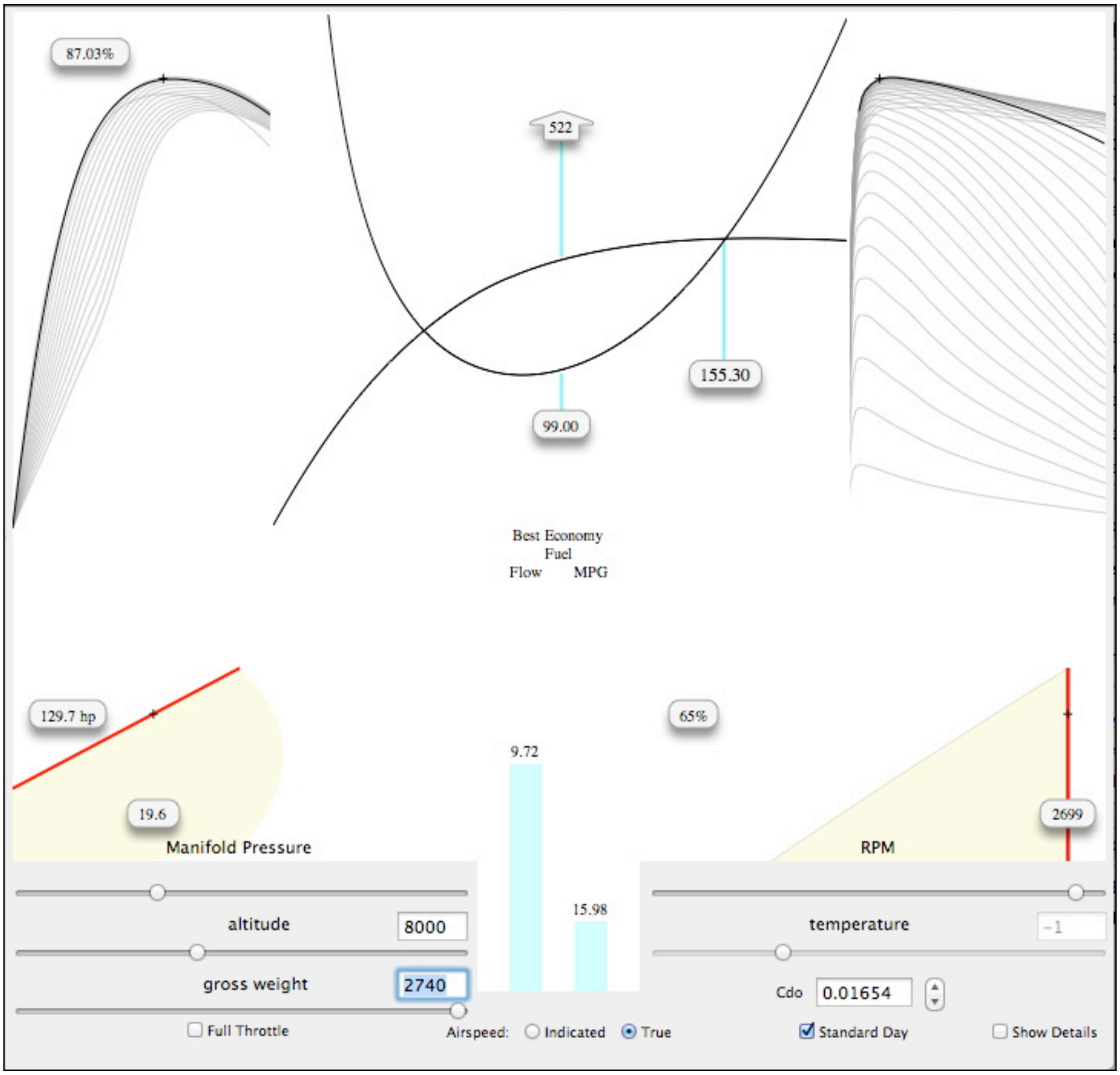


Figure 30: Benchmark predicted cruise performance, 65% power Best Economy, 8000', 2740 lb gross weight, standard day.

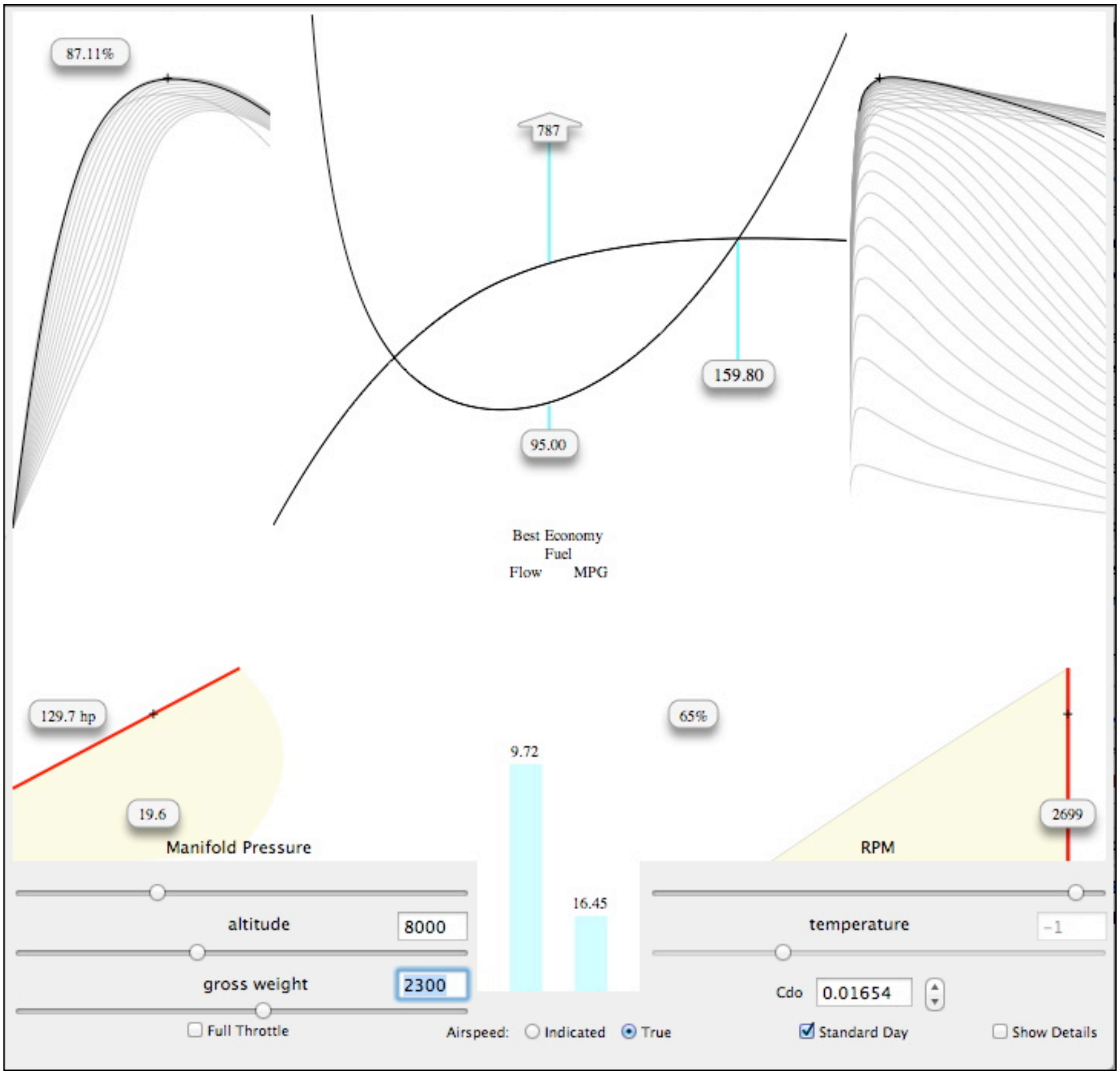


Figure 31: Benchmark predicted cruise performance, 65% power Best Economy, 8000', 2300 lb gross weight, standard day.

It is interesting to note the performance of the airplane is very slightly under-predicted for this data point, even though the prop data would suggest a very slight over-prediction of thrust horsepower at the same condition. However, referring to figure 15, it is obvious the set of POH cruise data points are somewhat scattered. This is to be expected as the state of the art in data handling in 1976 was not as good as the present day. In addition, the predicted data are very accurate when evaluated in the context of decades of flying the M20J by the researcher. The typical field evaluation by lay users is also illuminating: “The 201 [M20J] is a good 155 knot airplane.”

APPENDIX D

TABLES AND SPREADSHEETS

Climb Speed	Climb Mixture	65% Cruise Segment Mixture	Time (Minutes)	Fuel (Gallons)	Distance (Naut Miles)	Velocity Made Good (knots)	NMPG	CAFE Parameter VMG^1.3* NMPG
VZ	**Target EGT**	**N/A**	**12.8**	**3.4**	**25.5**	**119.5**	**7.6**	**3812**
VY (POH)	Full Rich		10.0	2.7	14.0			
	+65% Cruis	Best Power (PO	4.4	0.8	11.5	106.3	7.3	3133
VY	Full Rich		10.0	2.9	15.4			
	+65% Cruis	Best Power	3.9	0.7	10.1	110.3	7.1	3191
VY	Full Rich		10.0	2.9	15.4			
	+65% Cruis	Best Economy	3.9	0.6	10.1	110.2	7.3	3284
VY	Full Rich		10.0	2.9	15.4			
	+65% Cruis	25oF LOP	3.9	0.6	10.1	110.2	7.4	3326
VY	Target EGT		9.8	2.7	14.0			
	+65% Cruis	25oF LOP	4.4	0.6	11.5	107.6	7.6	3342
1.15*VY (Eckelbar)	Target EGT		10.5	2.8	18.2			
	+65% Cruis	25oF LOP	2.8	0.4	7.3	115.1	7.9	3764

Figure 32: 8000' V_Z worksheet.

Climb Speed	Climb Mixture	65% Cruise Segment Mixture	Time (Minutes)	Fuel (Gallons)	Distance (Naut Miles)	Velocity Made Good (knots)	NMPG	CAFE Parameter VMG^1.3* NMPG
VZ	**Target EGT**	**N/A**	**16.8**	**4.2**	**32.8**	**116.9**	**7.8**	**3795.6**
VY (POH)	Full Rich		13.5	3.5	19			
	+65% Cruis	Best Power (PO	5.2	0.9	13.8	105.4	7.4	3140.3
VY	Full Rich		13.6	3.8	21.05			
	+65% Cruis	Best Power	4.4	0.8	11.7	109.3	7.1	3163.8
VY	Full Rich		13.6	3.8	21.05			
	+65% Cruis	Best Economy	4.5	0.7	11.7	109.2	7.3	3244.6
VY	Full Rich		13.6	3.8	21.05			
	+65% Cruis	25oF LOP	4.5	0.6	11.7	109.2	7.4	3289.8
VY	Target EGT		13.5	3.5	21.05			
	+65% Cruis	25oF LOP	4.5	0.6	11.7	109.6	7.9	3561.8
1.15*VY (Eckelbar)	Target EGT		14.5	3.8	25.65			
	+65% Cruis	25oF LOP	2.7	0.4	7.1	114.5	7.9	3757.0

Figure 33: 10000’ V_Z worksheet.

Altitude - Feet	Increment - Feet	KTAS - Knots	FF - GPH	ROC - FPM	Time to Climb-Minutes		Fuel Used - Gallons	Slant Distance - NM	Climb Angle - Degrees		Horiz Distance - NM		Velocity Made Good - Knots		Effective NMPG		CAFE Parameter
6000					8.830		2.465	0.000			17.550						
6500	500	123	13.7	500	1.000		0.228	2.050	2.299		2.048						
7000	500	121	13.53	500	1.000		0.226	2.017	2.337		2.015						
7500	500	119	13.35	500	1.000		0.223	1.983	2.376		1.982						
8000	500	117	13.17	500	1.000		0.220	1.950	2.417		1.948						
Level Off 8K				Time to Climb:	12.830	Fuel to Climb:	3.361			Distance to Climb	25.543	VMG:	119.45	ENMPG:	7.60	CAFE Parameter:	3812
8500	500	113.6	13	500	1.000		0.217	1.893	2.489		1.892						
9000	500	111	12.82	500	1.000		0.214	1.850	2.548		1.848						
9500	500	107	12.64	500	1.000		0.211	1.783	2.643		1.781						
10000	500	103	12.47	500	1.000		0.208	1.717	2.746		1.715						
Level Off 10K				Time to Climb:	16.830	Fuel to Climb:	4.210			Distance to Climb	32.779	VMG:	116.86	ENMPG:	7.79	CAFE Parameter:	3796
	Note POH Values:		POH: 8000'	Time to Climb:	10.000	Fuel to Climb:	2.670		POH: 8000'	Distance to Climb	14.000	VMG:	84.00	ENMPG:	5.24	CAFE Parameter:	1664
	Vy = 86 KIAS SL																
	End 83 KIAS @ 8K - 82 KIAS @ 10K		POH: 10000'	Time to Climb:	13.500	Fuel to Climb:	3.500		POH: 10000'	Distance to Climb	19.000	VMG:	84.44	ENMPG:	5.43	CAFE Parameter:	1735
Level Off 19K	Aerostar data	AEROSTAR DATA		Time to Climb:	23.000	Fuel to Climb:	22.000			Distance to Climb	76.000	VMG:	198.26	ENMPG:	3.45	CAFE Parameter:	3348
	Note POH Values:		POH: 19000'	Time to Climb:	12.000	Fuel to Climb:	11.000		POH: 19000'	Distance to Climb	26.000	VMG:	130.00	ENMPG:	2.36	CAFE Parameter:	1323
	Vy = 117 KIAS SL																
				Time to Cruise	14.851	Fuel to Cruise	7.400			Distance	50.000	V	202.00	ENMPG:	6.76		6710
					26.851		18.400			Distance	76.000	VMG:	169.82		4.13		3273

Figure 34: 500 fpm V_Z stepper.

APPENDIX E

FLIGHT TEST DATA

V_Z MISSION CARD		DATE	5-31-12	SCHED TAKEOFF	1200L	
CALLSIGN	CREW		AIRBORNE		BLOCK	MSN FREQS
N11MH	S SELLMEYER	LND	:	IN	1359	1357
	N HOWELL	TO	:	OUT	1304	1309
		TOT	:	TOT	:	
ATIS	340/22 10 19/08 2999					
CLNC	SAF 3 X8/10 134.8 4605					

SET UP G696, G530, JPI 700, SONY CAM ✓	
STND GND OPS	
ALT SETTING 29.92, NOTE SAT & WINDS	19 340/22
TAKEOFF PER POH, NOTE EGT FOR TGT V_Y CLIMB 88 KIAS (86 KCAS) ~1300°F	
FLY ROUTE	
KAAO-IAAO-DEYEK-HUKAM-IAAO/001/18.0-IAAO/001/24.0-IAAO/001/30.0-IAAO/001/36.0-IAAO/001/42.0-HUKAM	
V_z CLIMB TASK:	
AT 2000' PA, MAINTAIN WOT/2700	
-ACCEL TO AND MAINTAIN 115 KIAS (113 KCAS)	
-CLIMB TO 8000' PA, CONSTANT 115 IAS	
-LEAN TO TGT EGT APPROX EA 1000'	~1300
-USE COWL FLAPS FOR CHT <380 DEG F	
-IF CLIMB = 500 FPM, MAINTAIN 500 FPM UNTIL SPEED = V_Y, THEN MAINTAIN V_Y	
-LEVEL AT 8000' PA, NOTE DIST TO WPT	
5 miles to AAO 003 19 miles	
DES PERF: AIRSPEED 115 KIAS +/- 5	
ADEQUATE PERF: 115 KIAS +10/-5, PER PVT. PILOT PTS (ADDING COMPLEX)	
ALTERNATE TASK: AT 2000' PA, MAINTAIN WOT/2700, FULL RICH MAINTAIN V_Y CLIMB (88-83 KIAS) TO 8000' FOR BASELINE PERFORMANCE	
RECORD C-H RATING AND COMMENTS	

ALTITUDE TIME	SAT 19	FF	VVI	COWL FLAP
2000	16	17.2	400	open
3000	13	17.1	750	T
4000	10	16.3	700	T closed 4.
5000	11	15.8	700	C
6000	10	14.4	550	T 5.3 C 6.2
7000 110 K	8 trans to	14.4 500'	500	T
8000 98	5	13.9	500	C
C-H SCORE	3	AP on	no concerns within private AP)	
COMMENTS	D 125 122 KIAS	19 22" 6C	4.1 used 2400 8000 8.6	T 15 LOP #1

WX	Current		Forecast	
Airport	Ceiling	Visibility	Ceiling	Visibility
AAO				
IAB				
ICT				

V_Z MISSION CARD		DATE	5-31-12	SCHED TAKEOFF	1200L	
CALLSIGN	CREW		AIRBORNE		BLOCK	MSN FREQS
N11MH	S SELLMEYER	LND	:	IN	1457	[illegible]
	N HOWELL	TO	:	OUT	1416	1422
		TOT	:	TOT		
ATIS	21C	2969	360/19/26			
CLNC	C DEYEK HUKAM WA	3/8 10 4758				

SET UP G696, G530, JPI 700, SONY CAM	
STND GND OPS	
ALT SETTING 29.92, NOTE SAT & WINDS	2°C 360 19G26
TAKEOFF PER POH, NOTE EGT FOR TGT V_Y CLIMB 88 KIAS (86 KCAS) FULL RICH	
FLY ROUTE	
KAAO-IAAO-DEYEK-HUKAM- IAAO/001/18.0-IAAO/001/24.0- IAAO/001/30.0-IAAO/001/36.0- IAAO/001/42.0-HUKAM	
V_z CLIMB TASK:	
AT 2000' PA, MAINTAIN WOT/2700	
-ACCEL TO AND MAINTAIN 115 KIAS (113 KCAS)	
-CLIMB TO 8000' PA, CONSTANT 115 IAS	
-LEAN TO TGT EGT APPROX EA 1000'	
-USE COWL FLAPS FOR CHT <380 DEG F	
-IF CLIMB = 500 FPM, MAINTAIN 500 FPM	
UNTIL SPEED = V_Y, THEN MAINTAIN V_Y	
-LEVEL AT 8000' PA, NOTE DIST TO WPT	
DES PERF: AIRSPEED 115 KIAS +/- 5	
ADEQUATE PERF: 115 KIAS +10/-5, PER	
PVT. PILOT PTS (ADDING COMPLEX)	
ALTERNATE TASK: AT 2000' PA, MAINTAIN WOT/2700, FULL RICH MAINTAIN V_Y CLIMB (88-83 KIAS) TO 8000' FOR BASELINE PERFORMANCE	
~~RECORD C-H~~ RATING AND COMMENTS	

ALTITUDE TIME	SAT	FF	VVI	COWL FLAP
2000 ~~16.9~~ 3000	17	16.8	800	0
4000	14	17	800	0
5000	11	16.6	700	0
6000	10	~~15~~ 16	700	0
7000	7	15.8	650	0
8000	5	15.6	500	0
C-H SCORE	3	T n	D 10.5 F 3.5	
COMMENTS	.5 mile to HUKAM TO FF 17.4 1433 TOC			

WX.	Current		Forecast	
Airport	Ceiling	Visibility	Ceiling	Visibility
AAO	CLR			
IAB	LOP Cruise 8000' PA 22" 2400	8.6 #2 15° LOP 6C		8000'
ICT		IAS ~~13~~ 122 TAS 139		

```
From: AAO -- Wichita KS (Colonel James Jabara)
To:   AAO -- Wichita KS (Colonel James Jabara)
Alt.: 8,000 ft.  Profile: YG202 Msn
Time: Thu May 31 19:20 (UTC)

Routing options selected:  Direct.
Flight plan route:
  DEYEK HUKAM HUKAM003006 HUKAM003012 HUKAM003018 HUKAM003024 HUKAM003030
  WUMPA
Flight totals: fuel: 1042 kilograms, time: 0:17, distance 107.3 nm.

    Ident  Type/Morse Code  |                          | Fuel
    Name or Fix/radial/dist |                          | Time
    Latitude Longitude Alt. | Route    Mag  KTS  Fuel  | Dist
---+--------+--------+-----| Winds    Crs  TAS  Time  |------
 1. AAO    Apt.             | Temp     Hdg   GS  Dist  |  0.0
    Wichita KS (Colonel Jam |--------+----+---+------| 0:00
    37:44:51  97:13:16   14 | Direct             65.1 |  107
---+--------+--------+-----| 337/26   001  320  0:01 |------
 2. DEYEK  Int.             | +13C     358  297     5 | 65.1
                            |--------+----+---+------| 0:01
    37:50:08  97:12:28   36 | Direct             74.3 |  102
---+--------+--------+-----| 331/30   001  320  0:01 |------
 3. HUKAM  Int.             | +10C     358  295     6 |139.4
    ICTr051                 |--------+----+---+------| 0:02
    37:56:07  97:11:33   60 | Direct             70.5 |   96
---+--------+--------+-----| 327/31   357  335  0:01 |------
 4. Wpt.       /003.0/006.0 | +8 C     354  310     6 |209.9
    HUKAM  ....  ..-  -.-   |--------+----+---+------| 0:03
    38:02:06  97:11:09   80 | Direct             55.2 |   90
---+--------+--------+-----| 323/32   357  420  0:01 |------
 5. Wpt.       /003.0/012.0 | +4 C     354  395     6 |265.1
    HUKAM  ....  ..-  -.-   |--------+----+---+------| 0:04
    38:08:05  97:10:45   80 | Direct             55.3 |   84
---+--------+--------+-----| 323/32   357  420  0:01 |------
 6. Wpt.       /003.0/018.0 | +4 C     354  395     6 |320.4
    HUKAM  ....  ..-  -.-   |--------+----+---+------| 0:05
    38:14:05  97:10:21   80 | Direct             55.1 |   78
---+--------+--------+-----| 323/31   357  420  0:01 |------
 7. Wpt.       /003.0/024.0 | +6 C     354  396     6 |375.5
    HUKAM  ....  ..-  -.-   |--------+----+---+------| 0:06
    38:20:04  97:09:57   80 | Direct             55.2 |   72
---+--------+--------+-----| 323/31   357  420  0:01 |------
 8. Wpt.       /003.0/030.0 | +6 C     354  395     6 |430.7
    HUKAM  ....  ..-  -.-   |--------+----+---+------| 0:07
    38:26:04  97:09:33   80 | Direct            441.9 |   66
---+--------+--------+-----| 325/31   172  412  0:07 |------
 9. WUMPA  Int.             | +7 C     175  437    53 |872.6
                            |--------+----+---+------| 0:14
    37:32:55  97:07:26   70 | Direct            169.9 |   13
---+--------+--------+-----| 337/26   333  300  0:03 |------
10. AAO    Apt.             | +13C     333  274    13 | 1042
    Wichita KS (Colonel Jam |--------+----+---+------| 0:17
    37:44:51  97:13:16   14 |                          |    0
---+--------+--------+-----|                          |------

NOTE: fuel calculations do not include required reserves.
Flight totals: fuel: 1042 kilograms, time: 0:17, distance 107.3 nm.
```

APPENDIX F

ARTICLES AND PRESENTATIONS

Articles - "Efficient Flight Planning for the Aerostar", published in *Aerostar World* magazine, Summer 2012, The Aerostar Owners Association, Tulsa, OK. Incorporated V_Z concept into an efficient flight planning protocol for a cabin class piston twin engine airplane.

Presentations - "Introducing V_Z: Best Efficiency of Climb Speed for Small Airplanes"
-CAFE Electric Aircraft Symposium, Santa Rosa, CA, April 28, 2012
-SETP Central Section Symposium, Wichita, KS, June 1, 2012
-ERAU Worldwide Conference, Orlando FL, Sept 19, 2012
-Aerostar Owners Association Convention, Oct 6, 2012
SETP San Diego Symposium, March 23, 2013