Engineering Management
Field Project

Method for Weight Control Engineering Management to Evaluate Single Engine Aircraft Weighing Activities

By

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Executive Summary

There is no greater task for a Weight Control Engineer than determining an aircraft's weight and center of gravity (CG). Although the concept of balance or CG is easy to grasp, calculating or measuring it for complex objects, such as an aircraft, is very difficult. The accurate calculation of an aircraft's CG is a primary factor in any flight operation. It directly affects aircraft safety, performance, and mission capability. This Field Project is a comparative analysis of the information that Weight Control Engineering Management at Cessna Aircraft Company should use to decide on a future weight and CG measuring system for single-engine aircraft. The scope includes the relevant Federal Aviation Regulations (FARs), Parts 23, 25, 43, and Advisory Circular (AC) 120-27E, as they pertain to aircraft weight and CG. The regulations dictate weight and CG conditions for aircraft design, manufacturing, and operations. There are over 300 references to weight and CG in the FARs. There are also a number of professional organizations with a stake in aircraft weight and CG. The General Aviation Manufacturer's Association (GAMA) along with the Society of Allied Weights Engineers (SAWE) provides weight and CG guidelines. Also within scope is a technology roadmap of past, present, and future aircraft weight and CG measurement systems. Example illustrations show the geometry and physical layout used for weighing aircraft. Example algorithms show the mathematical relationships necessary for CG calculations. A comparative business case for each aircraft weighing method is included. The business cases reflect the operating environment at Cessna's Single-Engine Aircraft Manufacturing Plant. Finally, based on the FAR's, the technology roadmap, and the comparative business case analyses, suggestions are made relating to the vision of the future and the necessary steps to get there.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

"*Wichita, Kan., Feb 6, 2007* - Cessna Aircraft Company, a Textron Inc (NYSE: TXT) company, delivered 1,239 aircraft last year, maintaining its leadership position as the world's largest manufacturer of general aviation aircraft [1]." The single-engine line accounted for 75% of those deliveries. They produced 865 piston aircraft and 67 turboprops [1]. Despite a 10-year hiatus from single-engine production, Cessna has produced over 150,000 single-engine aircraft in its 80-year history [2]!

Since opening its plant in Independence, Cessna has successfully introduced six single-engine models. Cessna will produce and deliver over 1,000 single-engine aircraft in 2007. "Cessna is also working to develop new products with concept designs proposed for both the light sport aircraft category and for a high-performance piston [3]." With the pending introduction of the Next-Generation-Prop (NGP) and Light Sport Aircraft (LSA) models, the facility could easily reach its production capacity of 2,500 units.

Designing, producing, and supporting eight models is a challenge. Producing and delivering 1,000 aircraft, let alone 2,500, is problematic. Not withstanding skilled labor, supply chain, and manufacturing issues, the engineering alone is staggering. For example, engineers write thousands of jobs for each model dictating exactly where, when, and how to assemble parts. Engineers create thousands of drawings illustrating every part, assembly, structure, and system. Engineers design the jigs for precise alignment and installation. Engineers insure that every part that goes onto an aircraft conforms to a standard and to any Federal Regulations that may apply to it. Engineers design the tools used for accurate measurement of everything from the thickness of a coat of paint to how much an aircraft weighs and where its CG is located.

The problem of determining an aircraft's weight and CG is the focus of this investigation. It is a primary concern for Weight Control Engineering Management. The solution of which must be accurate, and easily repeated. After all, why are weight and CG important? If any, what are the software and hardware needs? Are there software version controls in place? Whatever the measurement system is, it must be safe and economical. Does a permanent weight and CG system installed on each aircraft buy its way on? If a fixed weighing location is used, how much space does it take, and at what cost? If the weighing system is portable, how much does it weigh, and how many people does it take to operate? Is the process efficient? How many people, and how long does it take to complete the task? What is the line flow rate? How many weighings occur for each aircraft? What Federal Regulations about weight and CG affect design, production, support, and operations?

The following pages contain the results of an investigation into weight and center of gravity measurements as they pertain to single engine aircraft manufacturing operations. The investigation is comprised of four sections. They are the Literature Review, Procedure and Methodology, Results, and Suggestions for Additional Work.

2.0 Literature Review

Understanding the science of measuring an aircraft's weight and CG is not an easy task. Theoretical, practical, and even environmental considerations affect the capability to produce good measurements. The Federal Government, GAMA, and SAWE have written regulations and guidelines. Hundreds of patents exist relating to the measurement of aircraft weight and CG. Cessna itself has developed documents that control the conformity of every aspect of this activity to assure that its processes meet all of the regulatory and professional criteria.

The literature review follows a logical progression from the physical definition of CG to how it applies to Cessna's aircraft. The review consists of five sections and twelve sub-sections. Before any great discussion of aircraft weight and CG measuring methods can take place, mathematical and conceptual definition of CG are provided, Section 2.1. A working definition of CG leads directly to its impact on the FARS, Section 2.2. Section 2.3 contains a review of the relevant professional communities' guidelines, recommendations, and best practices for measuring aircraft weight and CG. Section 2.4 lays the groundwork for the discussion of the different aircraft weight and CG measuring methodologies by reviewing existing patents. The last section, Section 2.5, reviews the documents used at Cessna for the management of it single-engine aircraft weighing activities.

2.1 Weight and CG

What are weight and CG and why are their accurate measurements important? The literature review contained within the next three sub-sections addresses that question. The first sub-section treats the theoretical evaluation of weight and CG (Hibbeler, 1995). The second sub-section more specifically evaluates weight and CG as it relates to aircraft (Roskam, 1998).

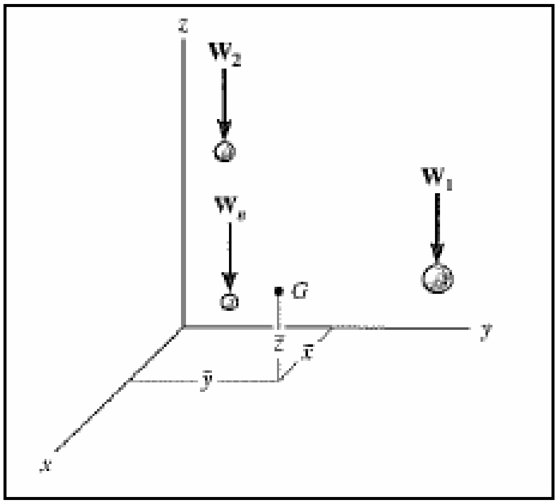
Finally, the third sub-section pays special attention to the details of accurate measurement techniques (Boynton, 2002).

<u>2.1.0 Theoretical Considerations</u>

The text, '*Engineering Mechanics Statics and Dynamics'* (Hibbeler, 1995), or something like it, is required reading for junior level college courses in Mechanical Engineering. For its technical content, it is a typical introductory level engineering text. It covers the topics of statics and dynamics of mechanical systems. A difficult read at best, it requires a working knowledge of geometry, algebra, and calculus (math subjects well beyond the scope of this review). It does nothing to increase the body of knowledge required to understand the importance of weight and CG of an airplane. It treats the concept of CG lightly while paying much larger tribute to the physical body of knowledge required for mechanical engineering. However, it does contain the fundamental definition and equation required to grasp the CG concept.

> "*Center of Gravity. Consider the system of n particles fixed within a region of space as shown in* ***Figure 1****. The weights of the particles comprise a system of parallel forces which can be replaced by a single (equivalent) resultant weight and a defined point of application. This point is called the Center of Gravity. This requires that the resultant weight be equal to the total weight of all n particles; that is,*
>
> $$W_R = \Sigma W.$$
>
> *The sum of the moments of all of the particles about the x, y, and z axes is then equal to the moment of the resultant weight about these axes [4].*"

Figure 1 Particle System



Mathematically, the longitudinal CG then becomes the sum of the moments ($W_i x_i$) divided by the sum of the weights (W_i),

$$x_{cg} = \frac{\sum_{i=1}^{i=n}(W_i x_i)}{\sum_{i=1}^{i=n} W_i}$$

That is simple enough for engineers and math majors, but for the layperson, it is painful. The following paragraph puts the concept into terms that everyone can understand.

Have you ever played on a teeter-totter (a.k.a. seesaw)? Like most of us, of course you have. Well then, you already grasp the concept of CG. Put two kids who weigh 40 pounds each on opposite ends and it takes only a little effort to balance the teeter-totter with both kids hovering in mid-air at the same distance from the ground, Figure 2. It is an unsettling realization for most small children. However, it only requires a small outward or inward movement of one of the kids to upset the equilibrium and return one of them back to Earth. By the same rationale, put a smaller sibling (say a 40-pound four-year-old) on one end, place their older sibling (say an 80-

pound nine-year-old) half the distance to the other end, then again, both siblings with little effort will achieve equilibrium, Figure 3. In both cases, the point at which the teeter-totter balances also represents the x-coordinate of the CG for the system.

Figure 2 Two Kids Find Equilibrium

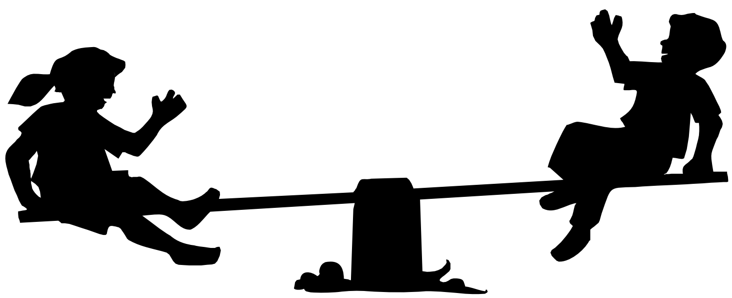
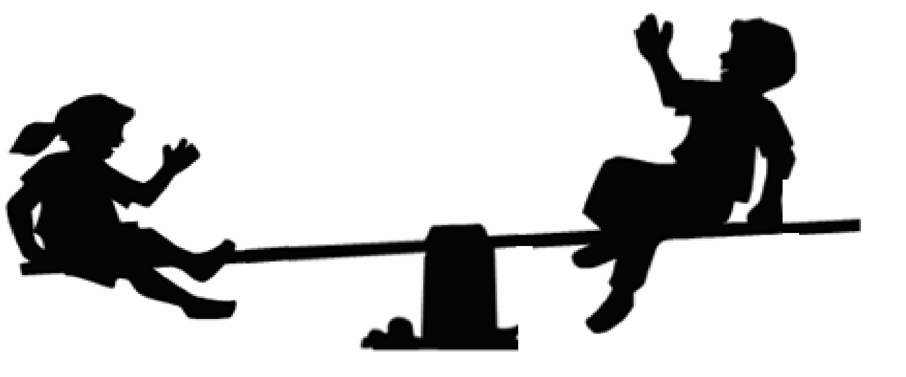


Figure 3 Two Siblings Find Equilibrium



In plain terms, the kids in Figure 1 weigh the same and are the same distance from the balancing point, therefore the sum of their moments equals zero. Similarly, in Figure 2, since the child who weighs twice as much is half-the distance from the balancing point, again, the sum of the moments equals zero.

What is important to understand, either from the text (Hibbeler, 1995) or from the example, is that the CG is the point at which the sum of all moments equals zero.

2.1.1 Practical Considerations

The introduction of the concept of CG as it related to particles and teeter-totters occurred in the previous sub-section. The review of weight and CG as they apply specifically to aircraft stability and control occurs in this sub-section. Much like the text (Hibbeler, 1995) of the previous sub-section, *'Airplane Flight Dynamics and Automatic Flight Controls'* (Roskam, 1995), is a required college text for junior and senior Aerospace Engineering (AE) students. Unless, you are an AE student, a lover of aircraft design, or a mathematician looking for a difficult read, do not consider this book. Otherwise, it is among the best texts on the subject, written by one of the fields most accomplished engineers and authors.

The introduction of the concept of moment (e.g. the weight of a particle times the distance to the CG) occurred in the previous sub-section. According to Roskam, "The CG location affects **all** stability and control moment derivatives," and of all of the derivatives, "CG has a major effect on the static longitudinal stability derivative, C_{m_α} [5]." There is no more important concept than that of the static margin (SM) which relates aircraft pitching moment and lift, to the locations of the aerodynamic center and the CG: $SM = -\frac{dC_m}{dC_L} = -\frac{C_{m_\alpha}}{C_{L_\alpha}} = -\left(\overline{x}_{cg} - \overline{x}_{ac}\right) = \left(\overline{x}_{ac} - \overline{x}_{cg}\right)$

Where: dC_m = the derivative of the airplane pitching moment coefficient
dC_L = the derivative of the airplane lift coefficient
C_{m_α} = the variation of the airplane pitching moment coefficient with angle of attack
C_{L_α} = the variation of the airplane lift coefficient with angle of attack
$\overline{x}_{cg}$ = CG location as a fraction of the mean geometric chord and measured from the leading edge of the mean geometric chord, positive aft
$\overline{x}_{ac}$ = aerodynamic center location as a fraction of the mean geometric chord

Arguably, an explanation of the coefficients is beyond the scope of this review. However, how the equation translates into this review is simple. The CG on all aircraft has forward and aft limits. If the CG exceeds those limits, at any time, the aircraft becomes unstable which may result in a catastrophic failure, Figure 4 [5].

Figure 4 Failure Mode Illustrations

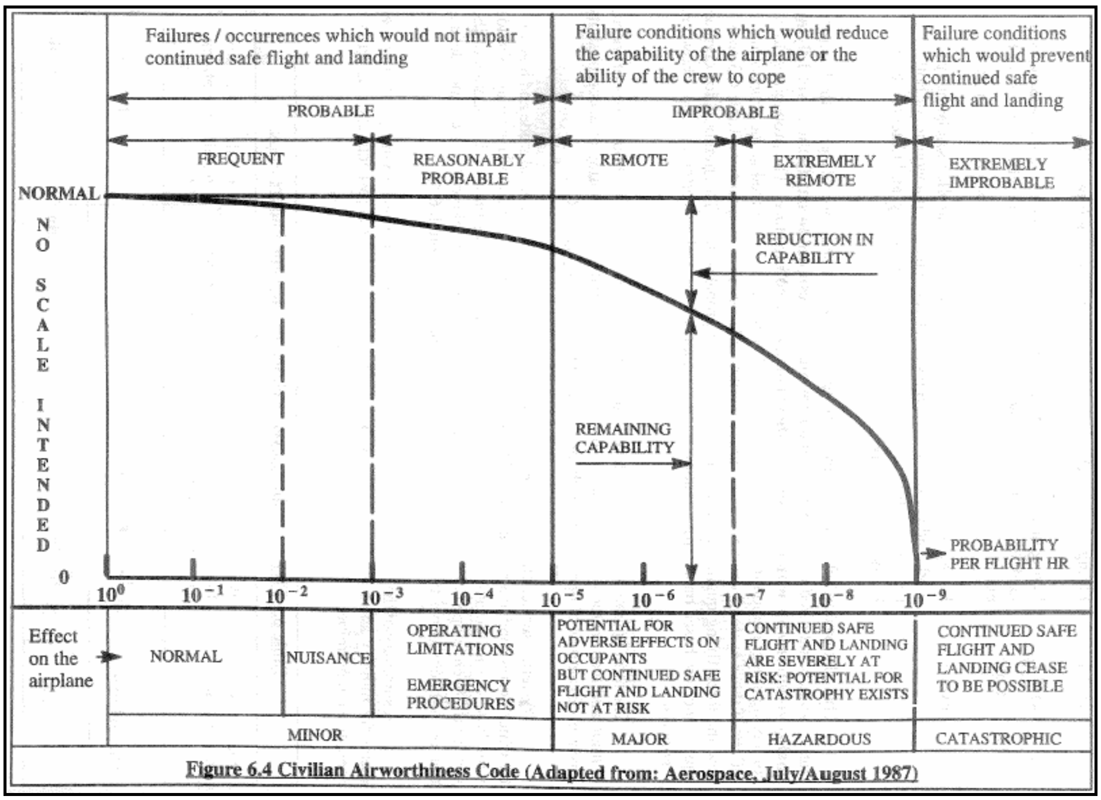


Figure 6.4 Civilian Airworthiness Code (Adapted from: Aerospace, July/August 1987)

It should be repeated for impact. If the CG exceeds either the forward or the aft limits, for any reason or at any time, continued safe flight and landing may cease to be possible!

2.1.2 Environmental Considerations

The review of the definition of CG and its relationship to aircraft safety took place in the first two sub-sections. The focus in this sub-section is the review of the environmental considerations affecting accurate weight and CG measurements. Scale accuracy is of paramount concern when trying to measure aircraft weight and CG. Most aviation grade scales have an accuracy of +/- 0.1% applied load, or three pounds, whichever is the greater. However, there are other sources for errors.

"Precise Measurement of Mass," (Boynton, 2002) is an article in "*Weight Engineering* [6]." In it, Boynton contends that, "scale considerations that are often overlooked can result in a total error of several percent [6]." For a single-engine Cessna aircraft that can translate into a plus or minus twenty pounds. The article (Boynton, 2002) is an eye-opening read for anyone interested in measuring weight and CG. For example, Boynton lists nine measuring concerns, "1. Latitude. 2. Altitude. 3. Tidal effects. 4. Gravity anomaly. 5. Buoyancy. 6. Moisture condensation or absorption of moisture. 7. Electrostatic attraction to the draft shield surrounding the scale. 8. Magnetic attraction to nearby objects and to the earth's magnetic north. 9. Downdrafts or updrafts [6]." Again, reading the article requires a working knowledge of physics, engineering, and mathematics.

For the most part, because there is no need for that level of accuracy when measuring a single-engine aircraft (as will be seen later in the document), Cessna can largely ignore items 1, 2, 3, 4, 5, 7, and 8. However, Boynton's items numbered 6 and 9 warrant discussion.

> "6. *Condensation. In areas with high humidity, sudden changes in temperature will produce condensation on the object being measured, which adds to the weight of the object. This most commonly occurs when an object is brought from an air-conditioned space to a non air-conditioned one. Condensation can be minimized by allowing the object's temperature to equalize before weighing it [6]."*

Clearly, the previous quote applies to the scales as well. It is common for Cessna to park dozens of aircraft out on the tarmac (subject to all kinds of weather) prior to weighing. Precautions should be written into the standard weighing procedures to account for the 'condensation' consideration.

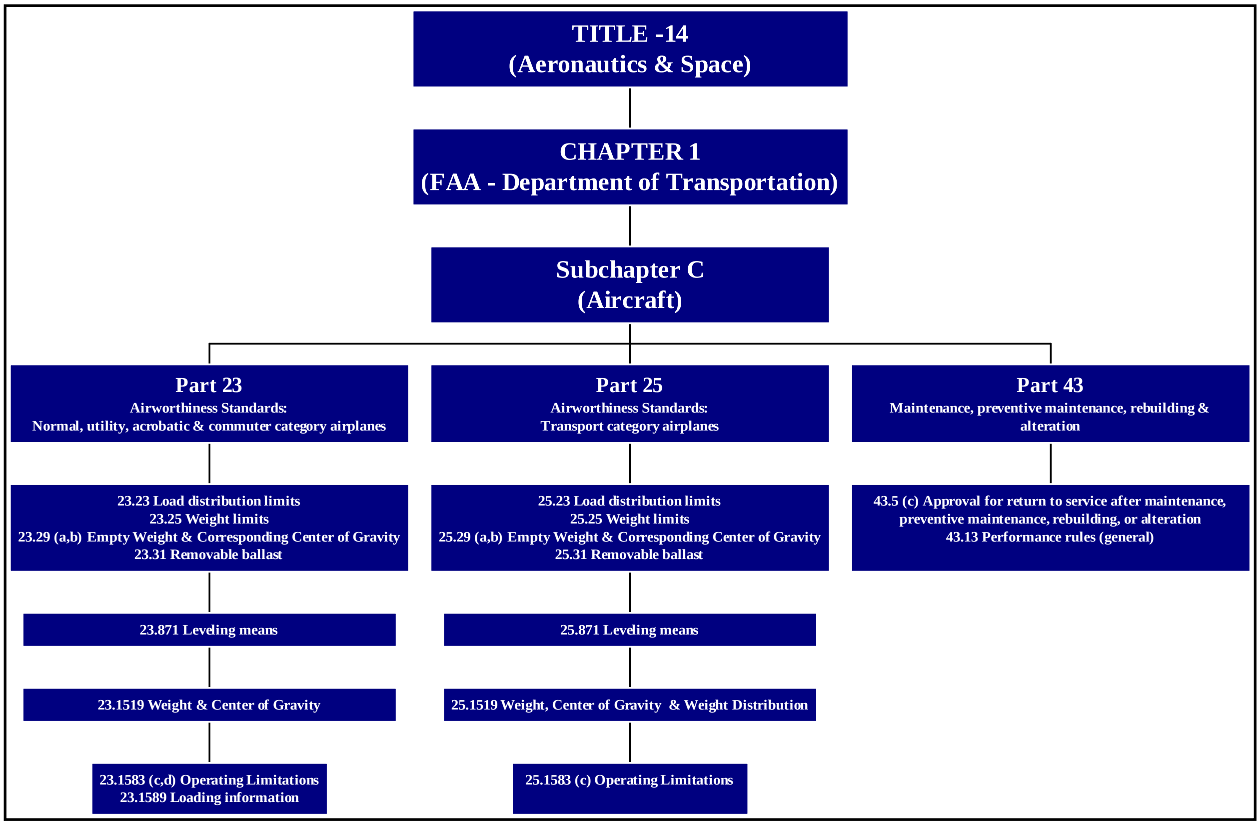
> “9. *Drafts or air currents. Generally, this effect will be quite obvious, since drafts will introduce a random variation in the readings. However, there are some instances where drafts can produce relatively steady downward or upward force. For example, if sunlight heats an object, then the updraft from the surface will produce an upward force, reducing the weight of the measured object. Conversely, if an object is brought in from an unheated storage area to be weighed, the cooler object will cause a downdraft, increasing the measured weight. These effects can be minimized by making sure the object is at the same temperature as the surrounding air and by avoiding direct sunlight or bright lights [6].”*

Boynton raises some legitimate concerns that should be explored at Cessna. Cessna’s standard operating procedure (SOP) for weighing aircraft does take into account things like overhead fans (turned off), and hanger doors (must be shut for all weighings), but Boynton ignores these issues, instead focusing on the force caused by convection.

2.2 Code of Federal Regulations

The previous section contained a review of some of the more technical aspects of aircraft weight and CG. It is the foundation for the reviews in this section. Title 14 of the Code of Federal Regulations (CFR) deals with Aeronautics and Space, Chapter 1 of Title 14 is the Federal Aviation Administration, Department of Transportation. It is in that Chapter, that the rules and regulations affecting aircraft weight and balance exist (Parts 23, 25, and 43, 2006). Figure 5 illustrates the general organization of the code.

Figure 5 Code of Federal Regulations



Aside from the regulations shown in Figure 5, the Federal Aviation Administration also published AC 120-27E. The review of AC 120-27E is the last topic covered in this section.

2.2.0 FARs Part 23

The FARs Part 23 contains all of the Federal Aviation Administration regulations for general aviation aircraft. Of the Part 23 sections listed in Figure 5, Parts 23.23, 23.25, 23.31, 23.1519, 23.1583 (c,d), and 23.1589 deal primarily with the structural and operational limits as established by the manufacturer and not the measurement of weight and or CG. However, the implication is that in order to establish those limitations the manufacturer must have an approved method for obtaining aircraft weight and CG information. Part 23.29 (a,b) addresses that issue specifically:

> **§23.29 Empty weight and corresponding center of gravity.**
>
> (a) The empty weight and corresponding center of gravity must be determined by weighing the airplane with—
>
> (1) Fixed ballast;
>
> (2) Unusable fuel determined under §23.959; and
>
> (3) Full operating fluids, including—
>
> (i) Oil;
>
> (ii) Hydraulic fluid; and
>
> (iii) Other fluids required for normal operation of airplane systems, except potable water, lavatory precharge water, and water intended for injection in the engines.
>
> (b) The condition of the airplane at the time of determining empty weight must be one that is well defined and can be easily repeated. [7]

Normally, for most manufacturers, the majority of Part 23.29 does not pose any problems. Part 23.29 sub-part (b), is ambiguous. What is 'well-defined' and 'easily repeated?' It is the responsibility of the manufacturer to establish working definitions and to obtain the FAA's buy-in.

Part 23.871 is also ambiguous:

> **§23.871 Leveling means.**
>
> There must be means for determining when the airplane is in a level position on the ground.
>
> [Amdt. 23–7, 34 FR 13092, Aug. 13, 1969] [8]

Who defines what the level position is? What is the reference plane for the level? How accurate must it be, one degree, a tenth of a degree, one one-hundredth of a degree, etc.? Adhering to Part 23.871 has an enormous impact on the ability to measure aircraft CG accurately. As a reference, for every degree in error of an aircraft's attitude, there is a corresponding one-half inch shift in CG.

2.2.1 FARs Part 25

The FARs Part 25 contains all of the Federal Aviation Administration regulations for commercial and transport category aircraft. Since the primary focus of this field project concerns itself with single-engine aircraft manufacturing, the Part 25 FARs are not applicable to this investigation. However, observe that as far as weight and CG are concerned, Parts 23 and 25 are mirror images of one another. That observance reiterates the fact that there are immutable laws governing weight and CG when it comes to aircraft flight control and safety.

2.2.2 FARs Part 43

The FARs Part 43 contains all of the Federal Aviation Administration rules regulating aircraft maintenance and repair. While this is not directly related to the topic of this field project, it is a downstream concern for the Engineering Manager.

According to Part 43.5 (c), 'if a repair or an alteration results in any change in the aircraft operating limitations or flight data contained in the approved aircraft flight manual, those operating limitations or flight data are appropriately revised…[9].' Simply put, if an aircraft changes in any way that affects weight and or CG significantly, CG must be reestablished and recorded. Again, the interpretation rests with the maintenance technician.

Part 43.13 is a primary downstream concern for the Engineering Manager. It explicitly states, 'each person performing maintenance, alteration, or preventive maintenance…shall use the methods, techniques, and practices prescribed in the current manufacturer's maintenance manual… [10].' In the case of this field project, the regulation refers to the manufacturer's responsibility to define aircraft weighing and CG determination procedures, clearly within scope.

2.2.3 AC 120-27E

AC 120-27E entitled, *'Aircraft Weight and Balance Control,'* is the means by which aircraft manufacturer's obtain approval for their weight and balance control system, part of which is measuring weight and CG. In particular,

> *"5. Weight and Balance Control Systems encompass the following:*
> > *a. Methods for establishing, monitoring, and adjusting individual aircraft or fleet empty weight and CG (CG) in conjunction with the initial and periodical reweighing of aircraft. [11]."*

While it does not prescribe actual methodologies or values, AC 120-27E provides the direction that is absent in the FARs Parts 23, 25, and 43 reviewed in the previous sub-sections. It implies continuous, measurable, actions relating to a specific well-defined aircraft configuration, i.e. fleet empty weight.

2.3 Professional Organizations

The focus of the review in this section is to transition from the theoretical and the legal of the previous sections, to the professional viewpoints. GAMA's Specification 1 translates the FARs into guidelines for manufacturers. SAWE's handbook provides a recipe for obtaining accurate and repeatable measurements. Finally, SAWE's Recommended Practice (RP) Number 1 expresses the organization's views on a future weight and balance system.

2.3.0 GAMA Specification 1

GAMA Specification 1 contains Pilot Operating Handbook (POH) writing guidelines for manufacturers. Section 6 of the guidelines is entitled '*Weight and Balance'* and defines the POH requirements for the 'Airplane Weighing Procedure' and 'Weight and Balance' as follows:

> **6.1 Airplane Weighing Procedure**
> This subsection will describe the procedure for establishing weight and moment (relative to reference datum) of the empty airplane. Each Handbook will have an "Airplane Weighing Form" similar to Figure 6–1. This includes a side airplane view which defines the location of weighing points (using jacking points or undercarriage) relative to the datum line. The form also includes tables for recording and correcting weighing data, and for establishing "basic empty weight" and moment. The text of the Handbook should describe these calculation procedures and define the "basic empty weight" data in relation to its use in loading calculations.
>
> **6.3 Weight and Balance Record**
> A procedure will be described for maintaining a record of airplane weight and balance. The record form layout will be defined in Figure 6-2. The airplane record will start with the "as delivered" weight and balance figures and will be updated each time a change is made in permanently installed equipment or aircraft modification which affects weight or moment. [12].

The association does not go so far as to say 'how' to weigh an aircraft or establish its CG. The association does clearly state how to present the information in the POH. Like the Part 43.13 of the FARs and AC 120-27E, the GAMA specification begins to define the scope of Weight Control Engineering Management's responsibilities in the aircraft weight and CG arena. It is not just weighing aircraft, or establishing a CG, it is also providing documentation of the process so that others may repeat it. Section 2.5 of this review contains an example of a Cessna POH following the GAMA guidelines.

2.3.1 SAWE

The SAWE publication entitled, *'Weight Engineer's Handbook,'* has in its contents a section on *'Mass Properties Measurement [13],'* a section well worth reviewing. As is SAWE's Recommended Practices (RP) Number 1, '*Requirements for On Board Weight and Balance System [14].'* The first topic is SAWE's guidelines for achieving accurate weight and CG measurements, while the latter deals specifically with their professional views on the requirements of aircraft integrated weight and balance systems.

According to the handbook, there are nine steps required to measure the mass properties of an object. They are:

> "*1.1 Define the particular mass properties you need to measure and the required measurement accuracy.*
> *1.2 Choose the correct type of measuring instrument.*
> *1.3 Define the coordinate system on the object to be used as the mass properties reference axes.*
> *1.4 Define the position of the object on the mass properties measuring machine.*
> *1.5 Determine the dimensional accuracy of the object being measured.*
> *1.6 Design the fixture required to mount the object at a precise location relative to the measuring instrument.*
> *1.7 Verify the position of the object on the instrument.*
> *1.8 Make the mass properties measurement.*
> *1.9 Report the mass properties data.* [13]."

Besides the written purpose of the previous steps, e.g. create accurate measurements, there is also an unspoken purpose; create a system of measurement that is repeatable. Observe that the steps follow a logical progression from definition to documentation. The steps are generic enough that they apply to all types of measurements, including aircraft weight and CG. The steps followed in Section 3.0 of this report follow a similar progression.

SAWE's RP 1 is an acknowledgement of the future. The RP, originally written in 1982, addresses the impending emergence of new on board weight and balance measuring systems

(OBWBS). 25 years later, little has changed. There are a few successful OBWBS, but only on large transport category and military aircraft. As yet, no system exists that is small enough, accurate enough, or whose price point is right that would warrant its use on general aviation aircraft. The RP is still a work in progress and is likely to affect the FARs in the future.

2.4 United States Patent Office

The reason for a review on patents is that they provide technical information that indicates how accurate, efficient, and costly a system may be. They also give some insights as to trends in the discipline and indications of what is to come. For that reason, the review contains past, present, and future categories, Sections 2.4.0 to 2.4.2.

2.4.0 Conventional Aircraft Weighing Patents

The vast majority of general aviation aircraft manufacturers currently use aircraft jacks with strain gauge load cells mounted on top for their aircraft weighing needs. Over 1,800 patents can be found in the U.S. patents database alone. No one patent is unique enough to mention here. However, it should be mentioned that this type of load cell could be used for weighing everything from 18-wheel semi-truck to a C-130 Hercules cargo airplane. The load cells are robust and can weigh tens-of-thousands-of-pounds. A typical Cessna single-engine aircraft weighs less than 2,000 pounds.

2.4.1 Weight on Wheels Patents

There are two patents relating to weighing aircraft on wheels worth reviewing. '*System and Apparatus for Determining the CG of an Aircraft,*' by Don S. Godwin is a unique patent granted for weighing small aircraft (example is a Cessna 208B) [15]. In addition, a Cessna process (patent pending) also fits into this section.

The first patent, Godwin's, is truly a unique concept. The inventor's concept is intuitive, while the solution is not. The premise of the invention is that by determining the reaction on the nose wheel alone, and by measuring a few distances, that there is a solution for the CG. The system takes into account the attitude of the aircraft, i.e. levelness. There are several drawbacks to this system. Primarily, the user must establish a total aircraft weight first, not a difficult task, but it does lengthen the total process time. Secondly, and most importantly, the user must take several measurements. When weighing one aircraft, that is not so bad. However, with thousands of aircraft weighings, it becomes problematic. For example, numbers are transposed or written down wrong, measurements are not taken accurately, equipment loses its calibration, etc. Godwin also makes an assumption about the vertical location of the CG, which in small aircraft, is generally acceptable because the inertia affects are comparatively small.

The Cessna process is also unique in that it too takes into account the levelness of the aircraft. It also minimizes the possibility of data entry errors by eliminating lengthy measurements, (i.e. measurements over great distances). However, there are still seven measurements needed to satisfy the equation. The three load reactions for each of the landing gears, the three lengths of exposed oleo, and the aircraft attitude. The load reactions are read from digital screens, the aircraft attitude is fed directly into the software application (thereby eliminating a potential data entry failure mode) and the oleo extensions are measured and entered manually. Like Godwin's system, the Cessna system also makes a generalized assumption about the vertical location of the CG, which again, is acceptable.

2.4.2 On-Board Weighing System Patents

There are two patents for aircraft on-board weighing systems well worth reviewing. The first, '*Aircraft Weight and CG Determination System Which Includes Alarm, Self-checking, and*

Fault Override Circuitry,' by Donald Senour is a system developed primarily for large aircraft [16]. The second patent, *'On-Board Aircraft Weighting and CG Determining Apparatus and Method,'* by George R. Lindberg is also a system developed for large aircraft [17]. What makes these two patents particularly interesting is their potential application to smaller aircraft.

What makes Senour's invention compelling isn't the transducers mounted in the axles for weight measuring, but rather the alarm, self-checking, and fault overriding circuitry. The implication to safety is profound. The pilot cannot advance the throttle for takeoff if the system senses an unsafe CG. Whether or not the actual weighing system is used, the safety feature alone warrants future investigation.

The on-board weighing patent developed by Lindberg is significantly different. The premise of the invention is that by cycling hydraulic pressure in the landing gear oleos (i.e. pressuring to full-extension followed by release of pressure to complete contraction), the system can measure the pressure differentials to obtain both weight and CG. The approach requires extensive hydraulic modifications and an on-board computer resulting in both increased weight and higher costs.

<u>2.5 Cessna Documents</u>

The Cessna documents reviewed in this section are representative of the aircraft weighing and CG documentation required for each model. The documents reflect the body of knowledge and activities necessary to conform to all of the Federal Regulations. They also demonstrate the level of detail necessary to obtain accurate and repeatable values for weight and CG. The documents are job L0024-02112 [18], CSPS-011, Appendix A [19], Model 206H Information Manual [20], and the *'Aircraft Leveling Software Control Drawing [21].'*

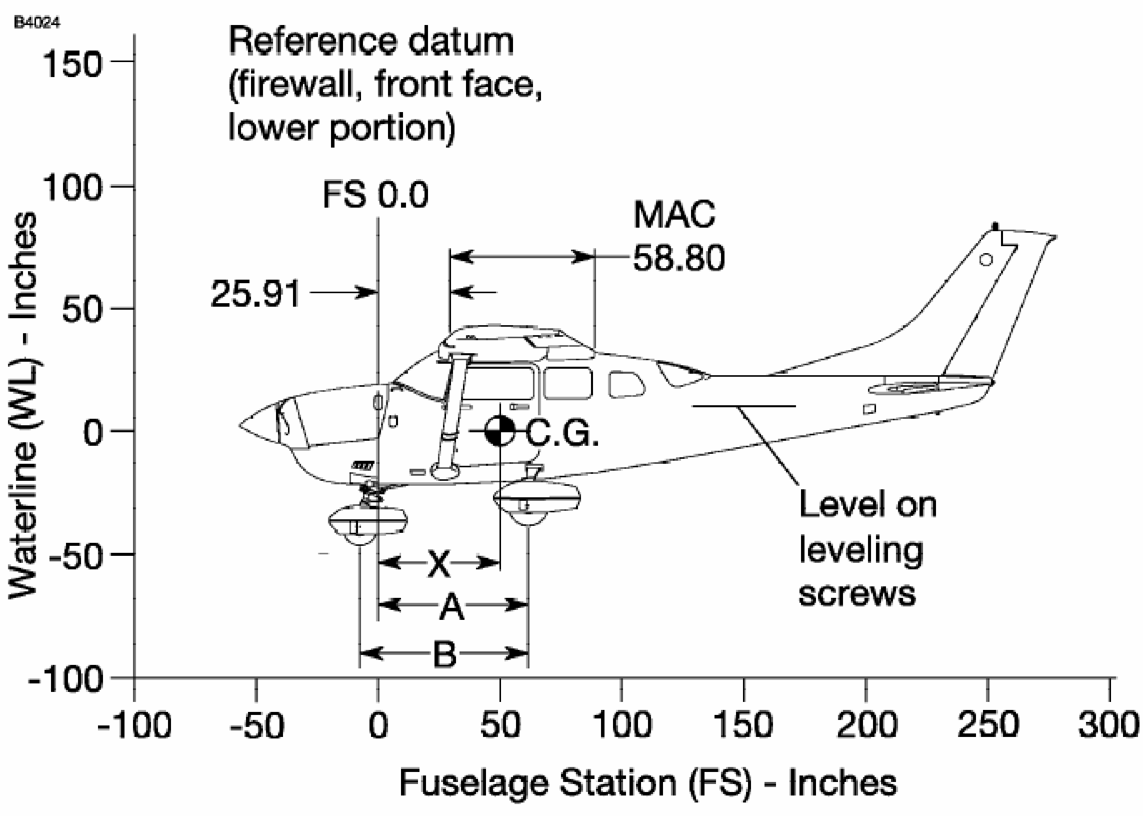
L0024-02112, '*Final A/C Weight,*' details the systematic process for weighing and verifying an aircraft's weight and CG [18]. It describes what equipment to use, how to set it up, how long it should take, and what to do with the data, Appendix B. It indicates what model(s) are applicable and references the appropriate engineering drawings (a separate job is written for each model). The information is cryptic, but given the operating environment, appropriate. The creation of the document requires inputs from Quality, Manufacturing, Industrial, and Weight Control Engineering. Such is a bureaucracy. The purpose of the document is to ensure the measurement of the most accurate and repeatable values. Although considerably more detailed, the process follows the SAWE guidelines (Section 2.3.1). It also references the Cessna's aircraft weighing specification drawing, CSPS-011.

'*Aircraft Weighing Specification,*' CSPS-011 is Cessna's counterpart to AC 120-27E. It specifies the aircraft weight and center of gravity validation process. It does not tell how to weigh the aircraft or obtain the CG. It does provide the acceptable variation range for both the weight and the center of gravity. It prescribes what the company must do in the event of a failure and how to document it. Last updated in 1986, the document is comprehensive.

The Model 206H Information Manual [20] precisely follows the GAMA Specification 1 guidelines (Section 2.3.0). Chapter 6 of the information manual contains all of the relevant weight and CG data. It contains an example of the aircraft weighing procedure, aircraft weighing forms, and the formula for determining the aircraft's longitudinal CG (Figure 6, pg 21-22).

Finally, the '*Aircraft Leveling Software Control Drawing [21],*' Cessna drawing number 7000901, details how to tack all leveling software versions. It also gives basic operating instructions for the software. It is an important document because it contains all of the information required to satisfy our Quality Department's regulations. The Quality regulations exist to guarantee documentation compliance in the event of a Federal Aviation Administration audit. The software itself sees use only at the Mid-Continent facility, which produces Cessna's Citation Jets. However, if the weigh on wheels method of determining aircraft weight and center of gravity were implemented on the single-engine line, the software tracking and version control drawing would have to be updated.

Figure 6 Aircraft Weighing Form



NOTE

It is the responsibility of the pilot to make sure that the airplane is loaded properly.

Locating CG with Airplane on Landing Gear

$$X \text{ (Inches Aft of Datum)} = A - \left[\frac{\text{Nosewheel Weight} \times B}{\text{Total Weight*}}\right]$$

*(Nose + L + R Wheel Weights)

Locating Percent MAC

$$\text{CG Percent MAC} = \frac{\text{(CG Arm of Airplane)} - 25.91}{0.5880}$$

Leveling Provisions

Longitudinal - Left side of tailcone at FS 152.20 and 180.60

Measuring A and B

Measure A and B per pilot's operating handbook instructions to assist in locating CG with airplane weighed on landing gear.

Airplane as Weighed Table

Position	Scale reading	Scale drift	Tare	Net weight
Left Wheel				
Right Wheel				
Nose Wheel				
Airplane total as weighed				

Basic Empty Weight and Center-of-Gravity Table

Item	Weight Pounds	CG Arm (Inches)	Moment (Inch-Pounds /1000)
Airplane (calculated or as weighed) (includes all undrainable fluids and full oil)			
Drainable unusable fuel at 6.0 pounds per gallon - (5 gallons)	30.0	48.00	1.4
Basic Empty Weight			

3.0 Procedure and Methodology

The procedure varies for each of the following sub-sections. The procedure for gathering data takes one of three forms, 1) historical data, 2) theoretical analysis, and 3) physical measurement. In all cases, the method of data evaluation is the same. It consists of statistical variation analysis of both weight and center of gravity for 30 consecutive single-engine aircraft, Model 206. Each sub-section starts with an introductory paragraph outlining why this aircraft weighing method is relevant to this investigation and how the data was gathered. Each sub-section also contains the pertinent formulas, illustrations, and process diagrams. The method employed follows the nine SAWE steps as outlined in Section 2.3.1. The complete data set for each sub-section is contained in the respective Appendix. Section 4.0 contains the results.

3.1 Analytic Weight and CG Method

The analytic weight and CG method follows directly from the CG equation contained in Section 2.1.0. It is relevant because it is useful to establish an anticipated weight and CG. A major drawback of this form of analysis is that it requires a detailed bill of material and an extensive database of mass properties data, Appendix B. Generating a database requires hundreds of engineering person-hours. The weight data usually consists of four types. They are estimated, calculated, actual, and specification. The percentage of each type of data is generally a good indicator of the quality of the database, i.e. the greater the percentage of actual weights, the better the data quality. However, the weight and CG obtained from a database alone, does not meet GAMA or SAWE guidelines, nor does it meet the FARs for establishing weight and CG. In any event, the weight and CG obtained using this method requires validation by actually weighing the aircraft.

The simplified steps for obtaining an anticipated standard empty weight and CG are as follows:

1) Obtain the unit specific bill of material
2) Perform mass properties analysis on each detail, part, and assembly to obtain its local weight and CG (all parts must be drawn in a common aircraft coordinate system), example Table 1.
3) Sum all component weights.
4) Sum all component moments.
5) Determine the aircraft CG by dividing the sum of all moments by the sum of all weights.
6) Record the anticipated weight and CG for reference, Figure 7.
7) Record the total number of person-hours required for the analysis and estimation.
8) Validate the anticipated weight and CG by weighing the aircraft.
9) Record the amount of time that it took to weigh the aircraft.
10) Record the differences between the anticipated and the actual weight.

Table 1 Example Mass Properties Calculations

2425001	1RIB ASSY INBD	1		81	6878	3900	3193	16	34	30	0	7	0	0522644-2
0523231	5BRACKET (1)	12WR32	1	1	6907	3939	3176	5	6	6	0	1	-11000	2425001-1
0523231	5BRACKET (2)	12WR31	1	1	6907	3861	3176	5	6	6	0	1	11000	2425001-1
1221010	3ANGLE	12WR32	1	1	6485	3944	2956	6	5	5	0	0	-11000	2425001-1
1221010	4ANGLE	12WR31	1	1	6485	3856	2956	6	5	5	0	0	11000	2425001-1
	2TRACK	12WR32	1	39	7023	3900	3128	12	29	27	0	14	-1000	2425001-1
	3RIB-LH	12WR32	1	19	6749	3948	3274	16	31	27	-1	15	11000	2425001-1
	4RIB-RH	12WR31	1	19	6749	3852	3274	16	31	27	1	15	-11000	2425001-1

Figure 7 Sample Anticipated Weight

Anticipated Weight with only provisional equipment installed:

Unit #	AO #	Target Wt.	Target C.G.	Weight Range	C.G. Range
1117	11	9024	290.84	8960 to 9087	290.43 to 291.24

Anticipated Weight with full system installations:

Unit #	AO #	Target Wt.	Target C.G.	Weight Range	C.G. Range
1117	11	9049	290.93	8986 to 9113	290.52 to 291.33

Notice how cryptic the data is in Table 1. It takes a trained eye to recognize that the rib assembly shown has a total weight of 0.81 pounds and has a center of gravity location of 68.78 inches from the datum line. Further complicating this method is the fact that many assemblies, such as wings, elevators, and vertical stabilizers have their own local reference coordinate system. Therefore, to arrive at the proper combined weight and center of gravity, the data must be translated to the global airplane coordinate system.

A somewhat quicker way of obtaining an anticipated weight is to start with the average standard empty weight (i.e. historical average value of the population or a subset of the population, normally the last ten units as weighed). Then, analyze the mass properties for all unit specific optional equipment and add its corresponding weight and moment effects to the standard empty airplane to arrive at the anticipated weight.

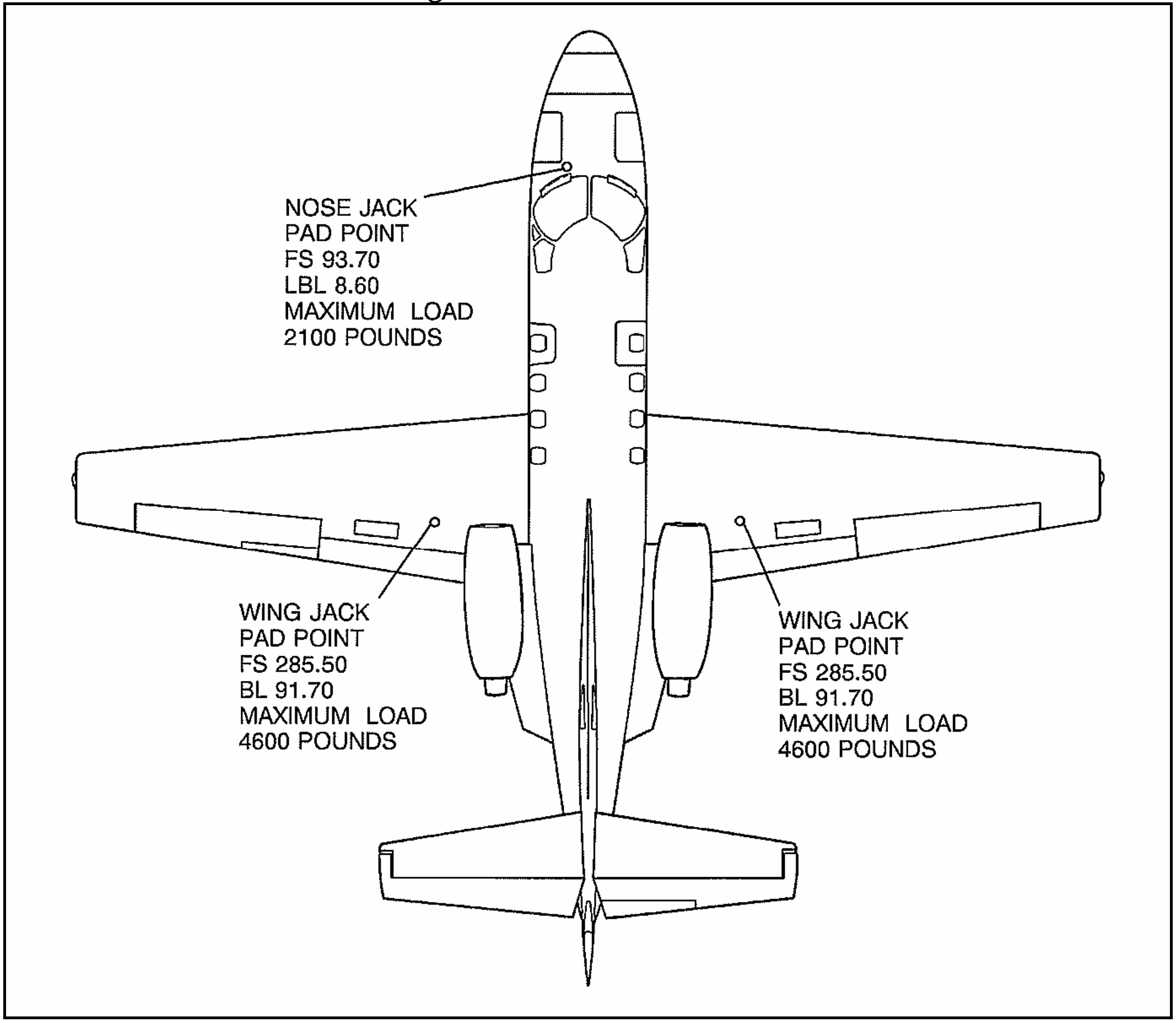
The sample anticipated weight example shown in Figure 7 warrants further explanation. In either the full-up or the provisional equipment installation scenario, there are acceptable ranges for both the weight and the CG. The ranges are +/- 0.7% pounds of the target weight and +/- 0.5% of the mean aerodynamic chord (approximately 0.40 inches) for the CG. Any values outside of either parameter necessitate an aircraft reweigh.

3.2 Aircraft 'Jacking' Weight and CG Method

Aircraft 'jacking' is the primary method used in general aviation for establishing aircraft weight and center of gravity, (hence, its relevancy to this investigation). It requires jack-points built into the aircraft structure for jack attachments, Figure 8 (pg. 27). Generally, three jack-points are required, one under each wing and one on or near the centerline of the aircraft close to the nose wheel. The aircraft jacks, with load cells and jack pads, are located directly under each jack-point. The aircraft mechanic literally jacks the aircraft into a level position. The load cell reactions read and recorded. Using the simple geometric arrangement, Figure 9 (pg. 28), and equation, Figure 10 (pg. 29), the mechanic can calculate the aircraft CG. The procedure is as follows:

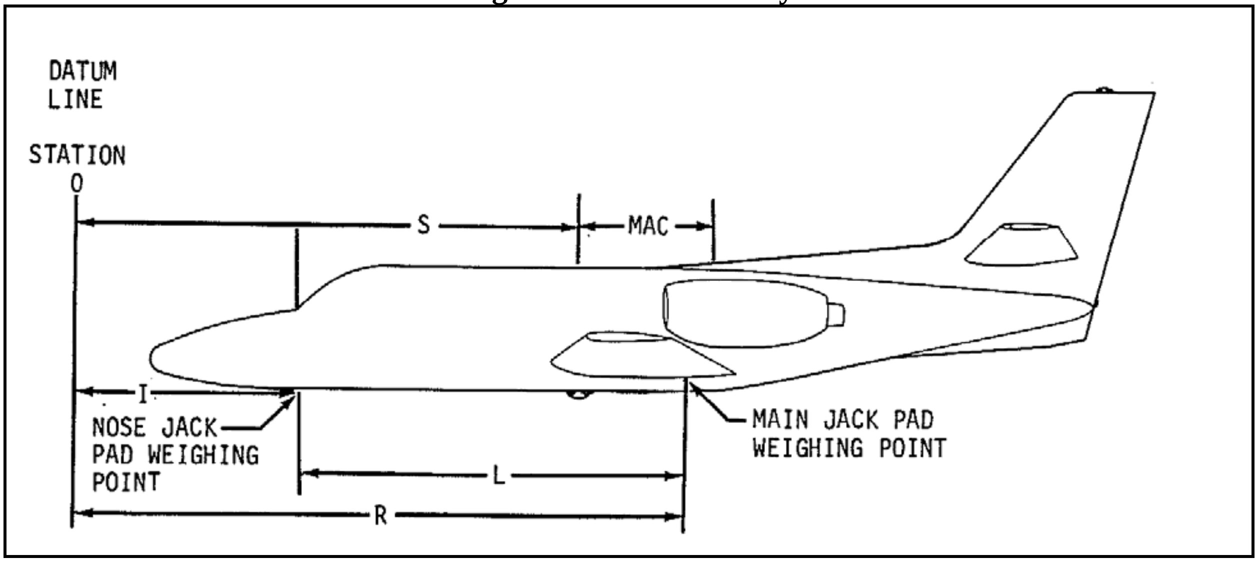
1. Preparation prior to weighing.
    a. Weighing should be accomplished with the airplane in a closed hangar.
    b. Calibrate, zero and use the scales in accordance with the scale manufacturer's instructions.
    c. Position the scales and jacks under the airplane jack pads.
2. Airplane preparation.
    a. Thoroughly inspect the airplane for loose items, items out of place and systems serviced.
        i. Loose items such as tools, floor mats, spare parts, etc., should be removed.
        ii. All items out of place should be placed in their standard location. All seats should be adjusted to their mid position with their seat backs in the most vertical position and the seat belts crossed on the seat cushions.
        iii. Service hydraulics, engine oil, fire extinguisher and oxygen systems to normal full level.
    b. Defuel the airplane
    c. Leveling on jack points
        i. Jack the airplane; refer to Maintenance Manual, Chapter 7, Lifting – Maintenance Practices.
        ii. Level the airplane; refer to Maintenance Manual, Chapter 8, Leveling – Description and Operation.
    d. Measuring
        i. When weighing on jack points, no physical measuring is required.
    e. Weighing
        i. Record each scale reading.
        ii. Record tare weight at each weighing point, where tare is used, to determine the 'as weighed' condition.
        iii. Locate the longitudinal CG and percent MAC.
    f. Down-jack the aircraft
        i. Service and stow weighing equipment.
        ii. Record person-hours for task completion.

Figure 8 Aircraft Jack Points



Besides illustrating the jack pad point locations, the top view (Figure 8) also contains the load limitations for each of the points. Overloading the hard point locations can result in severe damage to the aircraft (i.e. damaged or punctured wing skins). Side loading the load cells can result in damage to the cells, the aircraft, and in extreme cases potential harm to the mechanics conducting the weighing. Furthermore, side loading can affect the quality of the weight measurement.

Figure 9 Jack Geometry



The side view illustration (Figure 9) shows the relevant dimensions necessary for a CG calculation. Where;

R = Horizontal distance from datum line to main jack pad weighing points = 285.5 (550 Series). (R = I + L)
L = Horizontal distance form the main jack pad weighing point to nose jack pad weighing point = 191.8 inches (550 Series).
S = Horizontal distance from the datum line to leading edge of MAC = 232.04 inches (550 Series).
I = Horizontal distance from the datum line to nose jack point = 93.7 inches (550 Series).
MAC = Length of the mean aerodynamic chord = 79.61 inches (550 Series).
W_n = Weight on nose jack pad weighing point
W = Total airplane weight.

Figure 10 Longitudinal CG Equation

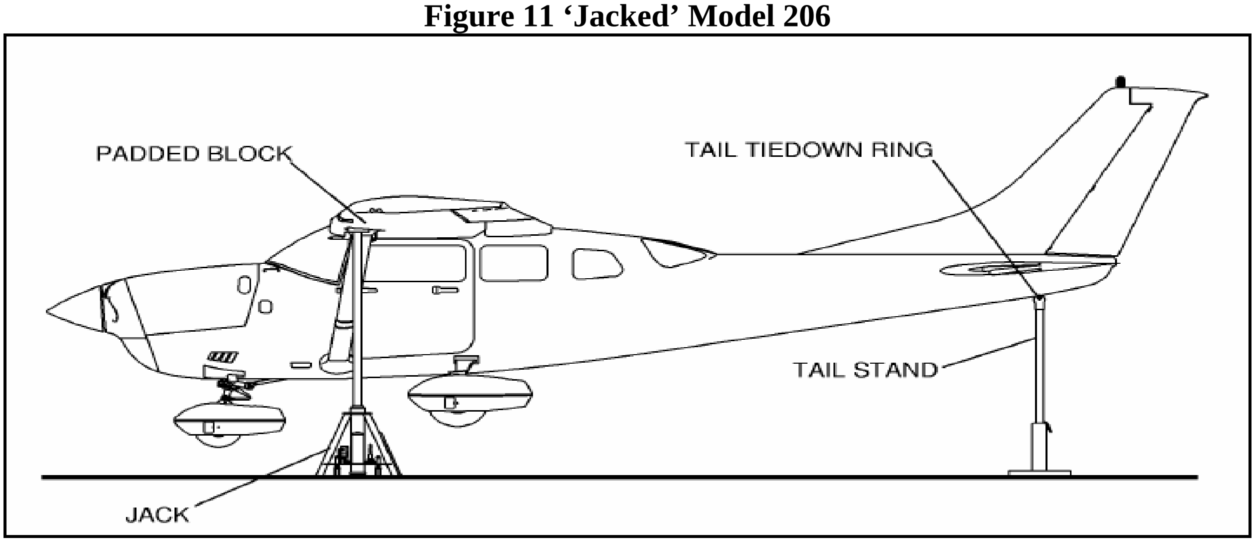
$$\text{Longitudinal Center-of-Gravity} = R - \frac{W_n(L)}{W} = 285.5 - \frac{W_n(191.8)}{W}$$

$$\text{Percent MAC} = \frac{CG-S}{MAC}(100) = \frac{CG-232.04}{79.61}(100)$$

The longitudinal CG and the Percent MAC equations (Figure 10) shown above are accurate for the Citation 550 Series of aircraft. The geometrical relationships are true for all aircraft using this type of weighing method. Of course, the physical dimensions R, L, S, I, and MAC must reflect the aircraft being weighed.

The typical SE Cessna jack arrangement is shown in Figure 11. As is clearly shown, Cessna’s SE aircraft do not have the three jack-points necessary for utilizing this type of weighing process. The tail stand is not a suitable location for a load cell. Therefore, this method will not be investigated in this field project.

Figure 11 ‘Jacked’ Model 206



3.3 Current SE Weight and CG Method

It is the evaluation of the current SE weight and CG process that provides the baseline for all other comparisons. The Model 206 Information Manual reviewed in Section 2.5 contains Cessna's relevant weight and CG determination method. There is a wealth of historical and physical data for analysis.

The current SE weight and CG data are measured as follows:

1. Preparation:
    a. Inflate tires to recommended operating pressures.
    b. Defuel airplane.
    c. Service engine oil as required to obtain a normal full indication.
    d. Move sliding seats to their most forward position.
    e. Raise flaps to their most fully retracted position.
    f. Place all control surfaces in their neutral position.
    g. Remove all non-required items from the airplane.
2. Leveling:
    a. Place scales under each wheel.
    b. Deflate the nose tire and/or lower or raise the nose strut to properly center the bubble in the level, **Figure 12**.
3. Weighing:
    a. Weigh the airplane in a closed hangar to avoid errors caused by air currents.
    b. With the airplane level and brakes released, record the weight shown on each scale. Deduct the tare, if any, from each reading.
4. Measuring:
    a. Obtain measurement A by measuring horizontally (along the airplane centerline) from a line stretched between the main wheel centers to a plumb bob dropped from the firewall (datum line), **Figure 13**.
    b. Obtain measurement B by measuring horizontally and parallel to the airplane centerline, from the center of nose wheel axle, left side, to a plumb bob dropped from the line between the main wheel centers, **Figure 14**. Repeat on the right side and average the measurements.
5. Using weights from item 3 and measurements from item 4, the airplane weight and CG can be determined, **Figure 6**.
6. Record the weight, CG, and the number of person-hours required to complete the job.

Figure 12 SE Leveling Photo

Figure 13 Distance 'A' Measurement

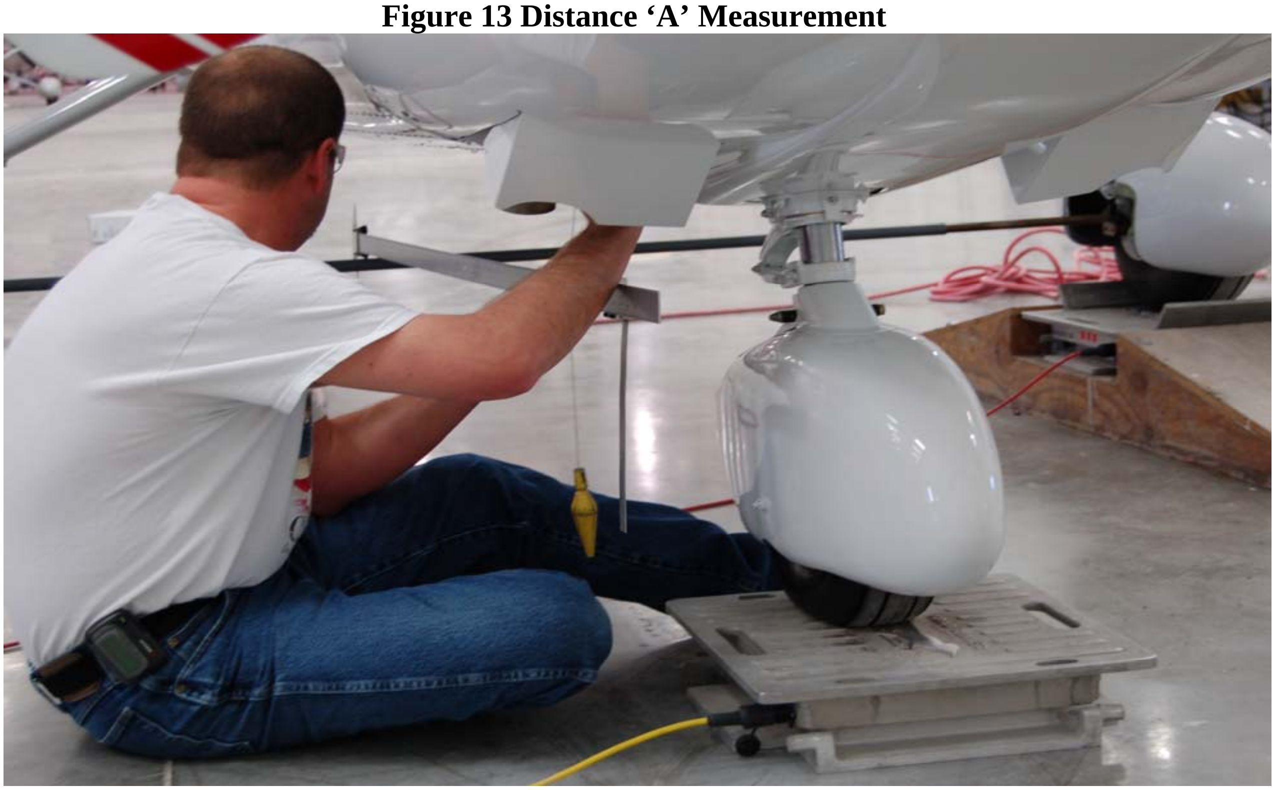


Figure 14 Distance 'B' Measurement

3.3 Future Methods

The literature review in Section 2.0 contained four possible future methods for weighing and determining the CG of aircraft. The first two, '*System and Apparatus for Determining the CG of an Aircraft,*' and '*Weigh on Wheels,*' involve determining the weight and CG of aircraft without physically leveling the aircraft. The last two, '*Aircraft Weight and CG Determination System Which Includes Alarm, Self-checking, and Fault Override Circuitry,*' and '*On-Board Aircraft Weighing and CG Determining Apparatus and Method,*' use integrated systems to determine aircraft weight and CG. While the latter two methods are exciting, the technology does not yet exist for their implementation on SE aircraft. Therefore, the first two future methods will be evaluated.

3.3.0 Weigh on Wheels Method

Cessna developed and deployed the 'Weigh on Wheels' aircraft weighing process at the Cessna Aircraft Company Mid-Continent Plant located in Wichita, Kansas. The process represents a new paradigm in the General Aviation Industry and is an innovative union of advanced electronics and weighing equipment.

It is relevant to this investigation because its future use could represent thousands of person-hours in savings. Its use could also result in more accurate weight and CG measurements directly affecting aircraft safety and performance.

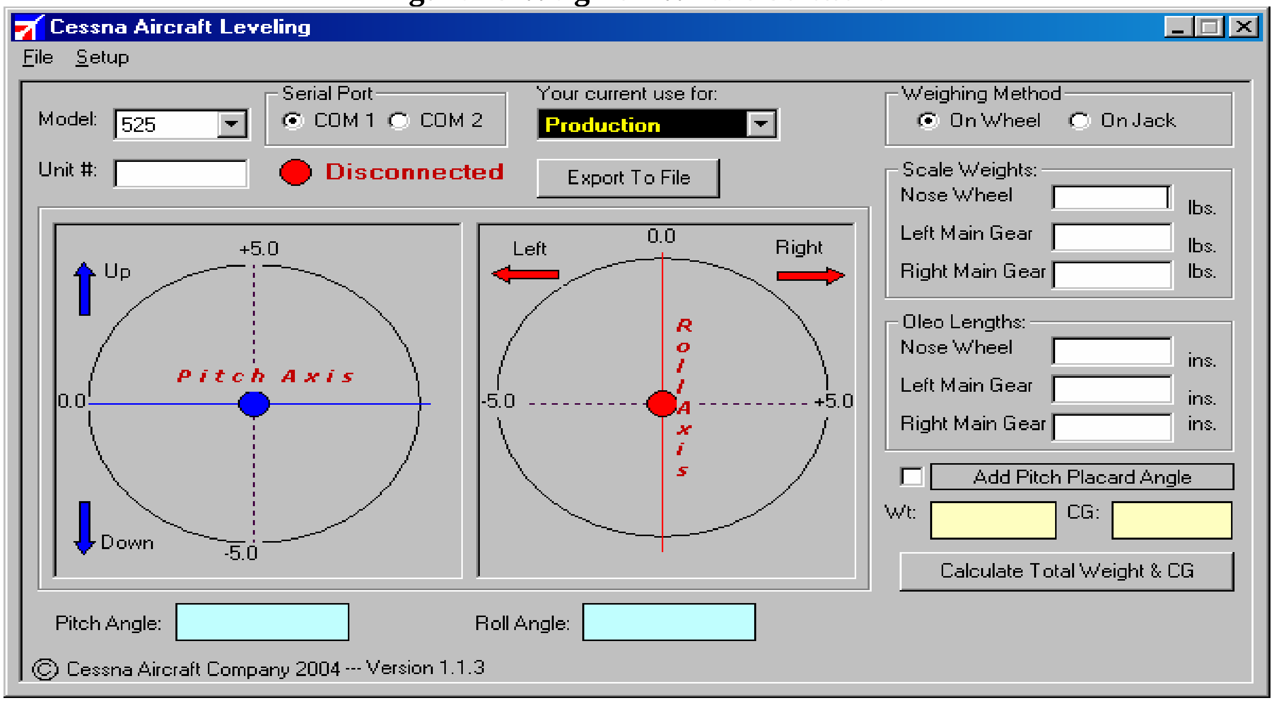
The procedure for data collection is as follows:

1. Preparation prior to weighing.
    a. Weighing should be accomplished with the airplane in a closed hangar.
    b. Position the platform scales and ramps in front of the tires so that the aircraft can be pulled on to them.
2. Airplane preparation.
    a. Thoroughly inspect the airplane for loose items, items out of place and systems serviced.
        i. Loose items such as tools, floor mats, spare parts, etc. should be removed.
        ii. All items out of place should be placed in their standard location. All seats should be adjusted to their mid position with their seat backs in the most vertical position and the seat belts crossed on the seat cushions.
        iii. Service hydraulics, engine oil, fire extinguisher and oxygen systems to normal full level.
    b. Defuel the airplane
    c. Check the scale certification. Calibrate, zero and use the scales in accordance with the scale manufacturer's instructions.
    d. Roll the aircraft onto the platform scales. Centering is not necessary, but full contact is.
        i. Set the parking brake.
        ii. Remove the tow bar.
        iii. Place the leveling device (i.e. inclinometer) on the leveling bar and attach to the aircraft with the leveling screws (**Figure 6**).

iv. Turn the computer on (do not have the test cable attached at this time).
v. Load the aircraft weighing and leveling software (**Figure 15**).
vi. Enter the unit number in the appropriate cell.
vii. Connect the leveling device to the computer.
viii. Measure the nose wheel exposed oleo length and enter into the appropriate cell in the software.
ix. Enter the scale readings in the appropriate cells in the software.
x. Check to make sure that the roll and pitch angles have stabilized (**Figure 15**).
xi. Click on the button labeled, 'calculate total weight and CG.'

e. Check to make sure that the aircraft is within the historical values as defined by CSPS-011 and its counterpart AC 120-27E (Section 2.5 and 2.3.3, respectively)
. i. If either the weight or the CG are outside of the prescribe ranges, roll the aircraft off of the scales, rotate the scales, and repeat step 1.d.
ii. If the weight and CG are still outside of the prescribed ranges reestablish per the CSPS-011 document.
iii. If the weight and CG are within the prescribed range submit the weight and CG.
iv. Record the person-hours.

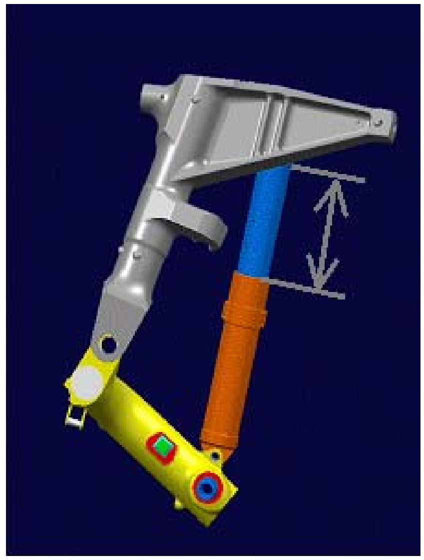
Figure 15 Weigh on Wheels Software



Please note that the SE weigh on wheels algorithm for the CG calculation is intentionally omitted from this document. It is still under development. However, a brief description of the basics is as follows.

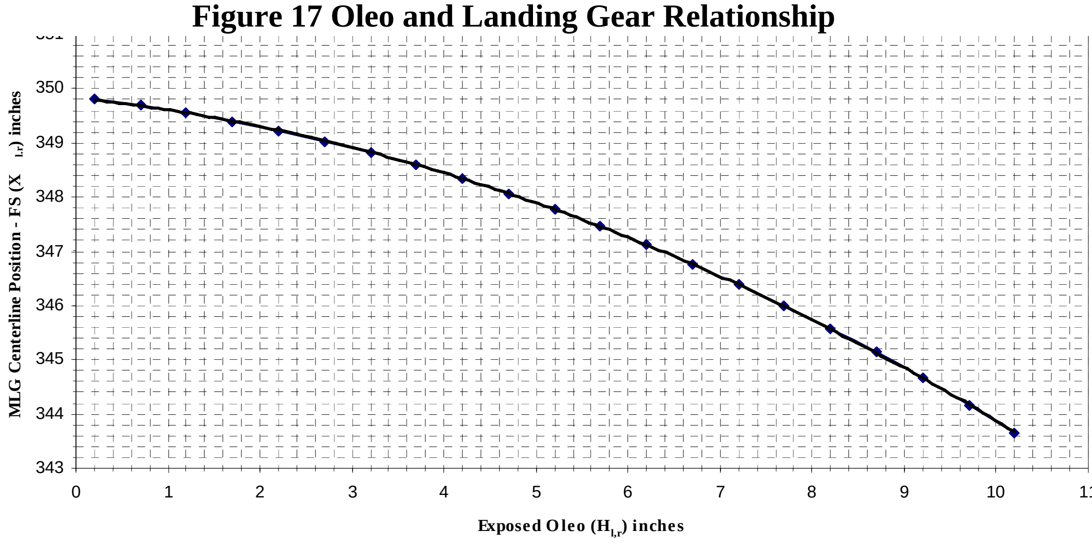
- Wheel positions become Weigh Points and are accounted for relevant to the aircraft datum.
- Measuring Oleo Shock Strut Extensions and inputting into the software (**Figure 16).**

Figure 16 Oleo Graphic



- Landing Gear Geometry is automatically calculated to obtain the weigh points, and then entered into CG formula. **Figure 17** illustrates the relationship between the oleo measurement and the CG of the landing gear.

Figure 17 Oleo and Landing Gear Relationship



The implication is that the algorithm accounts for the aircraft attitude, thereby eliminating the need to level the aircraft. The algorithm also eliminates the need to take the dimensional measurements 'A' and 'B' as described in the previous sub-section.

3.3.1 Godwin's Weighing Method

Godwin's method is relevant for the simple reason that it represents an intermediate stage between the current process and the weigh on wheels process described in the previous sub-section. Like the weigh on wheels method, Godwin's algorithm corrects for aircraft attitude. However, unlike weigh on wheels, Godwin adds back in the step of measuring the horizontal distance 'B' from the nose to the main landing gear. Although he eliminates the need to define the relationship between the exposed oleo on the nose landing gear to the CG of the reaction point, he reintroduces the potential human data measurement and entry failure modes.

The set-up and procedure for Godwin's aircraft weighing and CG determination method is as follow:

1. Preparation prior to weighing.
    a. Weighing should be accomplished with the airplane in a closed hangar.
    b. Position the platform scales and ramps in front of the tires so that the aircraft can be pulled on to them.
2. Airplane preparation.
    a. Thoroughly inspect the airplane for loose items, items out of place and systems serviced.
        i. Loose items such as tools, floor mats, spare parts, etc. should be removed.
        ii. All items out of place should be placed in their standard location. All seats should be adjusted to their mid position with their seat backs in the most vertical position and the seat belts crossed on the seat cushions.
        iii. Service hydraulics, engine oil, fire extinguisher and oxygen systems to normal full level.
    b. Defuel the airplane
    c. Check the scale certification. Calibrate, zero and use the scales in accordance with the scale manufacturer's instructions.
    d. Roll the aircraft onto the platform scales. Centering is not necessary, but full contact is.
        i. Set the parking brake.
        ii. Remove the tow bar.
        iii. Place the leveling device (i.e. spirit level) on the leveling bar and attach to the aircraft with the leveling screws (**Figure 6**).

3. Measurements.
    a. Record the scale readings for use in the weight and CG equation, **Figure 18**.
    b. Record the spirit bubble reading for use in the weight and CG equation.
    c. Record the distance L (formerly distance 'B'), **Figure 19.**
    d. Calculate and record weight and CG.
    e. Check to make sure that the aircraft is within the historical values as defined by CSPS-011 and its counterpart AC 120-27E (Section 2.5 and 2.3.3, respectively)
    . i. If either the weight or the CG are outside of the prescribed ranges, roll the aircraft off of the scales, rotate the scales, and repeat step 2.d through 3.e.
    iii. If the weight and CG are still outside of the prescribed ranges reestablish per the CSPS-011 document.
    iii. If the weight and CG are within the prescribed range submit the weight and CG.
    iv. Record the person-hours.

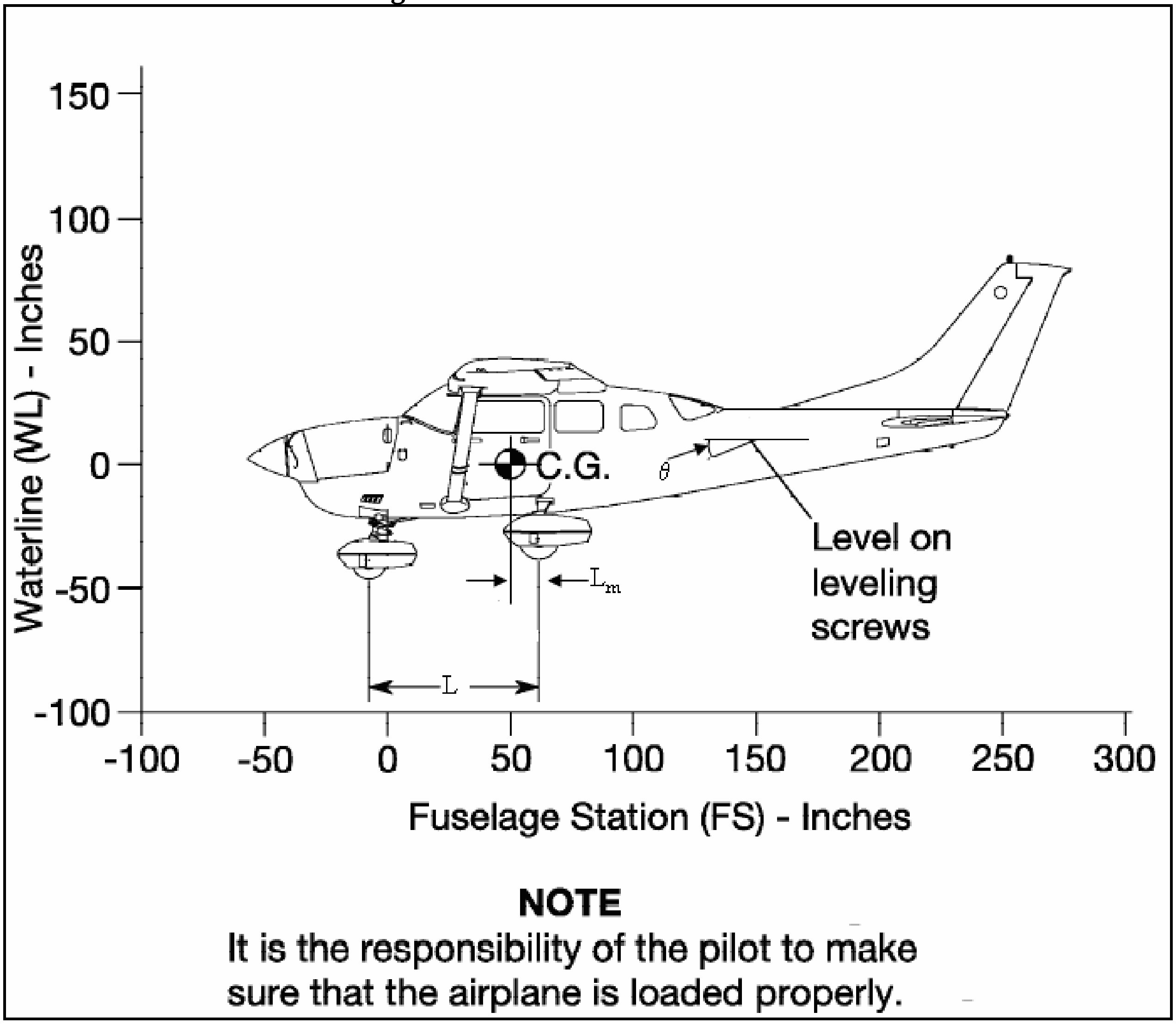
Figure 18 Godwin's Equation

$$L_m = \frac{P_n L}{(WT)\cos^2\theta} + L_{zm}\tan\theta$$

Where;

L_m = Horizontal distance from the center of the main landing gear wheel to the aircraft CG.
L = Horizontal distance from the center of the nose wheel to the center of the main landing gear.
L_{zm} = The vertical location of the aircraft CG (7.98 inches from the reference plane).
θ = Attitude of the aircraft as measured from the reference plane to earth center.
P_n = Weight on nose jack pad weighing point
WT = Total airplane weight.

Figure 19 Godwin's Measurements



Please note, in order to arrive at the aircraft CG using Godwin's method, L_m as solved for in the equation must be subtracted from distance 'A' as described in Sections 3.3 and 2.5.

4.0 Results

The analysis of thirty Cessna Model 206H's is contained in each of the following sub-sections. The processes and procedures as outlined in the previous section are used.

The space requirements for each weighing method are similar. Using on-and-off ramps and allowing sufficient room for ramps, clearance, and safety a 40' x 40' area is necessary. The scales and scale calibration costs are also very similar, $20,000 and $1,000, respectively. Additionally, utilizing Cessna's weigh on wheels process requires the use of a laptop, cable assembly, and inclinometer, $1,500, $35, and $500, respectively.

The queuing analysis is very important to this investigation because it is a true indication of the capability of the process to meet the manufacturing needs. It is also a good indicator of the resources necessary to support any particular product move rate. For this investigation, the product move rate remains the same regardless of the weighing method employed. The move rate is representative of the worst-case scenario. Based on the product move rate, the number of working hours in a year, and a single shift operation, there is an arrival rate of 0.56 aircraft per working hour (i.e. an aircraft weighing occurs once every 1.78 hours). Each of the weighing methods requires the same number of mechanics and quality inspectors, for a total of three. With the exception of the analytic method, there is only one weighing location and therefore only one server for the product line. However, the service rate does vary significantly dependent on the process used. The service rates are 0.8 units per hour for the current process, 1.18 units per hour for Godwin's method, and 1.82 units per hour for the weigh on wheels method. The service rate for the analytic method is 0.25 units per hour, or 4 hours per each unit.

Equally important as the queuing analysis is statistical variation analysis. The amount of variation in any given system indicates the capability of that system to produce repeatable results. In this investigation, those results must stand up to the guidelines established in Cessna's CSPS-011 document. They are 1.0% of the fleet weight and 0.5% of the mean aerodynamic cord, +/- 20.6 pounds and +/- 0.29 inches, respectively.

Finally, each system is subject to the sensitivities of the measuring equipment used. For example, scales have accuracies of +/- 0.1% of the applied load, spirit bubble levels have accuracies of +/- 1 degree, and the inclinometers Cessna uses have accuracies of +/- 0.01 degrees. Finally, the 'A,' 'B,' and 'L' measured distances have accuracies of +/- 0.10 inches. With the exception of the inclinometer, each of the other measuring techniques may also introduce errors resulting from humans.

4.1 Analytic Method Results

The results in this sub-section are purely hypothetical. The weights and CGs for the optional equipment were derived using data from another model. The data used to obtain the results is contained in Appendix C. This investigation merely illustrates the analytic method and concept.

Historically, calculating optional equipment weight and CG on SE aircraft does not occur because of the person-hours involved. Achieving that level of documentation to support a product move rate approaching two hours per station, i.e. an aircraft weighing once every two hours would require a minimum of three full-time engineers (Figure 20) with an annual price tag in excess of $300,000. It takes one engineer approximately four hours to calculate an aircraft's anticipated weight and CG.

The queuing analysis also illustrates that there is a 56% probability (Erlang C-function) that a customer would have to wait for an anticipated weight prior to conducting the aircraft weighing. Each delay in an aircraft weighing creates inventory carryover costs, data churn, internal customer dissatisfaction, and possibly external customer dissatisfaction.

Finally, the queuing analysis also indicates that the engineers would have a 74.7% utilization rate. Spending 75% of your available time on one task is tedious and would likely lead to poor work and or a high engineer turnover rate.

Figure 20 Analytic Method Queuing Analysis

G/G/s template using the Allen-Cunneen approximation	
Inputs	
Arrival rate	0.560
Service rate per server	0.250
Number of servers	3
SqCV for interarrival times	0.009
SqCV for service times	0.420000
Calculations of intermediate quantities	
Ratio of arrival rate to service rate	2.240
Server utilization	0.747
A Poisson quantity	0.754
Erlang C-function	0.563
Important outputs	
Expected wait in queue	0.634703
Expected queue length	0.355434
Expected wait in system	4.634703
Expected number in system	2.595434

Figures 21 and 22 illustrate the theoretical comparison of the anticipated versus the actual basic empty weights and CG's. According to the CSPS-011 guidelines, the majority of the weights and CG's shown are questionable. At the very least, the aircraft exhibiting those erroneous values would require a reweigh. Again, this drives labor, data churn, and satisfaction costs.

Figure 21 Anticipated Weight Comparison

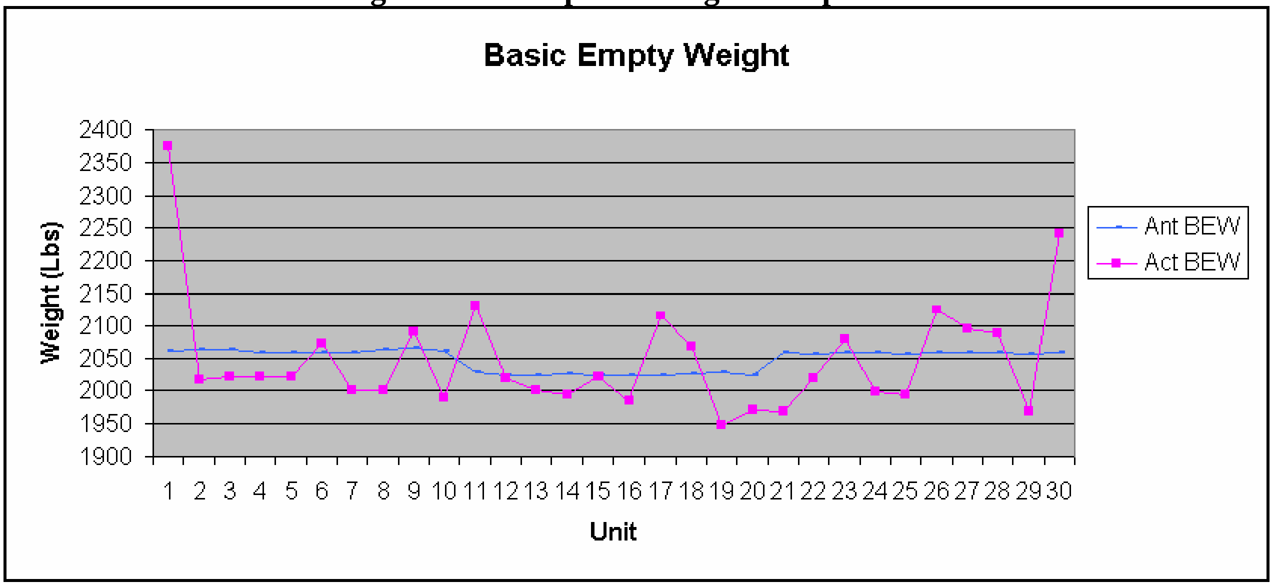
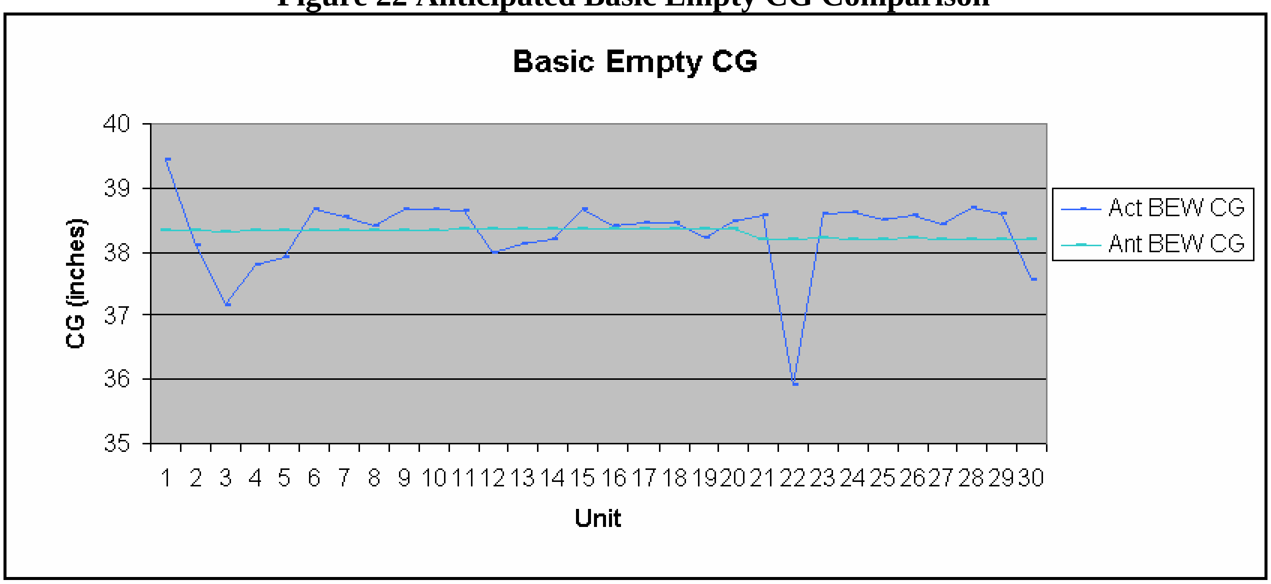


Figure 22 Anticipated Basic Empty CG Comparison



The anticipated values as shown in Figures 21 and 22 also illustrate very little variation when compared to the actual values. The variation in the actual values results from the inaccuracies of the weighing process and not the errors introduced in the anticipated calculation method. Generally, the benefit of this method is that whatever error exists in the weighing method also exists in the analytic method because of the use of the 10-plane average standard empty weight and CG. For example, a +/- 1% error in applied load translates into an error in the actual basic empty weight which then produces the same error in the standard empty weight calculation (standard empty weight equals basic empty weight minus optional equipment). Consequently, the calculation error introduced by the engineer in the optional equipment is proportionally smaller. Both of those factors have the overall affect of driving variation out.

4.2 Current Method Results

The results contained in this sub-section are representative of actual aircraft weighings and CGs for single engine Cessna Models. The data used to obtain the results is contained in Appendix D.

The weight and CG measuring method evaluated follows directly from Section 3.3. The queuing analysis is similar to that of the previous sub-section. The values of concern are the aircraft basic empty weight and its corresponding CG as they compare to the fleet weight averages and allowable as defined in CSPS-011. Also of concern is a sensitivity analysis of the process to the measuring inaccuracies.

The queuing analysis in Figure 23 reflects the arrival rate of 0.56 aircraft per hour that corresponds with the product move rate discussed in the introduction to this section. The service rate of 0.80 aircraft per hour reflects the historical average of time that is required to weigh an aircraft using the current process. The number of servers reflects operating environment of single line flow. There is only one station for weighing aircraft.

The one station mentality for weighing aircraft is readily apparent in the values for the utilization and probability that a customer waits. At 70%, those values show that there is a real potential for a bottleneck on the production line. Unfortunately, there is no chance that the customer could balk and choose to go elsewhere for service. The values indicate that either a second server is required, or the process must be leaned.

Figure 23 Current Method Queuing Analysis

G/G/s template using the Allen-Cunneen approximation	
Inputs	
Arrival rate	0.560
Service rate per server	0.800
Number of servers	1
SqCV for interarrival times	0.009
SqCV for service times	0.020000
Calculations of intermediate quantities	
Ratio of arrival rate to service rate	0.700
Server utilization	0.700
A Poisson quantity	0.588
Erlang C-function	0.700
Important outputs	
Expected wait in queue	0.042292
Expected queue length	0.023683
Expected wait in system	1.292292
Expected number in system	0.723683

Figures 24 and 25 show the BEW and BEW CG versus the fleet weight averages, respectively. The fleet weight averages reflect the guidelines established in the CSPS-011 and AC 120-27E documents. The fleet weight average varies between a high of 2,061 and 2,025 pounds. The actual BEW weights fall between a high of 2,374 and a low of 1,948 pounds. The fleet weight average CG varies between 38.21 and 38.37 inches as compared to the actual BEW CG, which has a high of 39.43 and a low of 35.90 inches.

Figure 24 Current Method BEW Comparisons

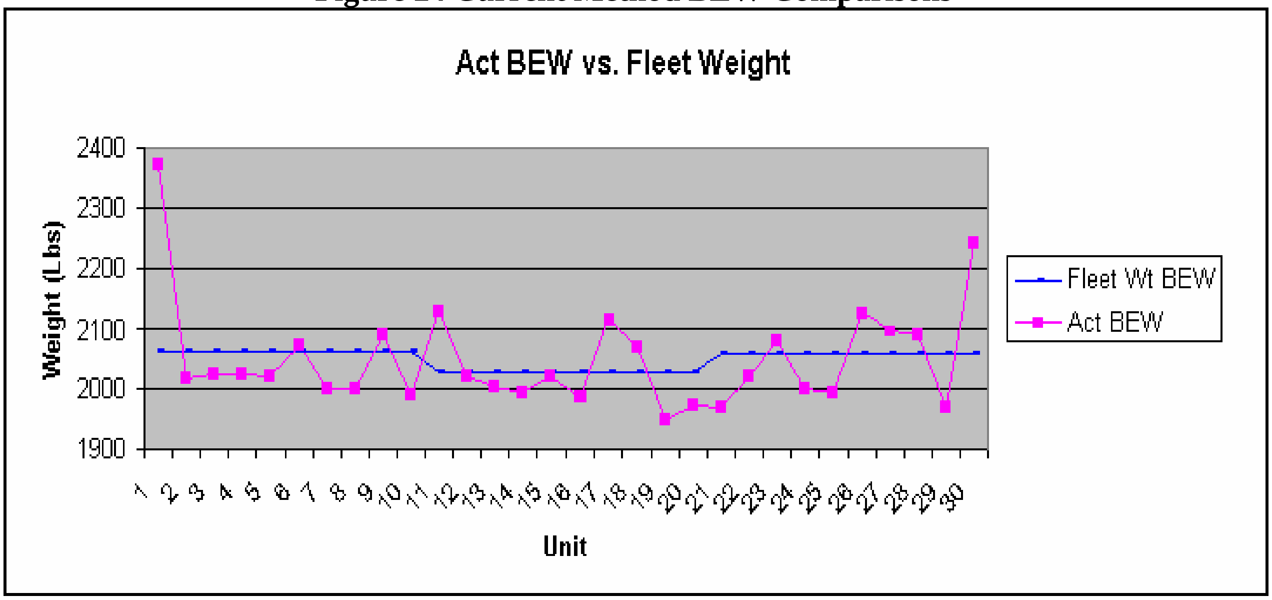
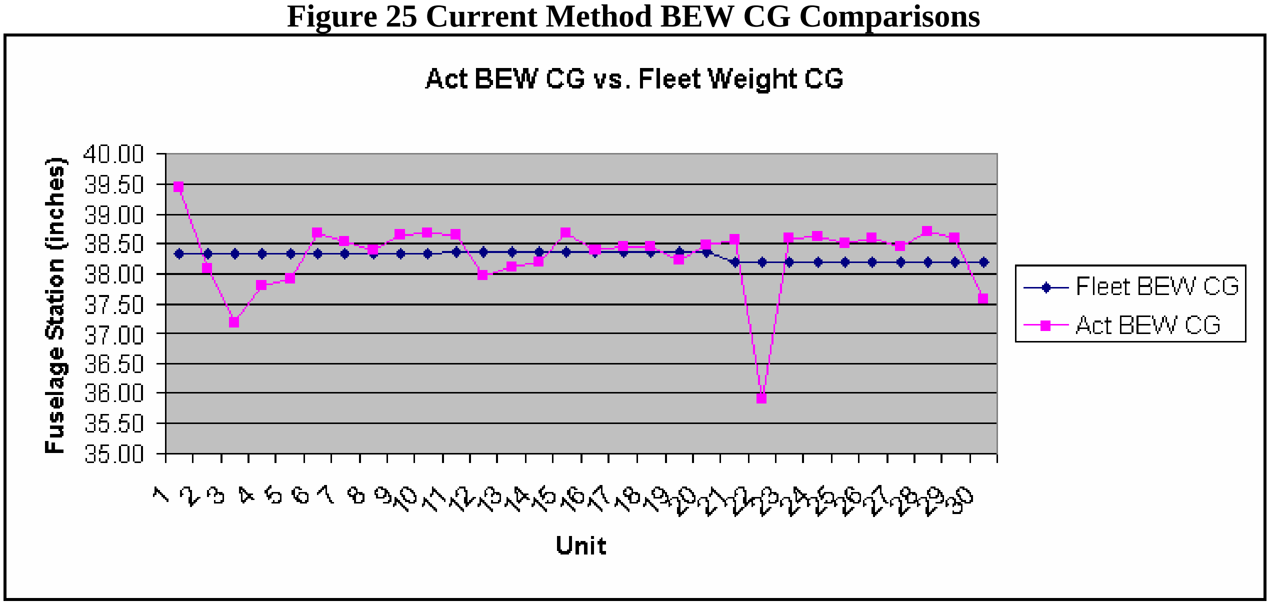


Figure 25 Current Method BEW CG Comparisons



Figures 26 and 27 show the probability plots for both the BEW and CG, respectively. Although there is no method in place for evaluating unit specific optional equipment weight and CG, the figures show a process stretched to its limits. The standard deviation for the actual BEW is 88.01 pounds and the standard deviation for the CG is 0.6125 inches. 50 pounds of optional equipment may represent a reasonable expectation; however, the probability plot clearly shows that it would take five times that to achieve a high degree of confidence. It is highly unlikely that any of the single engine models can have a 12.5% allowable weight budget for optional equipment. The standard deviation of the CG is also suspect; at a value of more than twice the allowable, it does not foster a high degree of confidence either. In fact, neither plot shows a normal probability distribution. The actual BEW plot appears to have several outliers, as does the CG plot.

Figure 26 Actual BEW Variation Analyses

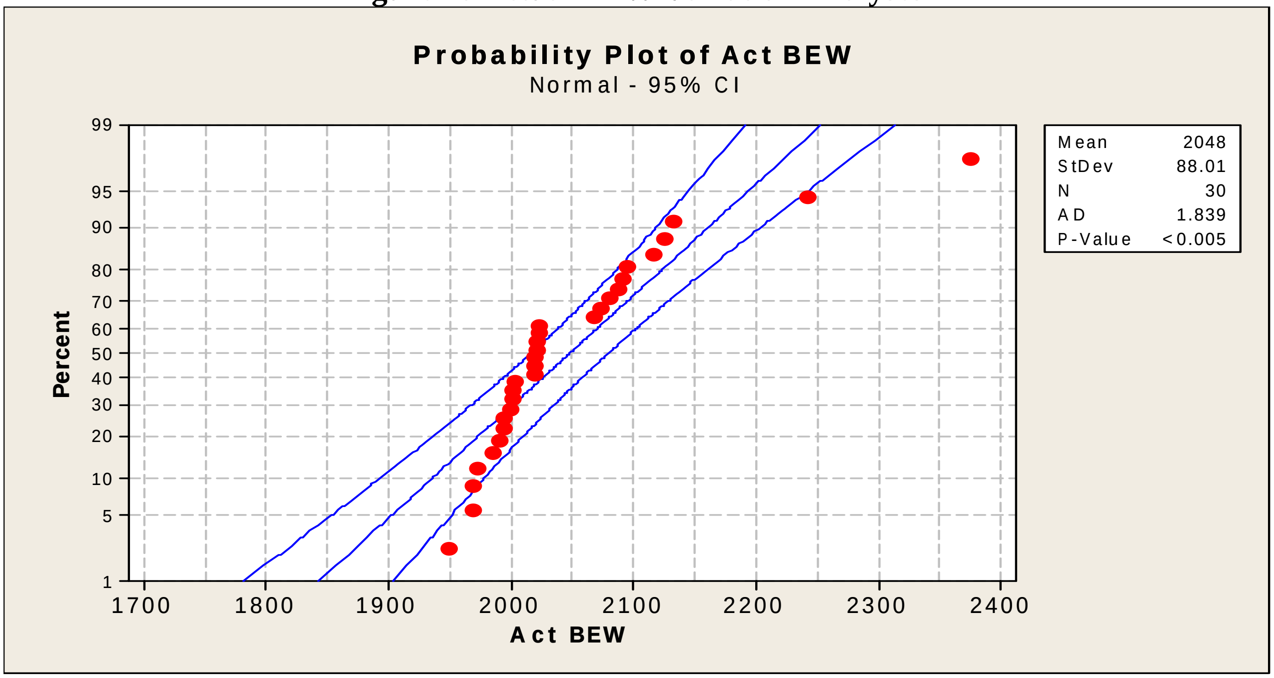
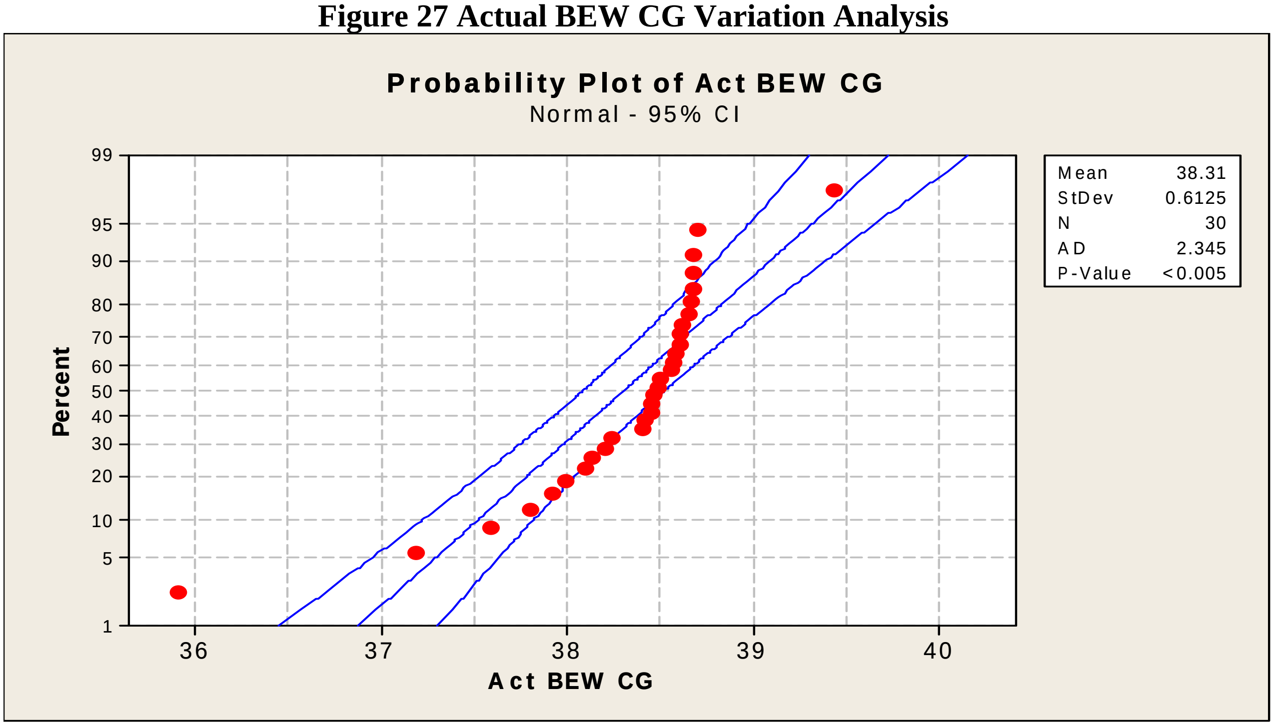


Figure 27 Actual BEW CG Variation Analysis



The probability plots for the left and right hand main landing gear, Figures 28 and 29, appear to be the inverse of the CG plot. There is no reasonable explanation for this since they are directly correlated. For example, heavy main reactions indicate an aft CG. Also, note that Figures 28 and 29 show a high degree of correlation. This suggests a high degree of confidence in the values.

Figure 28 Left Hand Main Weight Plot

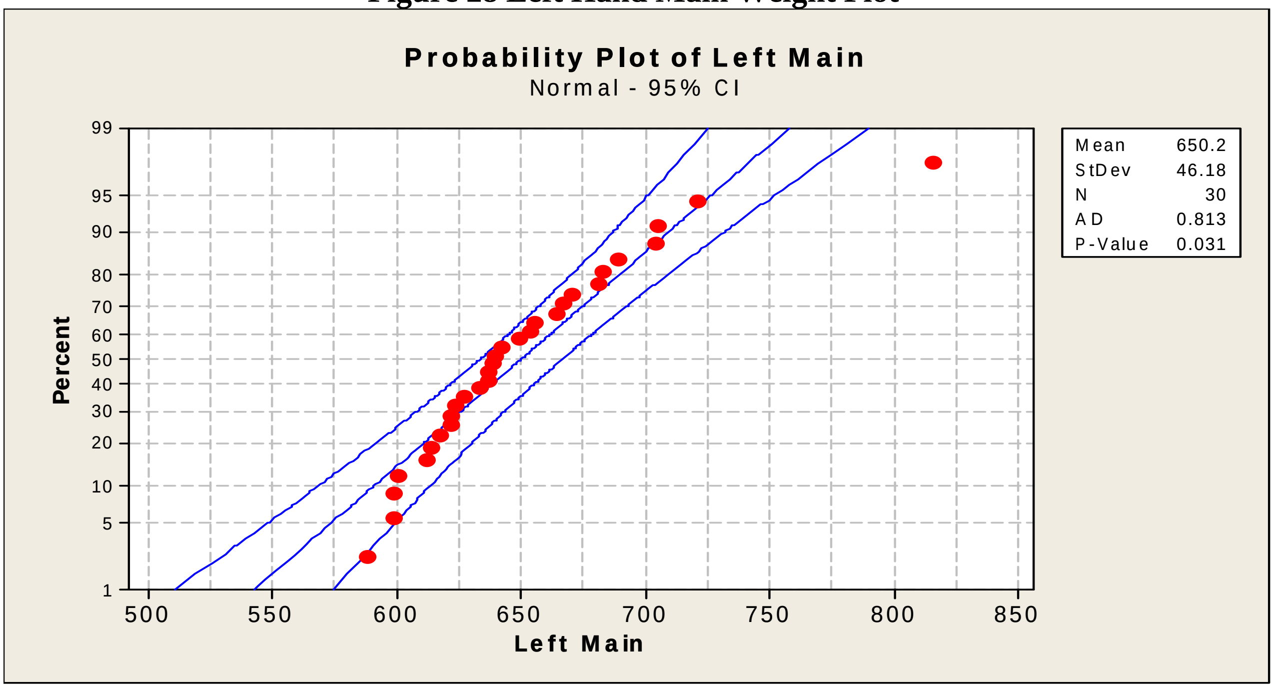
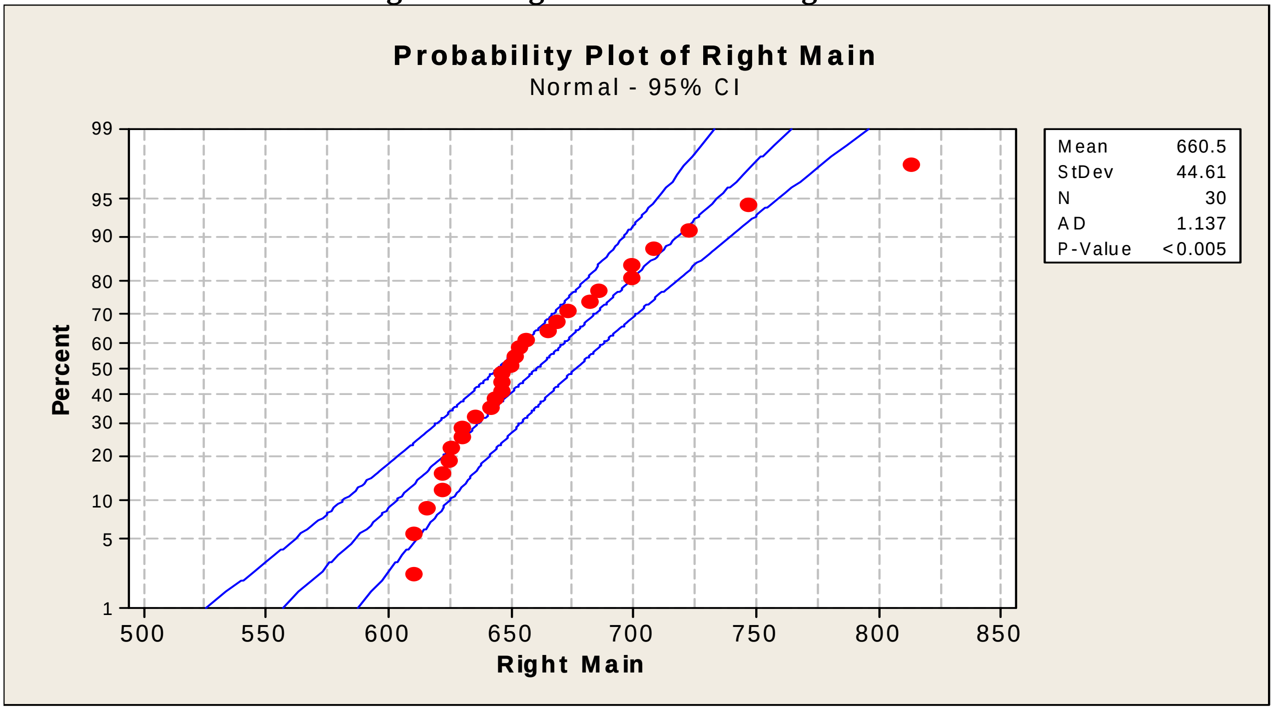


Figure 29 Right Hand Main Weight Plot



The probability plots for the nose gear reaction and the measured distances 'A' and 'B' are illustrated in Figures 30, 31, and 32, respectively. It is no surprise that the three plots appear correlated. Distances 'A' and 'B' are relative to the main landing gear and they are a function of the applied weight to the nose landing gear. However, what is surprising is that the plots are bi-modal. There is no physical explanation for the observed bi-modality.

Figure 30 Nose Gear Weight Plot

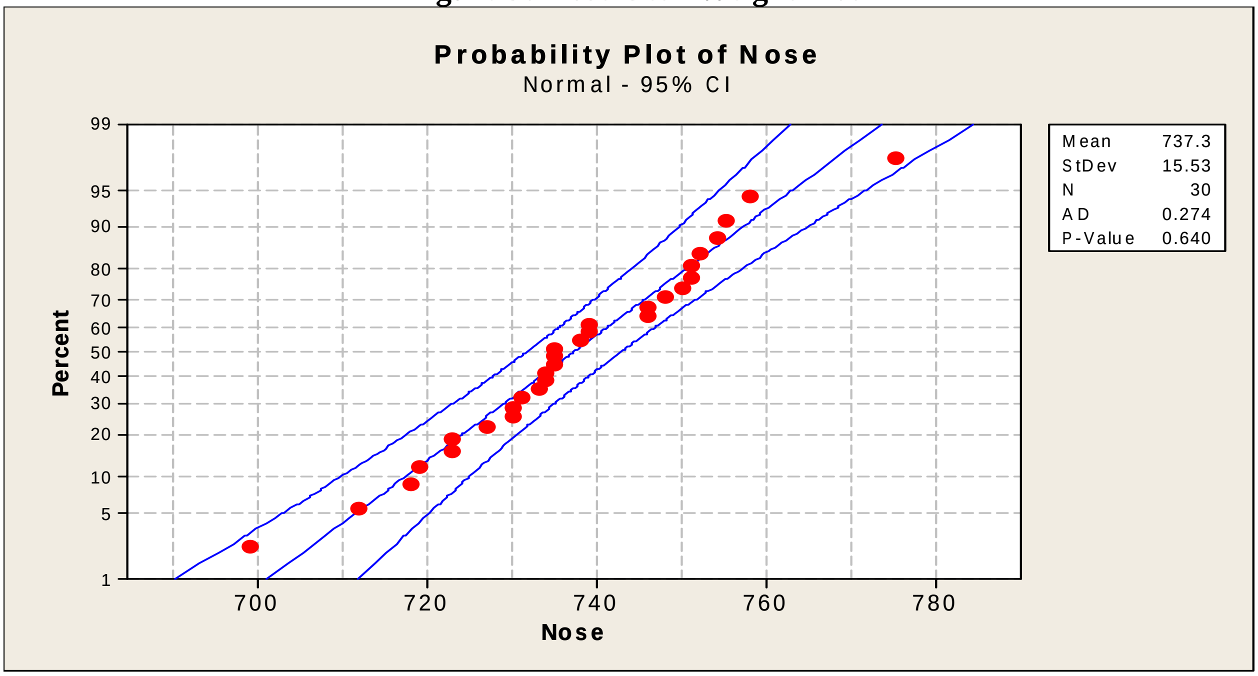


Figure 31 Measurement of Distance 'A' Plot

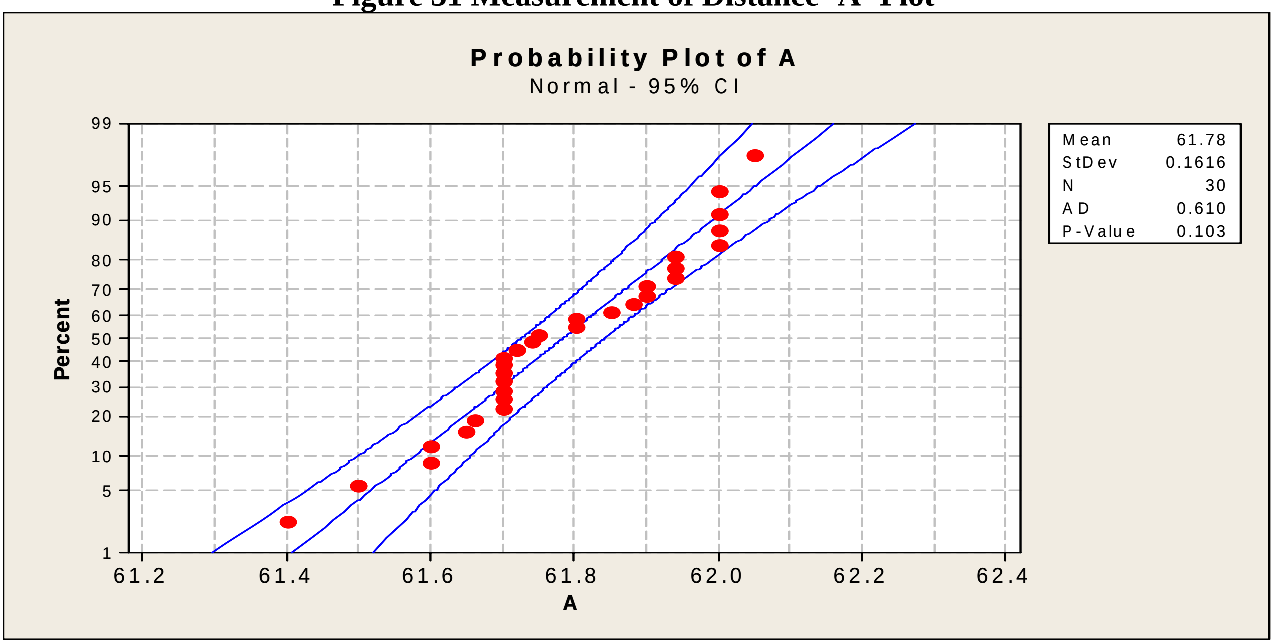
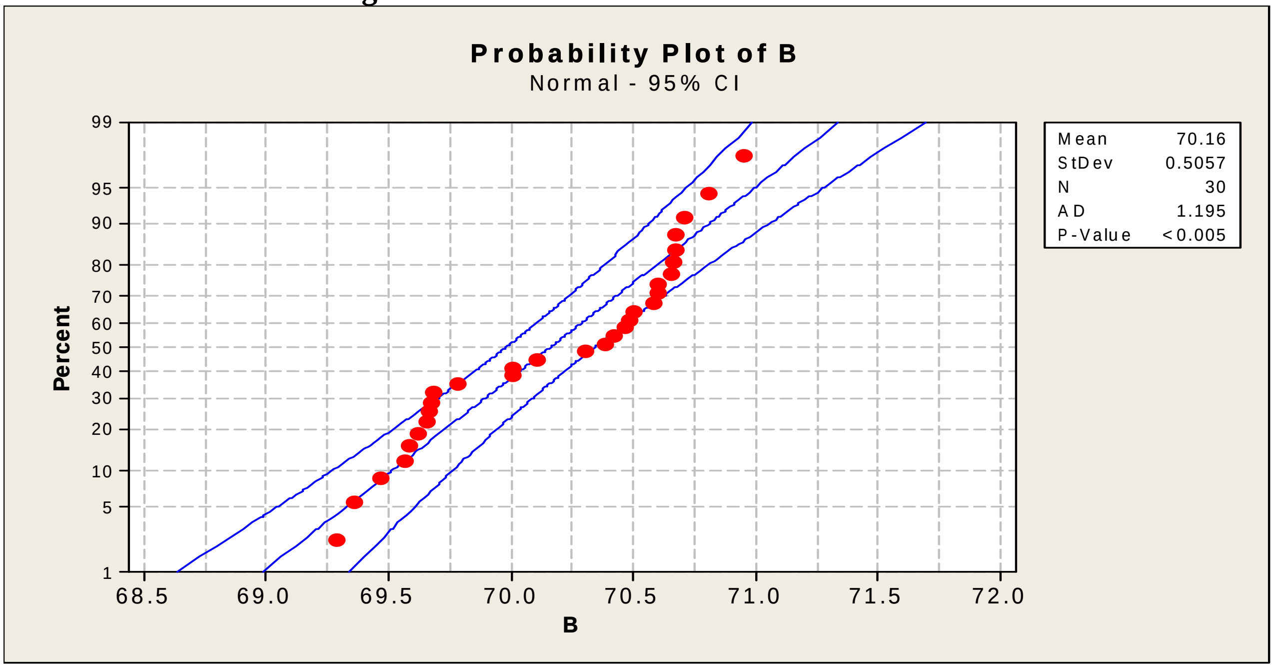


Figure 32 Measurement of Distance 'B' Plot



Finally, this process is sensitive to aircraft attitude, the scale reactions, and the measured distances. A +/- 0.1% error in measuring the distances 'A' has a +/- 0.06 inch impact on CG. Conversely, the same error introduced to measurement 'B' has an opposite effect of +/- 0.02 inches. The worst-case net effect (assuming no human error) and a true attitude of zero degrees, is +/- 9 pounds, and +/- .20 inches CG. However, a one-degree error in the aircraft attitude can translate into an additional +/- 0.50 inches in CG.

4.3 Godwin Method Results

The results contained in this sub-section are representative of aircraft weighings and CGs utilizing the method as described in Section 3.3.1. The data used to obtain the results is contained in Appendix E. The queuing analysis is similar to that of the previous sub-section. The values of concern are the aircraft basic empty weight and its corresponding CG as they compare to the current fleet basic empty weight and CG averages and allowables as defined in CSPS-011. Also of concern is a sensitivity analysis of the process to the measuring inaccuracies.

The queuing analysis in Figure 33 reflects the arrival rate of 0.56 aircraft per hour that corresponds with the product move rate discussed in the introduction to this section. The service rate of 1.18 aircraft per hour reflects the estimated average of time that is required to weigh an aircraft using this process. The number of servers reflects operating environment of single line flow and the fact that it is a minimum. There is still only one station for weighing aircraft.

The utilization rate of 47.5% is a significant improvement over the current method. Utilizing this method would save Cessna an estimated $60,000 in annual direct labor costs. The 47.5% probability that a customer waits is also an improvement. With less than one aircraft in the queue at any given time, the process will likely result in improved measurements and increased internal and external customers.

Figure 33 Godwin Method Queuing Analysis

G/G/s template using the Allen-Cunneen approximation	
Inputs	
Arrival rate	0.560
Service rate per server	1.180
Number of servers	1
SqCV for interarrival times	0.009
SqCV for service times	0.040000
Calculations of intermediate quantities	
Ratio of arrival rate to service rate	0.475
Server utilization	0.475
A Poisson quantity	0.678
Erlang C-function	0.475
Important outputs	
Expected wait in queue	0.018753
Expected queue length	0.010502
Expected wait in system	0.866211
Expected number in system	0.485078

Figures 34 and 35 show the Godwin equation derived BEW and BEW CG versus the fleet basic empty weight and CG averages, respectively. The current basic empty weight and CG averages are 2,048 pounds and 35.85 inches, respectively. For the purposes of this investigation, the current BEW weights from the previous sub-section are used. The total weight remains the same, but the nose weight decreases by multiplying the actual weight by the cosine of the angle to reflect the aft shift in weight with increasing angle. An aircraft attitude range of 3-to5 degrees is used. That range reflects the normal range of attitudes for Cessna single engine aircraft in the wheels down resting position.

Figure 34 Godwin Method BEW

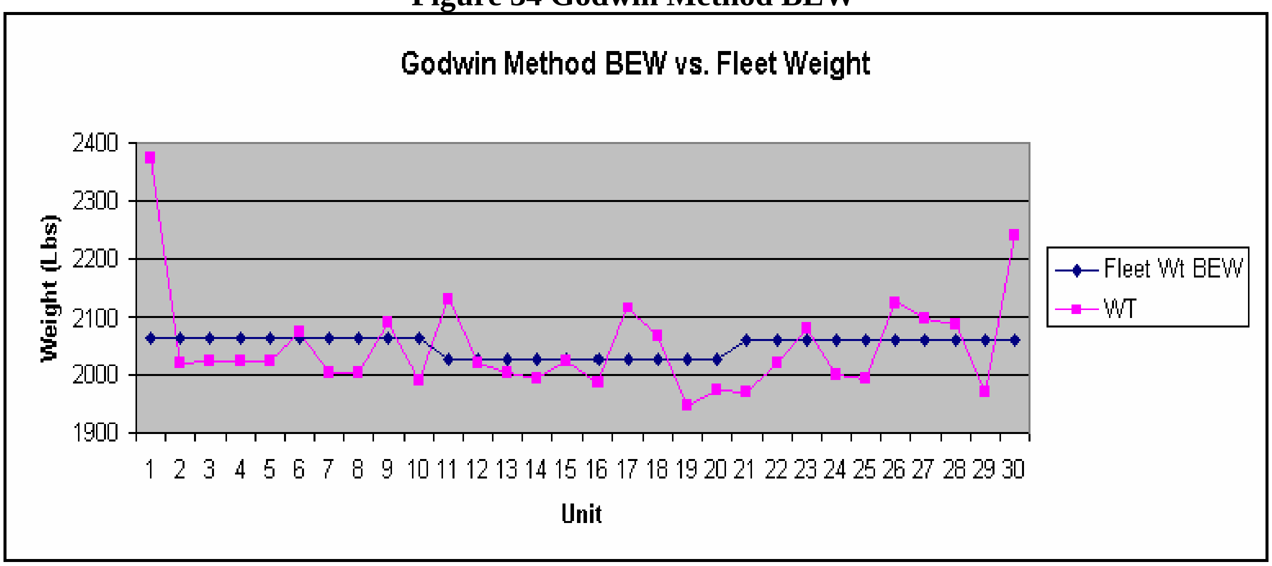
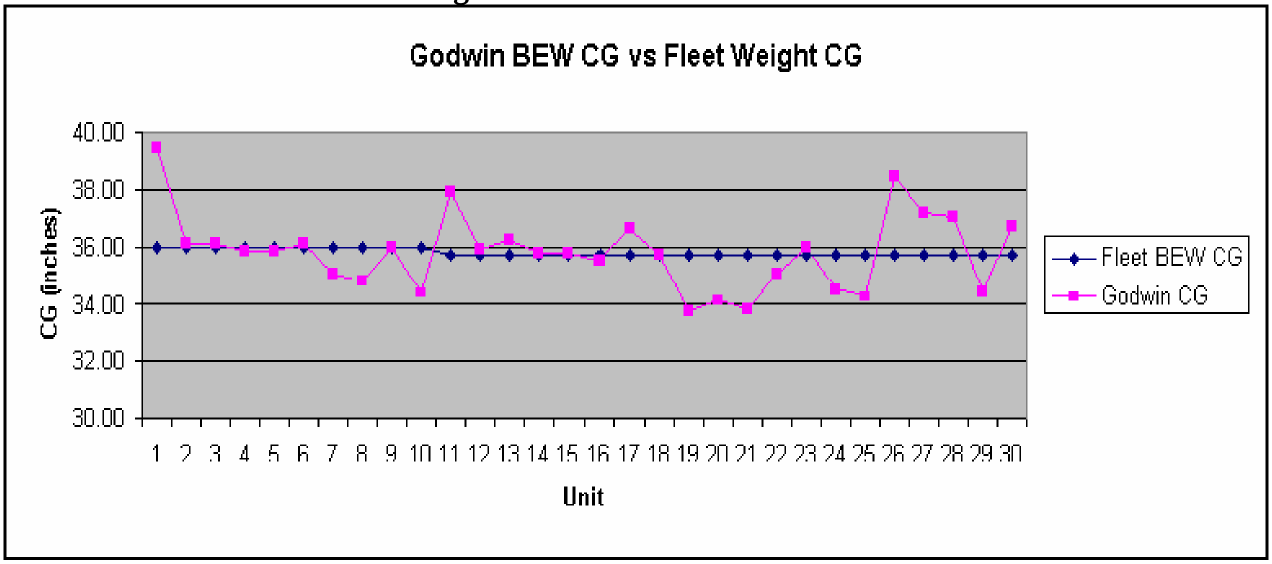


Figure 35 Godwin Method CG



Figures 24 and 34 are the same because of using the historical data. However, figures 25 and 35 have some significant differences. In fact, observe that data point number 23 now falls on the fleet weight CG average whereas in Figure 25 it is clearly an outlier. Figure 35 reflects a process that appears to align itself much more closely with the fleet weight CG.

Godwin's method has the same measurement sensitivities as the current Cessna method with the addition of the pitch angle. There is also an assumption of the vertical location of the CG of 7.98 inches. Based on the analytic data referenced in Section 4.1, its affect on symmetric single engine aircraft with low centers of gravity is negligible. Finally, and most critically, Godwin's method is dependent on the accurate measurement of aircraft attitude. The reference plane must be jig located and repeatable. It must also allow for a wide range of attitude values, even in excess of 5 degrees. A +/- 0.1% error in measuring the distances 'B' has a +/- 0.02 inch impact on CG. Conversely, the same error introduced to measurement 'A' has an opposite effect of +/- 0.06 inches. A one degree error in the determination of the aircraft attitude translates into a

+/- 0.16 inch shift in CG. The net maximum effect is +/- 9 pounds for BEW and +/- 0.22 shift in CG.

4.4 Weigh on Wheels Method Results

Cessna uses this new process exclusively at its Wichita manufacturing facility where 1,200 aircraft weighings occur each year. The Independence plant will exceed 1,000 annual aircraft weighings in 2007. Conservatively, implementing weigh on wheels for the SE plant would create net direct labor cost saving of $125,000.

The results contained in this sub-section are representative of aircraft weighings and CGs utilizing the method as described in Section 3.3.0. The general user interface shown in Figure 15 reflects the arrangement used for jets. For the single engine general user interface, the entries for the main gear oleo lengths are not necessary. The data used to obtain the results is contained in Appendix F. The queuing analysis is similar to that of the previous sub-section. The values of concern are the aircraft basic empty weight and its corresponding CG as they compare to the fleet basic empty weight and CG averages and allowables as defined in CSPS-011. Also of concern is a sensitivity analysis of the process to the measuring inaccuracies.

The queuing analysis in Figure 36 reflects the arrival rate of 0.56 aircraft per hour that corresponds with the product move rate discussed in the introduction to this section. The service rate of 1.82 aircraft per hour reflects the average actual time that is required to weigh an aircraft using this process. The number of servers reflects operating environment of single line flow and the fact that it is a minimum. There is still only one station for weighing aircraft.

The utilization rate of 30.8% is a significant improvement over the current method. The 30.8% probability that a customer waits is also an improvement. The total time in the queue is one-half of that of the current process. While eliminating a station is not likely, the shortened weighing time would lead to flexibilities in other manufacturing areas.

Figure 36 Weigh on Wheels Queuing Analysis

G/G/s template using the Allen-Cunneen approximation	
Inputs	
Arrival rate	0.560
Service rate per server	1.820
Number of servers	1
SqCV for interarrival times	0.009
SqCV for service times	0.090000
Calculations of intermediate quantities	
Ratio of arrival rate to service rate	0.308
Server utilization	0.308
A Poisson quantity	0.765
Erlang C-function	0.308
Important outputs	
Expected wait in queue	0.012088
Expected queue length	0.006769
Expected wait in system	0.561538
Expected number in system	0.314462

Figures 37 and 38 show the weigh on wheels derived BEW and BEW CG versus the fleet basic empty weight and CG averages, respectively. The current basic empty weight and CG averages are 2,048 pounds and 36.43 inches, respectively. For the purposes of this investigation, the current BEW weights from the current process sub-section are used. The total weight remains the same, but the nose weight decreases by multiplying the actual weight by the cosine of the angle to reflect the aft shift in weight with increasing angle. For the purpose of this comparison, the same aircraft attitudes used in the previous section are repeated here. Again, the values reflect the normal range of attitudes for Cessna single engine aircraft in the wheels down resting position.

Figure 37 WoW BEW Comparison

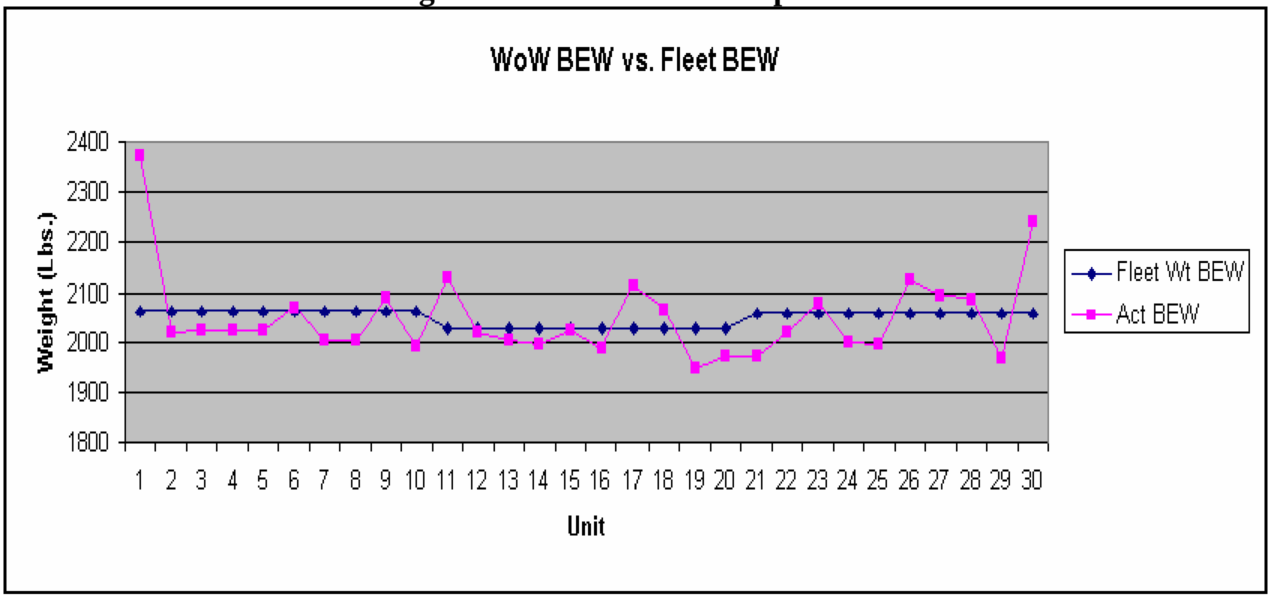
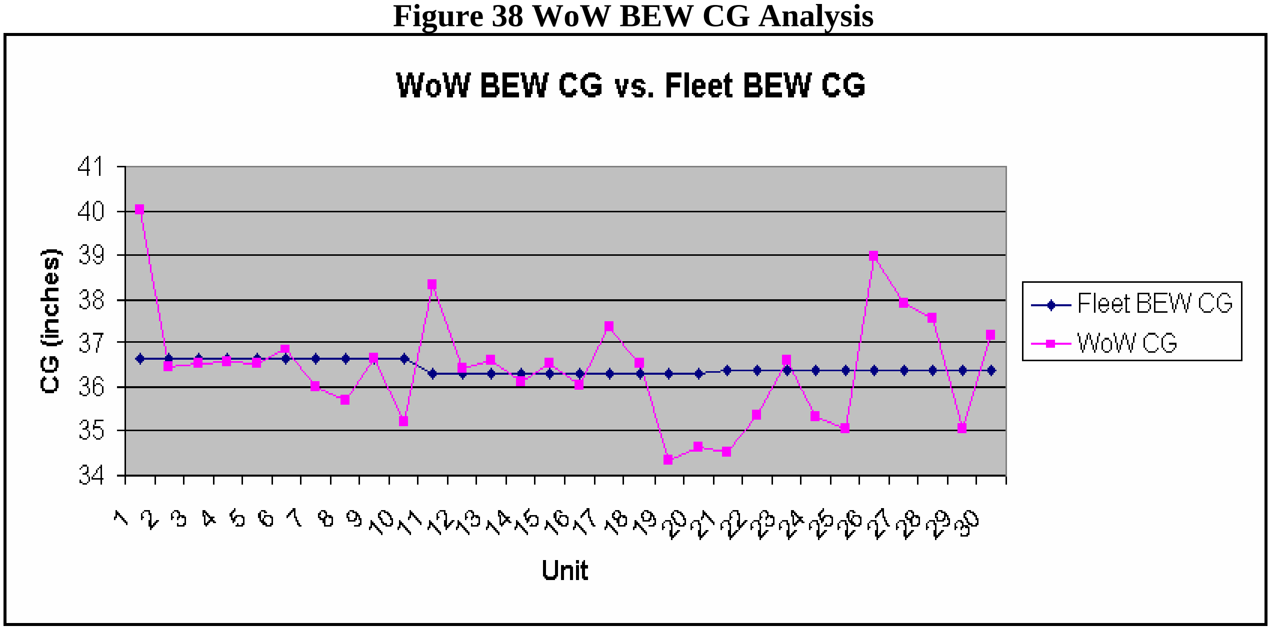
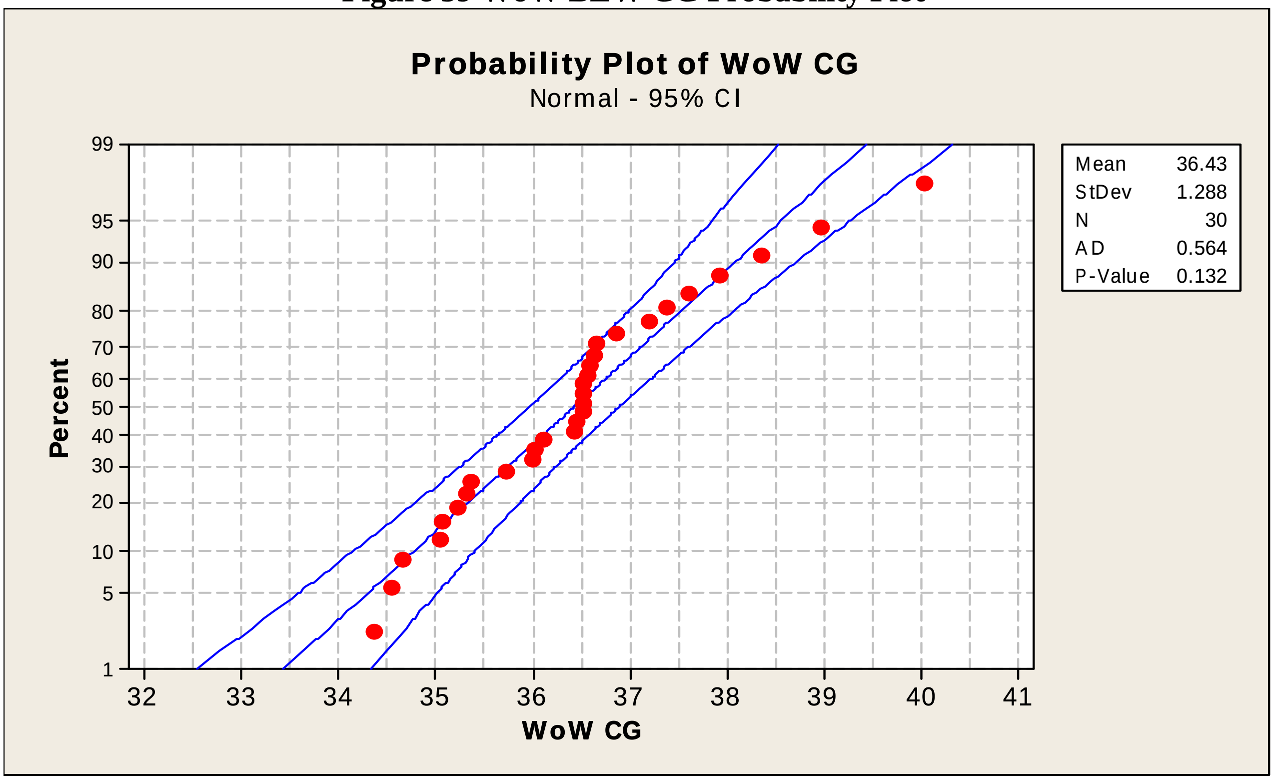


Figure 38 WoW BEW CG Analysis



Figures 37 and 38 are nearly the same as 34 and 35, not at all a surprise. The data is very similar. However, the probability plot shown in Figure 39 shows a marked improvement between the current method CG values (Figure 27) and the weigh on wheels process investigated in this sub-section. Observe that the probability plot now takes the bi-modal shape of the nose gear and distance plots illustrated in Section 4.2.

Figure 39 WoW BEW CG Probability Plot



The weigh on wheels method eliminates many of the measurement sensitivities from the previous methods. However, like Godwin's method, there is an assumption about the vertical location of the CG (7.98 inches). Finally, and most critically, the weigh on wheels method is dependent on the accurate measurement of the aircraft attitude and the nose oleo length shown in Figure 16. The attitude measurement drives a +/- 0.15 inch delta in CG. The process is very tolerant of errors in the measurement of the exposed oleo length. An error of 0.20 inches drives a +/- 0.01 inch change in the CG. The reference plane must be jig located and repeatable. It must also allow for a wide range of attitude values, even in excess of 5 degrees. Figure 40 illustrates the test set-up for the attitude measuring device, or inclinometer.

Figure 40 Inclinometer Test Fixture

5.0 Suggestions for Additional Work

The purpose of this final section is to provide illumination, direction, and the vision for future efforts. For the work to continue, there must be a broader illumination on the processes impacted by weight and CG. Engineering Management must direct the work by following sound investigatory principles. Finally, the vision furnished by the technology roadmap must guide future efforts.

The scope of this investigation was intentionally narrow. It focused first on the broad definition of weight and CG. It showed why the concept of accurately knowing an aircraft's weight and CG are important. It answered how the measurement of weight and CG are regulated and who has a stake. It considered the existing technologies through the investigation of patents. Lastly, it showed how all of those topics culminated in industry specific documents. However, the scope of weight and CG measurement goes far beyond this paper.

As was alluded to in the introduction, weight and CG affects over three hundred regulations. Those regulations encompass everything from the advanced design of an aircraft to manufacturing, certification, and the routines of fixed base operators and commercial carriers. Accurately measuring weight and CG and documenting it are a very small part of the FARs. For example, the development of an aircraft design requires weight and CG management. The size of the wing and cabin affects weight and CG decisions. The number and size of engines affects weight and CG decisions. The number of crew and passenger seats affects weight and CG decisions. There are no design decisions that do not affect weight and CG (and vice versa).

AC 120-27E is entitled 'Weight and Balance Control' for a reason. It details every aspect of weight and control systems. It provides the methods for establishing, monitoring, and adjusting individual aircraft or fleet empty weight and CG. It provides the guidelines for creating loading schedules composed of graphs, tables, and computations for weight and CG conditions to insure safe aircraft operation. It provided the procedures for using the loading schedule to document that the aircraft is operating within approved weight and CG limitations. It provides guidelines for the load manifest and procedures for its preparation. It provides procedures for all personnel concerned with aircraft loading and operations. Finally, it provides procedures for the operational accountability such as takeoff and landing weights and CGs.

Clearly, the literature review should be expanded in order to capture the entire life cycle of weight and CG as it pertains to aircraft. It should include all of the internal and external documents produced at Cessna that relate to an aircraft's weight and CG. For example, the POH was discussed as it relates to weight and CG calculation. However, there was no discussion about how to create the document. Nor was the timing of the POH creation discussed. At what time in product design and development do such topics arise? How are they managed? Who writes the manufacturing jobs for aircraft weight and CG activities? How are they created and managed? More importantly, who determines what method to employ for determining aircraft weight and CG? Who conducts the aircraft weighings? Who trains and certifies the people conducting the weighings?

The investigation included a review of four stepwise methods for determining an aircraft's weight and CG. They were the analytic, current, Godwin, and weigh on wheels methods. Each method has its pros and cons. Does engineering management need a decision matrix to determine which method is the best for any given set of circumstances? Are those the only applicable methods? The patent search could be expanded to include more obscure techniques. For example, is the use of moments of inertia (MOI) measuring machines as used in the aerospace industry applicable to SE aircraft? Is there a use for aircraft-jacking methods for SE aircraft weighings?

Each of the methods investigated have obvious pros and cons. Engineering Management should evaluate them for future decisions. Furthermore, the data indicates a need for further analysis. For example, in both the Godwin and the weigh on wheels methods there were signs of bi-modality in the probability plots. Why did that occur and what is its significance? The Godwin and weigh on wheels methods both need to capture possible regression equations. Can Cessna eliminate the need for any of the measurements? If Cessna can eliminate even something as simple as the nose gear oleo extension measurement in the weigh on wheels method, the data becomes more accurate and the process more repeatable.

Engineering management must provide clear direction in all aspects of aircraft weight and balance. As technologies change and data measurement techniques improve, management must facilitate the transitions. Management must control the life cycle of weight and CG just as they manage the life cycle of a product. Engineering management must look toward future technologies. For example, can Cessna develop an on board weight and balance system, if so, at what cost? Can a statistical model drive a heuristic aircraft weight and CG measuring method?

The vision of Engineering Management controlling the life cycle of a product’s weight and CG is not as far-fetched as it sounds. The FARs and organizations like GAMA and SAWE provide regulations, recommendations, and guidelines. There are clear beginning and ending points. The weight and CG management process begins with product concept and ends with the product replacement.

Appendix A CSPS-011

1.0 PURPOSE

To describe procedures for weighing and for determining Basic Empty Weight and center of gravity for commercial aircraft produced at Cessna Aircraft Division.

2.0 REFERENCES

Except where a specific issue is indicated, the current issue of the following publications shall form a part of this specification to the extent indicated herein.

2.1 Military Specifications

MIL-W-25140 Weight and Balance Control Data (for Airplanes and Rotorcraft)

2.2 Federal Specifications

Civil Air Regulations, Part 3

Federal Aviation Regulations, Part 23

Federal Aviation Regulations, Part 25

Cox - Stevens Electronic Scales Division - Operation and Maintenance Instructions

GAMA Specification No. 1, dated 15 February 1975

3.0 EQUIPMENT

3.1 Electronic Weighing Kit

The weighing kit shall be calibrated or certified correct by commercial scale company officials at least once every 12 months.

3.2 Platform Scales

The platform scales shall be capable of supporting the applied loads. The scales shall be certified correct by commercial scale company officials at least once every six months.

3.3 Floor Scales

The floor scales shall be certified according to the manufacturer's recommendations (refer to the Installation and Service Manual).

3.4 Hydraulic Jacks

Suitable hydraulic jacks capable of withstanding the applied loads shall be used. The jacks shall have a locking device on the ram and be of sufficient height to level the aircraft.

3.5 Data Recording Sheet

Cessna weight form X-158 or I-116 and Weight and Balance Control Data sheet are used to record the weighings.

Piston single engine Weight and Balance information are recorded on appropriate form(s), such as X-409, approved by Single Engine Quality Engineering.

4.0 DEFINITIONS

4.1 Calculated Empty Weight

The "Calculated Empty Weight" is in the weight of the structure, powerplant, furnishings, systems, and other items of equipment that are considered part of a particular aircraft configuration. It is a "dry" weight.

4.2 Standard Empty Weight (defined by ATA as "Manufacturer's Empty Weight")

The "Standard Empty Weight" is the "Calculated Empty Weight" plus the weight of equipment and fluids that
are considered an integral part of a particular aircraft configuration, not included in the "Calculated Empty Weight," but do not vary for aircraft of the same type. These items include:

- Unusable fuel
- Full oil
- Undrainable fuel and oil
- Hydraulic fluids
- Brake fluids

4.3 Basic Empty Weight (defined by ATA as "Operational Empty Weight")

"Basic Empty Weight" is the official legal empty weight of the total aircraft as defined by CAR 3.73,
FAR 23.29, or FAR 25.29 as applicable. It represents the actual aircraft, including paint, undrainable and unusable fuel and full oil, full hydraulic and brake fluids, plus those items of optional equipment that may be selected by the owner. It is essentially a "Standard Empty Weight" plus optional equipment.

4.4 Fleet Empty Weight

"Fleet Empty Weight" is an average weight established by weighing at least ten production aircraft of each model. The weight of each aircraft is corrected mathematically from the "as weighed" configuration by subtracting the weight of optional equipment from the "as weighed" condition and adding drainable, unusable fuel.

It is essentially a "Standard Empty Weight."

The weight of any fleet member cannot vary more than ±1% in weight or ±1/2% in M.A.C. center of gravity.

5.0 AIRCRAFT PREPARATION

5.1 Standard Equipment

Aircraft shall be complete per drawings and shall be in the Standard Empty Weight configuration, except for installed optional equipment.

Check the airplane for items of standard equipment that are not installed at the time of weighing. List any shortages on the weight sheet form X-158 or I-116.

5.2 Optional Equipment

Check the airplane for items of optional equipment that disagree (shortages or additions) with the airplane order. List these items on the weight sheet form X-158 or I-116, along with the change number and the date on the airplane order.

5.3 Inventory

Thoroughly inspect the aircraft for loose items, items out of place, and shortages of equipment. All items must be in their standard location. All seats on tracks shall be placed in the most forward position (against the forward seat stop); all seat backs shall be in the most nearly vertical position; all seatbelts shall be crossed on the seat cushion. Loose items such as tools, floormats, spare parts, etc., must be removed from the aircraft. All shortages must be filled or accurately accounted for to facilitate corrections to "Aircraft Standard Empty Weight" and "Center of Gravity" location. Flaps shall be in the fully-retracted positions. All control surfaces shall be in the neutral position. Entrance door and all baggage doors shall be closed at time of weighing.

5.4 Fuel Condition

Defuel the airplane while it is in the normal ground attitude by opening the drain plugs on the bottom of each tank (refer to Aircraft Maintenance Manual). Drain until the fuel drips at a slow rate (approximately one drip per second). The fuel remaining is trapped fuel and included in the Standard Empty Weight.

NOTE: Basic Empty Weight includes drainable, unusable fuel as determined by actual fuel burnoff test per CAR and FAR regulations. When the aircraft has been defueled as above, add unusable fuel to the "as weighed" condition to determine Basic Empty Weight. (Refer to Aircraft Weight and Balance Control Data sheet for unusable fuel weight.)

6.0 LEVELING

The aircraft must be level during weighing to determine the center of gravity. Always level laterally before leveling longitudinally.

6.1 Leveling on Landing Gear

Refer to Aircraft Information Manual, Chapter 6, for proper leveling procedures.

NOTE: Refer to Service/Maintenance Manual for proper reservicing of the gear struts.

6.2 Leveling on Jack Points

Refer to Chapter 6 in the Aircraft Information Manual or the Weight and Balance Manual for proper leveling procedure.

CAUTION: KEEP THE AIRCRAFT LEVEL WHILE JACKING TO PREVENT SLIPPING OFF JACK POINTS AND DAMAGING THE AIRCRAFT.

NOTE: When possible, secure nose gear strut to prevent extension. This will allow minimum total jacking height.

7.0 MEASURING

The relative locations of wheel positions and of jack points are shown on the Weight and Balance Control Data sheet. Any differences resulting from model modifications will be measured at the time of weighing.

8.0 WEIGHING

8.1 Atmospheric Conditions

Air movements or currents of air passing over the aircraft affect the accuracy of the scale readings; therefore, weighing operations will be conducted in a closed hangar free of any air movement.

Some scales are sensitive to temperature and/or humidity. Refer to the scale Operations Manual and observe these precautions.

8.2 Hoist the Aircraft

Jack the aircraft until it is entirely supported by the scales. Refer to the aircraft Service/Maintenance Manual for proper jacking procedure.

CAUTION: USE PROPER ADAPTERS TO PREVENT JACKS FROM SLIPPING OR BUCKLING. DAMAGE TO AIRCRAFT OR INACCURATE WEIGHT READINGS MAY RESULT IF THE WRONG ADAPTERS ARE USED.

8.3 Record the Weights

Weigh the aircraft according to instructions in the Operations Manual for the applicable scales. Record the weight at the support points on the airplane weighing form or the Weight and Balance Control Data sheet.

8.4 As-Weighed Condition

Add the shortages, if any, that were found during the aircraft preparation (refer to paragraph 5.0). Determine the Basic Empty Weight by using the information found on the Weight and Balance Control Data sheet. Refer to the Aircraft Information Manual for additional information.

8.5 Acceptable Weighings

If the total aircraft weight differs from the anticipated weight of the aircraft by 20 pounds or more for aircraft in the under-3,000 lb. range or 0.7% for aircraft over 3,000 lbs., repeat the weighing procedure.

8.6 Determination of Center of Gravity

Calculate the C.G. by using the applicable formula on the Weight and Balance Control Data sheet.

Calculate the % MAC C.G. location by using the applicable formula on the Weight and Balance Control Data sheet.

9.0 FLEET EMPTY WEIGHT DETERMINATION

(Part 3 and Part 23 Airplanes Only, Excluding Models 501 and 551)

9.1 Purpose

The Fleet Empty Weight is an average empty weight established by the manufacturer to avoid the necessity of weighing each airplane.

9.2 Select Airplanes

The Fleet Empty Weight will be the average weight of ten aircraft of a particular model with similar equipment installed. The “as weighed” condition is corrected to the Fleet Empty Weight mathematically by subtracting the weight of optional equipment installed at the time of weighing and adding drainable, unusable fuel.

9.3 Sample Weights

Spot check weights of each tenth airplane will be made as circumstances and conditions may warrant for the purpose of determining continued accuracy of the Fleet Empty Weight and C.G. The airplanes selected for these spot checks will have comparatively identical equipment to those weighed in establishing the Fleet Empty Weight.

9.4 Accepted Limits

Should the spot checks vary in weight in excess of 1% of the established Fleet Empty Weight and/or the C.G vary in excess of 1/2% MAC, a second airplane with comparatively identical equipment installed will be checked. Should the second spot check fall within the prescribed limits, the previous spot check will be considered an isolated case, and the Fleet Empty Weight will remain in effect. Should the second spot check exceed the limits, a new Fleet Empty Weight will be established.

9.5 Monitoring

The Weight Group will monitor the Fleet Empty Weight and maintain a history of the weighing spot checks.

Appendix B Final A/C Weight 'Job'

Oper	Dept	Grp	Mach	Op	Setup	Run	Std	Tool No.	Tl Cd	Text	Rev
0005	161		999							THIS JOB IS USED TO WEIGH A [redacted] AIRCRAFT	
										+++NOTE+++ THIS JOB WAS CREATED TO MEET ENGINEERING	
										REQUIREMENTS.	
								CSPS-011		+++NOTE+++ BASIC EMPTY WEIGHT REF. CSPS	
										THE FOLLOWING ENG DWG IS REQUIRED	R01
										[redacted] WEIGHING SPECIFICATION - MODEL [redacted]	
										[redacted] A/C LEVELING DEVICE INST R03	R02
										+++NOTE+++ ENTRANCE AND BAGGAGE DOORS SHALL BE CLOSED	
										AT TIME OF WEIGHING. CONDUCT WEIGHING	
										OPERATION IN CLOSED HANGER FREE OF AIR	
										MOVEMENT.	
										TOOLS REQUIRED:	R02
										WEIGH ON WHEEL SCALES	
								0F66-07365	ETE	LAPTOP/INCLINOMETER TEST HARNESS	
										LAPTOP COMPUTER	
0010	049		413P		.00	400.00	0104			1. VERIFY WEIGHING KIT HAS BEEN CERTIFIED IN THE LAST	
										12 MONTHS.CONDUCT WEIGHING OPREATION IN CLOSED HANGER,	
										FREE OF AIR MOVEMENT.	
										2. DEFUEL AND DRIP AIRCRAFT IN NORMAL GROUND	

										ATTITUDE.	
										3. ALL ITEMS MUST BE IN THEIR STANDARD LOC. SEATS	
										ON TRACKS MUST BE FORWARD POSTION AGAINST STOPS,SEAT	
										BACKS IN MOST VERTICAL POSITION, SEAT BELTS CROSSED ON	
										SEAT CUSHION, FLAPS SHALL BE FULLY RETRACTED AND ALL	
										CONTROL SURFACES IN NEUTRAL POSITION WITH CONTROL	
										LOCK ENGAGED.	
										4. CHECK AIRCRAFT FOR ITEMS OF STANDARD OR OPTIONAL	
										EQUIPMENT THAT DISAGREE WITH AIRCRAFT ORDER (SHORTAGE	
										OR ADDITIONS). LIST THESE ITEMS ON WEIGHT SHEET WITH	
										DATE AND CHANGE NUMBER ON AIRCRAFT ORDER.	
										REF ENG DWG [redacted]:	
										5. ASSEMBLE FLOOR SCALES AND POSITION IN FRONT OF	
										WHEELS. INSTALL LEVELING DEVICE. CONNECT LAPTOP TO	R01
								0F66-07365	ETE	AIRCRAFT LEVELING DEVICE.	R02
										6. ROLL AIRCRAFT ONTO SCALES, SECURE AND REMOVE TUG	
										AND TOW BAR.	
										7. ENTER LEVELING DEVICE PLACARD OFFSET VALUES INTO	
										LAPTOP.	
										8. MEASURE OLEO EXTENTIONS AND ENTER INTO LAPTOP.	
										9. ENTER SCALE WEIGHT VALUES INTO LAPTOP	

0020	164		049A							INSPECT-WEIGH AIRCRAFT. VERIFY TARGET WEIGHT AND C/G	
										PER WEIGHTS GROUP MEMO. IF FALSE READING IS SUSPECTED	
0030	164		049A							ROTATE FLOOR SCALES AND REPEAT WEIGHING PROCEDURE.	
										TAKE (3) READINGS AT EACH POINT & RECORD THE MEAN ON	
										ATTACHED WEIGHT SHEET.SEND WEIGHT SHEET TO ENGINEERIN	
										WEIGHT GROUP FOR WEIGHT AND BALANCE REQUIRENENTS.	
0040	049		413P		.00	100.00	0104			1. UPON COMPLETION OF OPERATION, TURN OFF SWITCHES,	
										DISCONNECT CABLES AND RETURN EQUIPMENT TO CASE. RETURN	
										AIRCRAFT TO PRE-TEST CONDITION.	
0050	164		049A							INSPECT	

Appendix C Sample Mass Properties Database Entries

Table 2 Sample Mass Properties Database 1

MEMBER	WT	FS	BL	WL	% EST	% CAL	% ACT
c0422229	0.36	64.57	0	33.14	0	100	0
c0422280	0.02	65.73	0	35.83	0	100	0
c0422291	0.01	29.41	-24.36	33.12	0	100	0
c0422292	0.01	28.9	-59.52	32.73	0	100	0
c0422406	1.56	34.03	0	31.07	0	100	0
c0422411	1.14	33.96	0	31.03	0	100	0
c0422412	0.4	33.8	0	33.77	0	100	0
c0422414	2.18	33.87	0	33.62	0	100	0
c0422430	0.61	65.36	-12.62	35.43	0	100	0
c0423016	0.02	68.25	0	35.44	0	100	0
c0426011	0.56	40.68	0	36.16	0	100	0
c0520018	3.7	52.09	2	34.26	0	100	0
c0522107	0.15	32.55	-108.38	34.43	0	100	0
c0522109	0.24	26.14	-108.91	33.96	0	100	0
c0522110	0.22	27.5	-108.89	34.51	0	100	0
c0522111	0.24	32.55	-108.38	34.43	0	100	0
c0522112	0.23	27.51	-108.95	34.08	0	100	0
c0522113	0.02	26.96	-108.94	34.05	0	100	0
c0522114	0.08	27.84	-109	34.21	0	100	0
c0522116	0.3	28.15	-108.38	34.1	0	100	0
c0522200	0.14	25.2	0	32.6	0	100	0
c0522630	0.84	61.63	66.36	32.97	0	100	0
c0522638	1.82	48.59	0	31.92	0	100	0
c0522639	2.02	48.53	0	31.91	0	100	0
c0522640	2.08	50.78	0	36.18	0	100	0
c0522641	1.64	50.38	0	34.23	0	100	0
c0522642	1.02	49.2	0	28.61	0	100	0

Table 3 Sample Mass Properties Database 2

			WT	FS	BL	WL	% EST	%CAL	%ACT
1	999999	TOTAL AIR	1307.65	39.87	0.20	7.98	80.96	19.04	0.00
1	49999	TOTAL WINGS/STR	245.70	52.57	0.01	34.29	7.20	92.80	0.00
50000	79999	TOTAL EMPENNAGE	63.10	220.46	0.00	26.72	100.00	0.00	0.00
80000	109999	TOTAL FUSELAGE	203.90	68.96	0.00	2.00	100.00	0.00	0.00
110000	129999	TOTAL LANDING GEAR	153.70	43.43	0.00	-24.18	100.00	0.00	0.00
130000	149999	TOTAL CONTROLS	38.60	61.53	0.72	13.94	64.82	35.18	0.00
150000	209999	TOTAL PROPULSION	384.90	-16.41	-0.07	4.21	98.85	1.15	0.00
210000	229999	TOTAL INSTRUMENT	11.30	19.87	-2.65	13.70	95.53	4.07	0.00
240000	249999	TOTAL ELECTRICAL	35.14	3.16	-7.23	23.24	93.34	6.66	0.00
250000	259999	TOTAL AVIONICS	33.21	40.63	0.00	0.00	100.00	0.00	0.00
280000	309999	TOTAL FURN & EQ	133.50	51.62	0.00	9.93	100.00	0.00	0.00
310000	319999	TOTAL VENT & A/C	4.60	-12.37	0.00	-4.32	95.65	4.35	0.00

Appendix D Analytic Method Data

Table 4 Analytic Method Spreadsheet Data

	Basic		Optional Equipment		Standard Empty Weight				Anticipated	
Serial	Act BE CG	Act BEW	Opt Wt	Opt CG	SEW	SEW CG	10 Plane SEW	10 Plane SEW CG	Ant BEW	Ant BEW CG
1	39.431	2374	8.02	39.04	2365.98	39.43	2052.42	38.35	2060.45	38.35
2	38.099	2018	11.39	35.03	2006.61	38.12	2052.42	38.35	2063.81	38.33
3	37.178	2022	11.42	34.18	2010.58	37.20	2052.42	38.35	2063.84	38.33
4	37.802	2022	5.78	36.94	2016.22	37.80	2052.42	38.35	2058.20	38.34
5	37.916	2021	6.98	36.55	2014.02	37.92	2052.42	38.35	2059.40	38.34
6	38.679	2072	5.92	37.80	2066.08	38.68	2052.42	38.35	2058.34	38.35
7	38.551	2001	6.89	38.05	1994.11	38.55	2052.42	38.35	2059.31	38.35
8	38.41	2001	11.37	36.03	1989.63	38.42	2052.42	38.35	2063.79	38.34
9	38.659	2090	11.84	37.38	2078.16	38.67	2052.42	38.35	2064.26	38.34
10	38.676	1990	7.19	34.58	1982.81	38.69	2052.42	38.35	2059.61	38.34
11	38.654	2131	12.07	37.38	2118.93	38.66	2017.26	38.37	2029.33	38.37
12	37.988	2019	6.48	36.88	2012.52	37.99	2017.26	38.37	2023.74	38.37
13	38.127	2002	6.75	35.53	1995.25	38.14	2017.26	38.37	2024.02	38.36
14	38.205	1994	8.08	35.16	1985.92	38.22	2017.26	38.37	2025.34	38.36
15	38.668	2021	7.14	37.46	2013.86	38.67	2017.26	38.37	2024.40	38.37
16	38.401	1985	7.04	37.26	1977.96	38.41	2017.26	38.37	2024.30	38.37
17	38.453	2115	6.94	37.33	2108.06	38.46	2017.26	38.37	2024.20	38.37
18	38.459	2067	9.50	38.85	2057.50	38.46	2017.26	38.37	2026.76	38.38
19	38.233	1948	10.83	36.81	1937.17	38.24	2017.26	38.37	2028.10	38.36
20	38.489	1972	6.54	37.86	1965.46	38.49	2017.26	38.37	2023.81	38.37
21	38.569	1969	9.23	34.31	1959.77	38.59	2049.90	38.21	2059.13	38.20
22	35.901	2019	7.00	35.47	2012.00	35.90	2049.90	38.21	2056.91	38.21
23	38.602	2079	7.21	38.14	2071.79	38.60	2049.90	38.21	2057.12	38.21
24	38.618	1998	7.28	37.06	1990.72	38.62	2049.90	38.21	2057.19	38.21
25	38.498	1993	6.58	37.18	1986.42	38.50	2049.90	38.21	2056.49	38.21
26	38.583	2125	7.37	38.13	2117.63	38.58	2049.90	38.21	2057.28	38.21
27	38.445	2094	7.63	36.89	2086.37	38.45	2049.90	38.21	2057.54	38.21
28	38.695	2087	7.72	37.61	2079.28	38.70	2049.90	38.21	2057.62	38.21
29	38.599	1968	6.73	37.05	1961.27	38.60	2049.90	38.21	2056.63	38.21
30	37.581	2242	8.20	36.09	2233.80	37.59	2049.90	38.21	2058.10	38.21

Appendix E Current Method Data

Table 5 Current Method Spreadsheet Data

	206H		Basic						Fleet History				CSPS-011 Allowance	
Serial	A	B	Act BEW CG	Left Main	Right Main	Nose	Act BEW	Fleet Wt BEW	Fleet BEW CG	Delta Fleet Wt	Delta Fleet CG	.5% MAC	.7% WT
1	62	69.66	39.431	815	813	746	2374	2061.10	38.34	-312.90	-1.09	0.29	14.43
2	61.7	69.28	38.099	639	649	730	2018	2061.10	38.34	43.10	0.24	0.29	14.43
3	62	69.62	37.178	637	651	734	2022	2061.10	38.34	39.10	1.16	0.29	14.43
4	61.74	70.38	37.802	649	646	727	2022	2061.10	38.34	39.10	0.54	0.29	14.43
5	61.75	70.42	37.916	655	643	723	2021	2061.10	38.34	40.10	0.42	0.29	14.43
6	61.88	70.7	38.679	653	685	734	2072	2061.10	38.34	-10.90	-0.34	0.29	14.43
7	61.94	70.95	38.551	627	635	739	2001	2061.10	38.34	60.10	-0.21	0.29	14.43
8	62	70.67	38.41	623	630	748	2001	2061.10	38.34	60.10	-0.07	0.29	14.43
9	61.7	70.46	38.659	670	682	738	2090	2061.10	38.34	-28.90	-0.32	0.29	14.43
10	61.65	70.58	38.676	614	630	746	1990	2061.10	38.34	71.10	-0.34	0.29	14.43
11	61.9	69.67	38.654	705	708	718	2131	2025.40	38.37	-105.60	-0.29	0.29	14.18
12	61.8	69.56	37.988	638	646	735	2019	2025.40	38.37	6.40	0.38	0.29	14.18
13	61.94	69.58	38.127	637	646	719	2002	2025.40	38.37	23.40	0.24	0.29	14.18
14	61.85	69.46	38.205	622	641	731	1994	2025.40	38.37	31.40	0.16	0.29	14.18
15	61.9	70.67	38.668	642	656	723	2021	2025.40	38.37	4.40	-0.30	0.29	14.18
16	61.72	69.65	38.401	633	622	730	1985	2025.40	38.37	40.40	-0.03	0.29	14.18
17	61.7	70.48	38.453	681	699	735	2115	2025.40	38.37	-89.60	-0.09	0.29	14.18
18	61.6	70.6	38.459	664	668	735	2067	2025.40	38.37	-41.60	-0.09	0.29	14.18
19	61.4	70.1	38.233	588	610	750	1948	2025.40	38.37	77.40	0.13	0.29	14.18
20	61.5	70	38.489	599	622	751	1972	2025.40	38.37	53.40	-0.12	0.29	14.18
21	61.7	70.8	38.569	599	615	755	1969	2057.40	38.21	88.40	-0.36	0.29	14.40
22	61.66	69.36	35.901	612	653	754	2019	2057.40	38.21	38.40	2.31	0.29	14.40
23	61.7	70.5	38.602	667	673	739	2079	2057.40	38.21	-21.60	-0.39	0.29	14.40
24	61.7	70.65	38.618	622	625	751	1998	2057.40	38.21	59.40	-0.41	0.29	14.40
25	61.6	70.6	38.498	617	624	752	1993	2057.40	38.21	64.40	-0.29	0.29	14.40
26	61.94	69.78	38.583	704	722	699	2125	2057.40	38.21	-67.60	-0.37	0.29	14.40
27	61.8	70.66	38.445	683	699	712	2094	2057.40	38.21	-36.60	-0.24	0.29	14.40
28	62.05	69.68	38.695	689	665	733	2087	2057.40	38.21	-29.60	-0.49	0.29	14.40
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Appendix F Godwin Method Data

Table 6 Godwin Method Spreadsheet Data

L_{zm}	P_n	L	WT	θ	$\cos^2\theta$	$\tan\theta$	L_m	Godwin CG	Fleet Wt BEW	Fleet BEW CG
7.98	744	69.66	2374	4	1.00	0.07	22.50	39.50	2061.10	38.34
7.98	729	69.28	2018	3	1.00	0.05	25.51	36.19	2061.10	38.34
7.98	732	69.62	2022	3.8	1.00	0.07	25.86	36.14	2061.10	38.34
7.98	725	70.38	2022	3.7	1.00	0.06	25.87	35.87	2061.10	38.34
7.98	721	70.42	2021	4.1	0.99	0.07	25.83	35.92	2061.10	38.34
7.98	732	70.7	2072	4.5	0.99	0.08	25.75	36.13	2061.10	38.34
7.98	737	70.95	2001	4.2	0.99	0.07	26.86	35.08	2061.10	38.34
7.98	745	70.67	2001	4.7	0.99	0.08	27.16	34.84	2061.10	38.34
7.98	735	70.46	2090	4.9	0.99	0.09	25.66	36.04	2061.10	38.34
7.98	743	70.58	1990	5	0.99	0.09	27.26	34.39	2061.10	38.34
7.98	717	69.67	2131	3.3	1.00	0.06	23.97	37.93	2025.40	38.37
7.98	734	69.56	2019	3.2	1.00	0.06	25.81	35.99	2025.40	38.37
7.98	717	69.58	2002	4.1	0.99	0.07	25.63	36.31	2025.40	38.37
7.98	730	69.46	1994	3.6	1.00	0.06	26.02	35.83	2025.40	38.37
7.98	720	70.67	2021	4.9	0.99	0.09	26.06	35.84	2025.40	38.37
7.98	729	69.65	1985	3.6	1.00	0.06	26.17	35.55	2025.40	38.37
7.98	734	70.48	2115	3.3	1.00	0.06	24.99	36.71	2025.40	38.37
7.98	733	70.6	2067	4.7	0.99	0.08	25.85	35.75	2025.40	38.37
7.98	748	70.1	1948	4.5	0.99	0.08	27.70	33.70	2025.40	38.37
7.98	749	70	1972	4.5	0.99	0.08	27.37	34.13	2025.40	38.37
7.98	752	70.8	1969	5	0.99	0.09	27.95	33.75	2057.40	38.21
7.98	752	69.36	2019	4.2	0.99	0.07	26.56	35.10	2057.40	38.21
7.98	737	70.5	2079	4.1	0.99	0.07	25.70	36.00	2057.40	38.21
7.98	749	70.65	1998	4	1.00	0.07	27.18	34.52	2057.40	38.21
7.98	750	70.6	1993	4.6	0.99	0.08	27.37	34.23	2057.40	38.21
7.98	698	69.78	2125	3.2	1.00	0.06	23.44	38.50	2057.40	38.21
7.98	711	70.66	2094	3.7	1.00	0.06	24.59	37.21	2057.40	38.21
7.98	732	69.68	2087	3.1	1.00	0.05	24.94	37.11	2057.40	38.21
7.98	757	70.3	1968	3	1.00	0.05	27.53	34.47	2057.40	38.21
7.98	773	70	2242	4.6	0.99	0.08	24.92	36.78	2057.40	38.21

Appendix G Weigh on Wheels Method Data

Table 7 Weigh on Wheels Method Spreadsheet Data

L_{zm}	P_n	L_{no}	WT	θ	WoW CG	Fleet Wt BEW	Fleet BEW CG
7.98	745	2.45	2374	3	40.03	2061.10	36.65
7.98	729	3	2018	3	36.44	2061.10	36.65
7.98	732	3.15	2022	3.8	36.51	2061.10	36.65
7.98	725	2.34	2022	3.7	36.55	2061.10	36.65
7.98	721	4	2021	4.1	36.52	2061.10	36.65
7.98	732	3.6	2072	4.5	36.85	2061.10	36.65
7.98	737	2.6	2001	4.2	35.98	2061.10	36.65
7.98	745	1.5	2001	4.7	35.71	2061.10	36.65
7.98	735	4	2090	4.9	36.65	2061.10	36.65
7.98	743	1.8	1990	5	35.22	2061.10	36.65
7.98	717	2.2	2131	3.3	38.34	2025.40	36.29
7.98	734	1.7	2019	3.2	36.42	2025.40	36.29
7.98	717	4	2002	4.1	36.62	2025.40	36.29
7.98	730	3.9	1994	3.6	36.10	2025.40	36.29
7.98	720	4.2	2021	4.9	36.52	2025.40	36.29
7.98	729	1.8	1985	3.6	36.02	2025.40	36.29
7.98	734	2.7	2115	3.3	37.38	2025.40	36.29
7.98	733	2.3	2067	4.7	36.51	2025.40	36.29
7.98	748	2	1948	4.5	34.35	2025.40	36.29
7.98	749	3.3	1972	4.5	34.65	2025.40	36.29
7.98	752	4	1969	5	34.54	2057.40	36.35
7.98	752	3.6	2019	4.2	35.36	2057.40	36.35
7.98	737	4.8	2079	4.1	36.58	2057.40	36.35
7.98	749	3	1998	4	35.30	2057.40	36.35
7.98	750	1.8	1993	4.6	35.07	2057.40	36.35
7.98	698	2	2125	3.2	38.95	2057.40	36.35
7.98	711	3	2094	3.7	37.92	2057.40	36.35
7.98	732	1.4	2087	3.1	37.59	2057.40	36.35
7.98	757	4.5	1968	3	35.04	2057.40	36.35
7.98	773	4.4	2242	4.6	37.20	2057.40	36.35

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