

# CHAPTER 4

## WEIGHT AND BALANCE AND AIRPLANE PERFORMANCE

### INTRODUCTION

Airplane performance is the capability of the airplane, if operated within its limitations, to accomplish maneuvers which serve a specific purpose. For example, most present-day airplanes are designed clean and sleek, which results in greater range, speed, payload, and increased efficiency. This type of airplane is preferred for cross-country flights. Airplanes used for short flights and carrying heavy loads, such as those used in certain agricultural operations, are designed differently, but still exhibit good performance for their purpose. Some of the factors which represent good performance are short takeoff and landing distance, increased climb capability, and greater speeds using less fuel.

Because of its effect on performance, airplane weight and balance information is included in this chapter. Also included is an introduction to determining takeoff, cruise, and landing performance. For information relating to weight and balance, takeoff, cruise, and landing performance for a specific make and model of airplane, reference should be made to that Airplane's Flight Manual or Pilot's Operating Handbook.

### WEIGHT CONTROL

Weight is the force with which gravity attracts a body toward the center of the Earth. It is a product of the mass of a body and the acceleration acting on the body. Weight is a major problem in airplane construction and operation, and demands respect from all pilots.

The force of gravity continually attempts to pull the airplane down toward Earth. The force of lift is the only force that counteracts weight and sustains the airplane in flight. However, the amount of lift produced by an airfoil is limited by the airfoil design, angle of attack, airspeed, and air density. Therefore, to assure that the lift generated is sufficient to counteract weight, loading the airplane beyond the manufacturer's recommended weight must be avoided. If the weight is greater than the lift generated, altitude cannot be maintained.

#### Effects of Weight

Any item aboard the airplane which increases the total weight significantly is undesirable as far as performance is concerned. Manufacturers attempt to make the airplane as light as possible without sacrificing strength or safety.

The pilot of an airplane should always be aware of the consequences of overloading. An overloaded airplane may not be able to leave the ground, or if it does become airborne, it may exhibit unexpected and unusually poor flight characteristics. If an airplane is not properly loaded, the initial indication of poor performance usually takes place during takeoff.

Excessive weight reduces the flight performance of an airplane in almost every respect. The most important performance deficiencies of the overloaded airplane are:

- Higher takeoff speed.
- Longer takeoff run.
- Reduced rate and angle of climb.
- Lower maximum altitude.
- Shorter range.
- Reduced cruising speed.
- Reduced maneuverability.
- Higher stalling speed.
- Higher landing speed.
- Longer landing roll.
- Excessive weight on the nosewheel.

The pilot must be knowledgeable in the effect of weight on the performance of the particular airplane being flown. Preflight planning should include a check of performance charts to determine if the airplane's weight may contribute to hazardous flight operations. Excessive weight in itself reduces the safety margins available to the pilot, and becomes even more hazardous when other performance-reducing factors are combined with overweight. The pilot must also consider the consequences of an overweight airplane if an emergency condition arises. If an engine fails on takeoff or ice forms at low altitude, it is usually too late to reduce the airplane's weight to keep it in the air.

### Weight Changes

The weight of the airplane can be changed by altering the fuel load. Gasoline has considerable weight—6 pounds per gallon—30 gallons may weigh more than one passenger. But it must be remembered that if weight is lowered by reducing fuel, the range of the airplane is decreased. During flight, fuel burn is normally the only weight change that takes place. As fuel is used, the airplane becomes lighter and performance is improved.

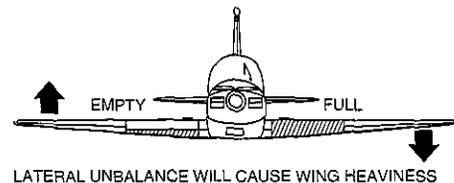
Changes of fixed equipment have a major effect upon the weight of the airplane. An airplane can be overloaded by the installation of extra radios or instruments. Repairs or modifications usually affect the weight of the airplane.

## BALANCE, STABILITY, AND CENTER OF GRAVITY

Balance refers to the location of the center of gravity (CG) of an airplane, and is important to airplane stability and safety in flight. The center of gravity is a point at which an airplane would balance if it were suspended at that point.

The prime concern of airplane balancing is the fore and aft location of the CG along the longitudinal axis. Location of the CG with reference to the lateral axis is also important. For each item of weight existing to the left of the fuselage centerline, there is an equal weight existing at a corresponding location on the right. This may be upset, however, by unbalanced lateral loading. The position of the lateral CG is not computed, but the pilot must be aware that adverse effects will certainly arise as a result of a laterally unbalanced condition. Lateral unbalance will occur if the fuel load is mismanaged by supplying the engine(s) unevenly from tanks on one side of the airplane. The pilot can compensate for the resulting

wing-heavy condition by adjusting the aileron trim tab or by holding a constant aileron control pressure. However, this places the airplane controls in an out-of-streamline condition, increases drag, and results in decreased operating efficiency. Since lateral balance is relatively easy to control and longitudinal balance is more critical, further reference to balance in this handbook will mean longitudinal location of the center of gravity. [Figure 4-1]



LONGITUDINAL UNBALANCE WILL CAUSE EITHER NOSE OR TAIL HEAVINESS

**FIGURE 4-1.—Lateral or longitudinal unbalance.**

The center of gravity is not necessarily a fixed point; its location depends on the distribution of weight in the airplane. As variable load items are shifted or expended, there is a resultant shift in CG location. The pilot should realize that if the CG of an airplane is displaced too far forward on the longitudinal axis, a nose-heavy condition will result. Conversely, if the CG is displaced too far aft on the longitudinal axis, a tail-heavy condition will result. It is possible that an unfavorable location of the CG could produce such an unstable condition that the pilot could not control the airplane. [Figure 4-1]

In any event, flying an airplane which is out of balance can produce increased pilot fatigue with obvious effects on the safety and efficiency of flight. The pilot's natural correction for longitudinal unbalance is a change of trim to remove the excessive control pressure. Excessive trim, however, has the effect of not only reducing aerodynamic efficiency but also reducing primary control travel distance in the direction the trim is applied.

### Effects of Adverse Balance

Adverse balance conditions affect airplane flight characteristics in much the same manner as those mentioned for an excess weight condition. In addition, there are two essential airplane characteristics which may be seriously affected by improper balance; these are stability and control. Loading in a nose-heavy condition causes problems in controlling and raising

the nose, especially during takeoff and landing. Loading in a tail-heavy condition has a most serious effect upon longitudinal stability, and can reduce the airplane's capability to recover from stalls and spins. Another undesirable characteristic produced from tail-heavy loading is that it produces very light control forces. This makes it easy for the pilot to inadvertently overstress the airplane.

Limits for the location of the airplane's center of gravity are established by the manufacturer. These are the fore and aft limits beyond which the CG should not be located for flight. These limits are published for each airplane in the Type Certification Data Sheet or Aircraft Specification. If, after loading, the CG is not within the allowable limits, it will be necessary to relocate some items within the airplane before flight is attempted.

The forward center of gravity limit is often established at a location which is determined by the landing characteristics of the airplane. It may be possible to maintain stable and safe cruising flight if the CG is located ahead of the prescribed forward limit; but during landing which is one of the most critical phases of flight, exceeding the forward CG limit may cause problems. Manufacturers purposely place the forward CG limit as far rearward as possible to aid pilots in avoiding damage to the airplane when landing.

A restricted forward center of gravity limit is also specified to assure that sufficient elevator deflection is available at minimum airspeed. When structural limitations or large stick forces do not limit the forward CG position, it is located at the position where full-up elevator is required to obtain a high angle of attack for landing.

The aft center of gravity limit is the most rearward position at which the CG can be located for the most critical maneuver or operation. As the CG moves aft, a less stable condition occurs which decreases the ability of the airplane to right itself after maneuvering or after disturbances by gusts.

For some airplanes the CG limits, both fore and aft, may be specified to vary as gross weight changes. They may also be changed for certain operations such as acrobatic flight, retraction of the landing gear, or the installation of special loads and devices which change the flight characteristics.

The actual location of the CG can be altered by many variable factors and is usually controlled by the pilot. Placement of baggage and cargo items determine the CG location. The assignment of seats to passengers can also be used as a means of obtaining a favorable balance. If the airplane is tail-heavy, it is only logical to place heavy passengers in forward seats.

## Management of Weight and Balance Control

Weight and balance control should be a matter of concern to all pilots. The pilot has control over loading and fuel management (the two variable factors which can change both total weight and CG location) of a particular airplane.

The airplane owner or operator should make certain that up-to-date information is available in the airplane for the pilot's use, and should ensure that appropriate entries are made in the airplane records when repairs or modifications have been accomplished. Weight changes must be accounted for and the proper notations made in weight and balance records. The equipment list must be updated if appropriate. Without such information, the pilot has no foundation upon which to base the necessary calculations and decisions.

## Terms and Definitions

The pilot should be familiar with terms used in working the problems related to weight and balance. The following list of terms and their definitions is well standardized, and knowledge of these terms will aid the pilot to better understand weight and balance calculations of any airplane.

- **Arm (moment arm)**—is the horizontal distance in inches from the reference datum line to the center of gravity of an item. The algebraic sign is plus (+) if measured aft of the datum, and minus (-) if measured forward of the datum.
- **Center of gravity (CG)**—is the point about which an airplane would balance if it were possible to suspend it at that point. It is the mass center of the airplane, or the theoretical point at which the entire weight of the airplane is assumed to be concentrated. It may be expressed in inches from the reference datum, or in percent of mean aerodynamic chord (MAC).
- **Center of gravity limits**—are the specified forward and aft points within which the CG must be located during flight. These limits are indicated on pertinent airplane specifications.
- **Center of gravity range**—is the distance between the forward and aft CG limits indicated on pertinent airplane specifications.
- **Datum (reference datum)**—is an imaginary vertical plane or line from which all measurements of arm are taken. The datum is established by the manufacturer. Once the datum has been selected, all moment arms and the location of CG range are measured from this point.

- **Delta**—is a Greek letter expressed by the symbol  $\Delta$  to indicate a change of values. As an example,  $\Delta$  CG indicates a change (or movement) of the CG.
- **Fuel load**—is the expendable part of the load of the airplane. It includes only usable fuel, not fuel required to fill the lines or that which remains trapped in the tank sumps.
- **Moment**—is the product of the weight of an item multiplied by its arm. Moments are expressed in pound-inches (lb-in). Total moment is the weight of the airplane multiplied by the distance between the datum and the CG.
- **Moment index (or index)**—is a moment divided by a constant such as 100, 1,000, or 10,000. The purpose of using a moment index is to simplify weight and balance computations of airplanes where heavy items and long arms result in large, unmanageable numbers.
- **Mean aerodynamic chord (MAC)**—is the average distance from the leading edge to the trailing edge of the wing.
- **Standard weights**—have been established for numerous items involved in weight and balance computations. These weights should not be used if actual weights are available. Some of the standard weights are:

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General aviation—crew and passenger.....	170 lb each
Gasoline .....	6 lb/US gal
Oil .....	7.5 lb/US gal
Water .....	8.35 lb/US gal

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- **Station**—is a location in the airplane which is identified by a number designating its distance in inches from the datum. The datum is, therefore, identified as station zero. An item located at station +50 would have an arm of 50 inches.
- **Useful load**—is the weight of the pilot, copilot, passengers, baggage, usable fuel, and drainable oil. It is the empty weight subtracted from the maximum allowable gross weight. This term applies to general aviation aircraft only.
- **Weight, basic empty**—consists of the airframe, engines, and all items of operating equipment that have fixed locations and are permanently installed in the airplane. It includes optional and special equipment, fixed ballast, hydraulic fluid, unusable (residual) fuel, and full engine oil (some older aircraft only include undrainable residual oil; refer to the aircraft weight and balance documents).

## Control of Loading—General Aviation Airplanes

Before any flight, the pilot should determine the weight and balance condition of the airplane. Simple and orderly procedures, based on sound principles, have been devised by airplane manufacturers for the determination of loading conditions. The pilot must use these procedures and exercise good judgment. In many modern airplanes, it is not possible to fill all seats, baggage compartments, and fuel tanks, and still remain within the approved weight and balance limits. If the maximum passenger load is carried, the pilot must often reduce the fuel load or reduce the amount of baggage.

## Basic Principles of Weight and Balance Computations

It might be advantageous at this point to review and discuss some of the basic principles of how weight and balance can be determined. The following method of computation can be applied to any object or vehicle where weight and balance information is essential; but to fulfill the purpose of this handbook, it is directed primarily toward the airplane.

By determining the weight of the empty airplane and adding the weight of everything loaded on the airplane, a total weight can be determined. This is quite simple; but to distribute this weight in such a manner that the entire mass of the loaded airplane is balanced around a point (CG) which must be located within specified limits presents a greater problem, particularly if the basic principles of weight and balance are not understood.

The point where the airplane will balance can be determined by locating the center of gravity, which is, as stated in the definitions of terms, the imaginary point where all the weight is concentrated. To provide the necessary balance between longitudinal stability and elevator control, the center of gravity is usually located slightly forward of the center of lift. This loading condition causes a nosedown tendency in flight, which is desirable during flight at a high angle of attack and slow speeds.

A safe zone within which the balance point (CG) must fall is called the CG range. The extremities of the range are called the forward CG limits and aft CG limits. These limits are usually specified in inches, along the longitudinal axis of the airplane, measured from a datum reference. The datum is an arbitrary point, established by airplane designers, which may vary in location between different airplanes. [Figure 4-2]

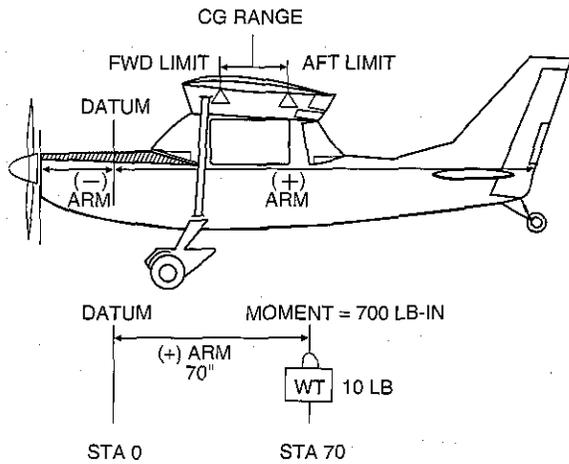
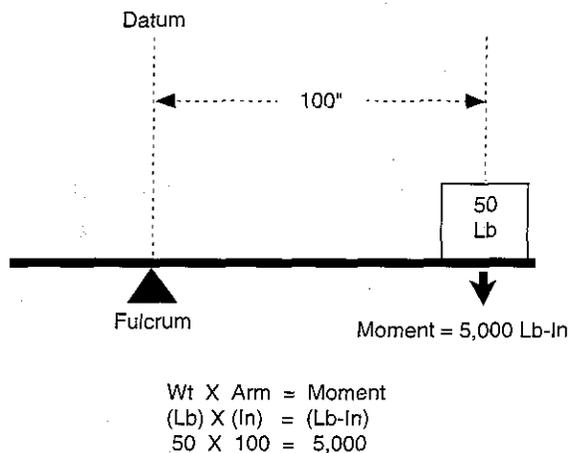


FIGURE 4-2.—Weight and balance illustrated.

The distance from the datum to any component part of the airplane, or any object loaded on the airplane, is called the arm. When the object or component is located aft of the datum, it is measured in positive inches; if located forward of the datum, it is measured as negative inches, or minus inches. The location of the object or part is often referred to as the station. If the weight of any object or component is multiplied by the distance from the datum (arm), the product is the moment. The moment is the measurement of the gravitational force which causes a tendency of the weight to rotate about a point or axis and is expressed in pound-inches. [Figure 4-2]

To illustrate, assume a weight of 50 pounds is placed on the board at a station or point 100 inches from the datum. The downward force of the weight can be determined by multiplying 50 pounds by 100 inches, which produces a moment of 5,000 lb-in. [Figure 4-3]



Note: The datum is assumed to be located at the fulcrum.

FIGURE 4-3.—Determining moments.

To establish a balance, a total of 5,000 lb-in must be applied to the other end of the board. Any combination of weight and distance which, when multiplied, produces 5,000 lb-in moment will balance the board. For example, as illustrated in figure 4-4, if a 100-pound weight is placed at a point (station) 25 inches from the datum, and another 50-pound weight is placed at a point (station) 50 inches from the datum, the sum of the product of the two weights and their distances will total a moment of 5,000 lb-in which will balance the board.

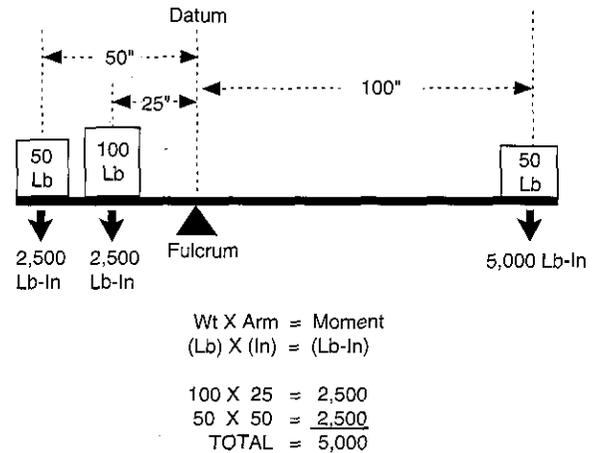


FIGURE 4-4.—Establishing a balance.

## Weight and Balance Restrictions

The airplane's weight and balance restrictions should be closely followed. The loading conditions and empty weight of a particular airplane may differ from that found in the Airplane Flight Manual or Pilot's Operating Handbook because modifications or equipment changes may have been made. Sample loading problems in the Airplane Flight Manual or Pilot's Operating Handbook are intended for guidance only; therefore, each airplane must be treated separately. Although an airplane is certified for a specified maximum gross takeoff weight, it will not safely take off with this load under all conditions. Conditions which affect takeoff and climb performance such as high elevations, high temperatures, and high humidity (high density altitudes) may require a reduction in weight before flight is attempted. Other factors to consider prior to takeoff are runway length, runway surface, runway slope, surface wind, and the presence of obstacles. These factors may require a reduction in weight prior to flight.

Some airplanes are designed so that it is impossible to load them in a manner that will place the CG out of limits. These are usually small airplanes

with the seats, fuel, and baggage areas located near the CG limit. These airplanes, however, can be overloaded in weight.

Other airplanes can be loaded in such a manner that they will be out of CG limits even though the useful load has not been exceeded.

Because of the effects of an out-of-balance or overweight condition, a pilot should always be sure that an airplane is properly loaded.

## DETERMINING LOADED WEIGHT AND CENTER OF GRAVITY

There are various methods for determining the loaded weight and center of gravity of an aircraft. There is the computation method, as well as methods which utilize graphs and tables provided by the aircraft manufacturer.

### Computational Method

The computational method involves the application of basic math functions. The following is an example of the computational method:

#### Given:

Maximum Gross Weight .....	3400 lb
Center-of-Gravity Range .....	78-86 in
Front Seat Occupants .....	340 lb
Rear Seat Occupants .....	350 lb
Fuel .....	75 gal
Baggage Area 1 .....	80 lb

To determine the loaded weight and CG, follow these steps.

**Step 1**—List the weight of the aircraft, occupants, fuel, and baggage. Remember, fuel weighs 6 pounds per gallon.

**Step 2**—Enter the moment for each item listed. Remember “weight x arm = moment.” To simplify calculations, the moments are divided by 100.

**Step 3**—Total the weight and moments.

**Step 4**—To determine the CG, divide the moments by the weight.

**NOTE:** The weight and balance records for a particular aircraft will provide the empty weight and moment as well as the information on the arm distance.

	Weight	Arm	Moment/100
Airplane Empty Weight	2100	78.3	1652.1
Front Seat Occupants	340	85.0	289.0
Rear Seat Occupants	350	121.0	423.5
Fuel	450	75.0	337.5
Baggage Area 1	80.0	150.0	120.0
<b>Total</b>	<b>3330</b>		<b>2822.1/100</b>
			2822.1/100 divided by 3330 = 84.7

The total loaded weight of 3,330 pounds does not exceed the maximum gross weight of 3,400 pounds and the CG of 84.7 is within the 78-86 inch range; therefore, the aircraft is loaded within limits.

### Graph Method

Another method used to determine the loaded weight and CG is the use of graphs provided by the manufacturers. The following is an example of the graph method. [Figures 4-5 and 4-6]

#### Given:

Front Seat Occupants .....	340 lb
Rear Seat Occupants .....	300 lb
Fuel .....	40 gal
Baggage Area 1 .....	20 lb

SAMPLE LOADING PROBLEM	SAMPLE AIRPLANE	
	Weight (Lb)	(Lb-In/ 1000)
1. Basic Empty Weight (Use the data pertaining to your airplane as it is presently equipped.) Includes unusable fuel and full oil .....	1467	57.3
2. Usable Fuel (At 6 Lb/Gal)		
Standard Tanks (40 Gal Maximum) . . . .	240	11.5
Long Range Tanks (50 Gal Maximum) . .		
Integral Tanks (62 Gal Maximum) . . . .		
Integral Reduced Fuel (42 Gal) . . . . .		
3. Pilot and Front Passenger (Station 34 to 46) .	340	12.6
4. Rear Passengers . . . . .	300	21.8
5. Baggage Area 1 or Passenger on Child's Seat (Station 82 to 108, 120 Lb Max) . . . . .	20	1.9
6. Baggage Area 2 (Station 108 to 142, 50 Lb Max.) . . . . .		
7. WEIGHT AND MOMENT	2367	104.8

FIGURE 4-5.—Weight and balance data.

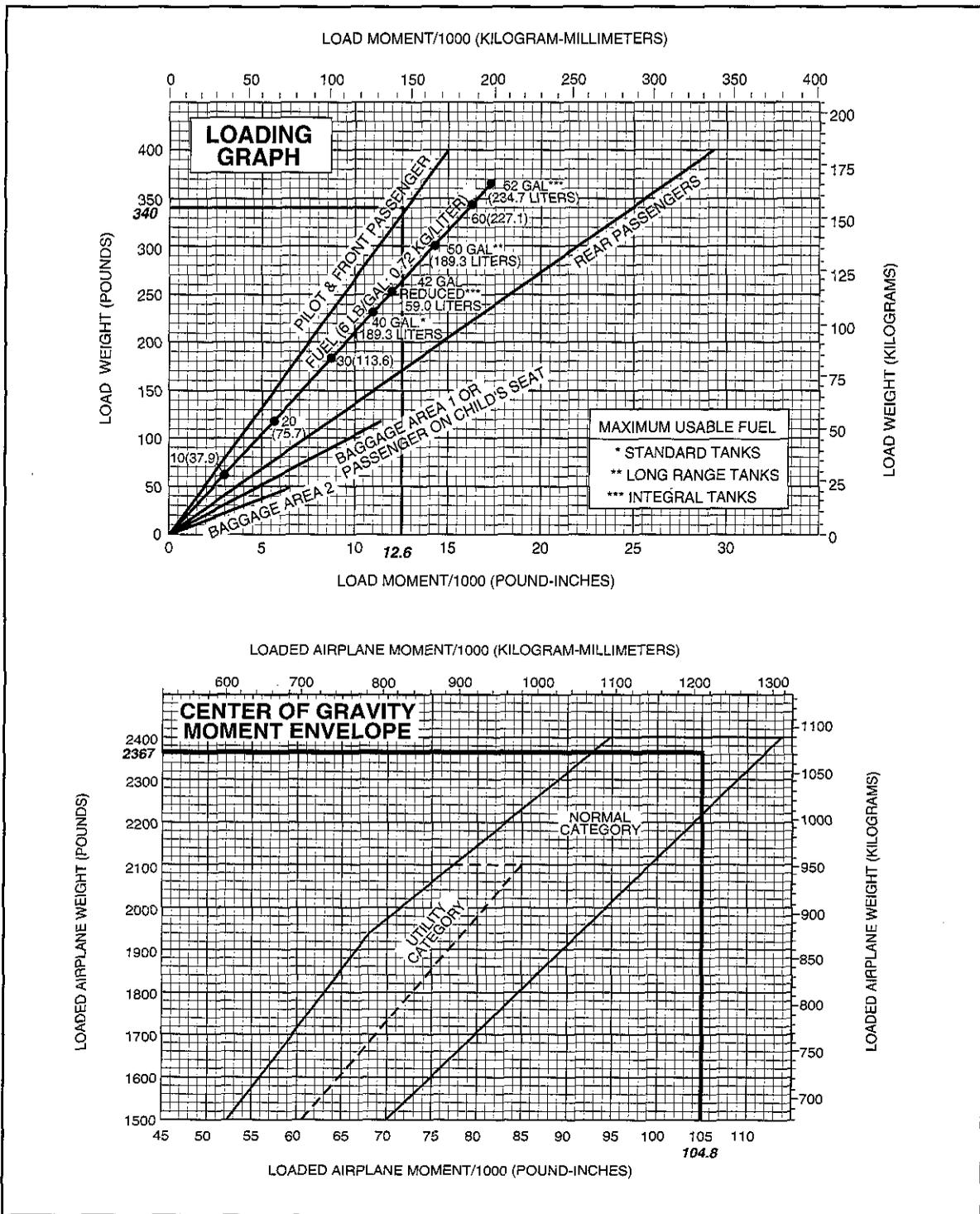
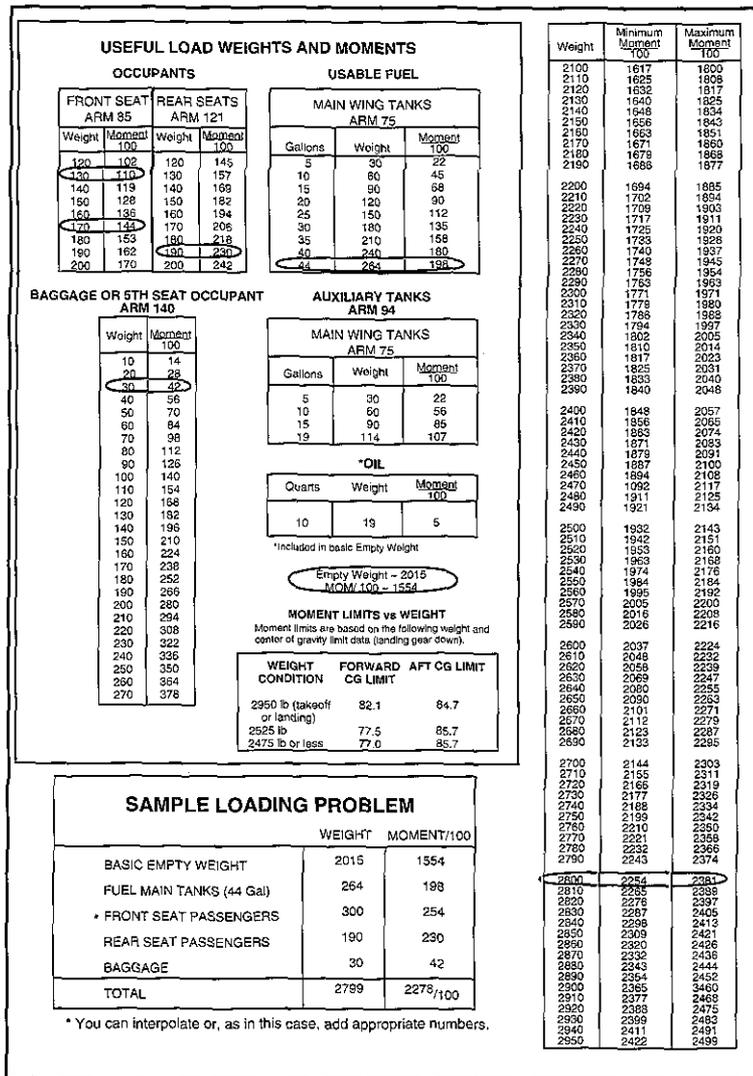


FIGURE 4-6.—CG moment envelope and loading graph.

The same steps should be followed as in the computational method except the graphs provided will calculate the moments and allow the pilot to determine if the aircraft is loaded within limits. To determine the moment using the loading graph, find the weight and draw a line straight across until it intercepts the item for which you are calculating the moment. Then draw a line straight down to determine the moment. (The red line on the loading graph represents the

moment for the pilot and front passenger. All other moments were determined in the same way.) Once this has been done for each item, total the weight and moments and draw a line for both weight and moment on the center-of-gravity envelope graph. If the lines intersect within the envelope, the aircraft is loaded within limits. In this sample loading problem, the aircraft is loaded within limits.



**FIGURE 4-7.—Loading schedule placard.**

### Table Method

The table method applies the same principles as the computational and graph methods. The information and limitations are contained in tables provided by the manufacturer. Figure 4-7 is an example of a table and a weight and balance calculation based on that table. In this problem, the total weight of 2,799 pounds and moment of 2,278/100 is within the limits of the table.

### Shifting, Adding, and Removing Weight

A pilot must be able to accurately and rapidly solve any problems which involve the shift, addition, or removal of weight. For example, the pilot may load the aircraft within the allowable takeoff weight limit, then find a CG limit has been exceeded. The most satisfactory solution to this problem is to shift baggage, passengers, or both. The pilot should be able to determine the minimum load shift needed to make the aircraft safe for flight. Pilots should be able to

determine if shifting a load to a new location will correct an out-of-limit condition. There are some standardized calculations which can help make these determinations.

### Weight Shifting

When weight is shifted from one location to another, the total weight of the aircraft is unchanged. The total moments, however, do change in relation and proportion to the direction and distance the weight is moved. When weight is moved forward, the total moments decrease; when weight is moved aft, total moments increase. The moment change is proportional to the amount of weight moved. Since many aircraft have forward and aft baggage compartments, weight may be shifted from one to the other to change the CG. If starting with a known aircraft weight, CG, and total moments, calculate the new CG (after the weight shift) by dividing the new total moments by the total aircraft weight.

To determine the new total moments, find out how many moments are gained or lost when the weight is shifted. Assume that 100 pounds has been shifted from station 30 to station 150. This movement increases the total moments of the aircraft by 12,000 lb-in.

Moment when  
 at station 150 = 100 lb x 150 in = 15,000 lb-in  
 Moment when  
 at station 30 = 100 lb x 30 in = 3,000 lb-in  
 Moment change = 12,000 lb-in

By adding the moment change to the original moment (or subtracting if the weight has been moved forward instead of aft), the new total moments are obtained. Then determine the new CG by dividing the new moments by the total weight:

$$\text{Total moments} = 616,000 + 12,000 = 628,000$$

$$\text{CG} = \frac{628,000}{8,000} = 78.5 \text{ in}$$

The shift has caused the CG to shift to station 78.5

A simpler solution may be obtained by using a computer or calculator and a proportional formula. This can be done because the CG will shift a distance which is proportional to the distance the weight is shifted.

**EXAMPLE**

$\frac{\text{Weight Shifted}}{\text{Total Weight}}$	=	$\frac{\Delta\text{CG (change of CG)}}{\text{Distance weight is shifted}}$
$\frac{100}{8,000}$	=	$\frac{\Delta\text{CG}}{120}$
$\Delta\text{CG}$	=	1.5 in

The change of CG is added to (or subtracted from when appropriate) the original CG to determine the new CG:

$$77 + 1.5 = 78.5 \text{ inches aft of datum}$$

The shifting weight proportion formula can also be used to determine how much weight must be shifted to achieve a particular shift of the CG. The following problem illustrates a solution of this type.

**EXAMPLE**

**Given:**

---

Aircraft Total Weight .....	7,800 lb
CG .....	Station 81.5
Aft CG Limit .....	80.5

---

Determine how much cargo must be shifted from the aft cargo compartment at station 150 to the forward cargo compartment at station 30 to move the CG to exactly the aft limit.

**Solution:**

---

$\frac{\text{Weight to be Shifted}}{\text{Total Weight}}$	=	$\frac{\Delta\text{CG}}{\text{Distance Weight Shifted}}$
$\frac{\text{Weight to be Shifted}}{7,800}$	=	$\frac{1.0 \text{ in}}{120 \text{ in}}$
Weight to be Shifted	=	65 lb

---

**Weight Addition or Removal**

In many instances, the weight and balance of the aircraft will be changed by the addition or removal of weight. When this happens, a new CG must be calculated and checked against the limitations to see if the location is acceptable. This type of weight and balance problem is commonly encountered when the aircraft burns fuel in flight, thereby reducing the weight located at the fuel tanks. Most small aircraft are designed with the fuel tanks positioned close to the CG; therefore, the consumption of fuel does not affect the CG to any great extent.

The addition or removal of cargo presents a CG change problem which must be calculated before flight. The problem may always be solved by calculations involving total moments. A typical problem may involve the calculation of a new CG for an aircraft which, when loaded and ready for flight, receives some additional cargo or passengers just before departure time.

**EXAMPLE**

**Given:**

---

Aircraft Total Weight .....	6,680 lb
CG Station .....	80.0

---

Determine the location of the CG if 140 pounds of baggage is added to station 150.

**Solution:**

$$\frac{\text{Added Weight}}{\text{New Total Weight}} = \frac{\Delta\text{CG}}{\text{Distance between weight and old CG}}$$

$$\frac{140}{6,860 + 140} = \frac{\Delta\text{CG}}{150 - 80}$$

$$\frac{140}{7,000} = \frac{\Delta\text{CG}}{70}$$

$$\text{CG} = 1.4 \text{ in aft}$$

Add  $\Delta\text{CG}$  to old CG

$$\text{New CG} = 80.0 \text{ in} + 1.4 \text{ in} = 81.4 \text{ in}$$

**EXAMPLE**

**Given:**

Aircraft Total Weight.....	6,100 lb
CG Station.....	80.0

Determine the location of the CG if 100 pounds is removed to station 150.

**Solution:**

$$\frac{\text{Weight Removed}}{\text{New Total Weight}} = \frac{\Delta\text{CG}}{\text{Distance between weight and old CG}}$$

$$\frac{100}{6,100 - 100} = \frac{\Delta\text{CG}}{150 - 78}$$

$$\frac{100}{6,000} = \frac{\Delta\text{CG}}{72}$$

$$\text{CG} = 1.2 \text{ in forward}$$

Subtract  $\Delta\text{CG}$  from old CG

$$\text{New CG} = 78 \text{ in} - 1.2 \text{ in} = 76.8 \text{ in}$$

In the previous examples, the  $\Delta\text{CG}$  is either added or subtracted from the old CG. Deciding which to accomplish is best handled by mentally calculating which way the CG will shift for the particular weight change. If the CG is shifting aft, the  $\Delta\text{CG}$  is added to the old CG; if the CG is shifting forward, the  $\Delta\text{CG}$  is subtracted from the old CG.

## AIRPLANE PERFORMANCE

Many accidents occur because pilots fail to understand the effect of varying conditions on airplane performance. In addition to the effects of weight and balance previously discussed, the following factors have a profound effect in changing airplane performance:

- Density Altitude
- Humidity
- Winds
- Runway Surface Conditions
- Runway Gradient

### Density Altitude

Air density is perhaps the single most important factor affecting airplane performance. It has a direct bearing on the power output of the engine, efficiency of the propeller, and the lift generated by the wings.

As previously discussed in this handbook, when the air temperature increases, the density of the air decreases. Also, as altitude increases, the density of the air decreases. The density of the air can be described by referring to a corresponding altitude; therefore, the term used to describe air density is density altitude. To avoid confusion, remember that a decrease in air density means a high density altitude; and an increase in air density means a lower density altitude. Density altitude is determined by first finding pressure altitude, and then correcting this altitude for nonstandard temperature variations. It is important to remember that as air density decreases (higher density altitude), airplane performance decreases; and as air density increases (lower density altitude), airplane performance increases.

### Effect of Density Altitude on Engine Power and Propeller Efficiency

An increase in air temperature or humidity, or decrease in air pressure resulting in a higher density altitude, significantly decreases power output and propeller efficiency.

The engine produces power in proportion to the weight or density of the air. Therefore, as air density decreases, the power output of the engine decreases. This is true of all engines that are not equipped with a supercharger or turbocharger. Also, the propeller produces thrust in proportion to the mass of air being

accelerated through the rotating blades. If the air is less dense, propeller efficiency is decreased.

The problem of high-density altitude operation is compounded by the fact that when the air is less dense, more engine power and increased propeller efficiency are needed to overcome the decreased lift efficiency of the airplane wing. This additional power and propeller efficiency are not available under high-density altitude conditions; consequently, airplane performance decreases considerably.

## **Humidity**

Because of evaporation, the atmosphere always contains some moisture in the form of water vapor. This water vapor replaces molecules of dry air and because water vapor weighs less than dry air, any given volume of moist air weighs less—is less dense—than an equal volume of dry air.

Usually during the operation of small airplanes, the effect of humidity is not considered when determining density altitude; but keep in mind that high humidity will decrease airplane performance which, among other things, results in longer takeoff distances and decreased angle of climb.

## **Effect of Wind on Airplane Performance**

Wind has a direct effect on airplane performance. During takeoff, a headwind will increase the airplane performance by shortening the takeoff distance and increasing the angle of climb. However, a tailwind will decrease performance by increasing the takeoff distance and reducing the angle of climb. The decrease in airplane performance must be carefully considered by the pilot before a downwind takeoff is attempted.

During landing, a headwind will increase airplane performance by steepening the approach angle and reducing the landing distance. A tailwind will decrease performance by decreasing the approach angle and increasing the landing distance. Again, the pilot must take the wind into consideration prior to landing.

During cruise flight, winds aloft have somewhat an opposite effect on airplane performance. A headwind will decrease performance by reducing groundspeed, which in turn increases the fuel requirement for the flight. A tailwind will increase performance by increasing the groundspeed, which in turn reduces the fuel requirement for the flight.

## **Runway Surface Condition and Gradient**

The takeoff distance is affected by the surface condition of the runway. If the runway is muddy, wet, soft, rough, or covered with tall grass, these conditions will act as a retarding force and increase the takeoff distance. Some of these surface conditions may decrease landing roll, but there are certain conditions such as ice or snow covering the surface that will affect braking action and increase the landing roll considerably.

The upslope or downslope of the runway (runway gradient) is quite important when runway length and takeoff distance are critical. Upslope provides a retarding force which impedes acceleration, resulting in a longer ground run on takeoff.

Landing uphill usually results in a shorter landing roll. Downhill operations will usually have the reverse effect of shortening the takeoff distance and increasing the landing roll.

## **Ground Effect**

When an airplane is flown at approximately one wing span or less above the surface, the vertical component of airflow is restricted and modified, and changes occur in the normal pattern of the airflow around the wing and from the wingtips. This change alters the direction of the relative wind in a manner that produces a smaller angle of attack. This means that a wing operating in ground effect with a given angle of attack will generate less induced drag than a wing out of ground effect. Therefore, it is more efficient. While this may be useful in specific situations, it can also trap the unwary into expecting greater climb performance than the airplane is capable of sustaining. In other words, an airplane can take off, and while in ground effect establish a climb angle and/or rate that cannot be maintained once the airplane reaches an altitude where ground effect can no longer influence performance. Conversely, on a landing, ground effect may produce "floating," and result in overshooting, particularly at fast approach speeds.

## **Use of Performance Charts**

Most airplane manufacturers provide adequate information from which the pilot can determine airplane performance. This information can be found in Airplane Flight Manuals or Pilot's Operating Handbooks. Two commonly used methods of depicting performance data are tables and graphs.

Because all values are not listed on the tables or graphs, interpolation is often required to determine intermediate values for a particular flight condition or performance situation. Interpolation will be discussed later in this chapter.

The information on airplane performance charts is based on flight tests conducted under normal operating conditions, using average piloting skills, with the airplane and engine in good operating condition. Any deviation from the above conditions will affect airplane performance.

The performance data extracted from performance charts is accurate. To attain this accuracy, reasonable care must be exercised when computing performance information. It is important to consider that the performance of an older airplane will be less than that predicted by the performance charts.

Standard atmospheric conditions (temperature 59 °F/15 °C, zero relative humidity, and a pressure of 29.92 in. Hg. at sea level) are used in the development of performance charts. This provides a base from which to evaluate performance when actual atmospheric conditions change.

## Interpolation

To interpolate means to compute intermediate values between a series of given values. In many instances when performance is critical, an accurate determination of the performance values is the only acceptable means to enhance safe flight. Guessing to determine these values should be avoided.

Interpolation is simple to perform if the method is understood. The following are examples of how to interpolate or accurately determine the intermediate values between a series of given values.

The numbers in column A range from 10 to 30 and the numbers in column B range from 50 to 100. Determine the intermediate numerical value in column B that would correspond with an intermediate value of 20 placed in column A.

A	B
10	50
20	X = Unknown
30	100

It can be visualized that 20 is halfway between 10 and 30; therefore, the corresponding value of the unknown number in column B would be halfway between 50 and 100, or 75.

Many interpolation problems are more difficult to visualize than the preceding example; therefore, a systematic method must be used to determine the required intermediate value. The following describes one method that can be used.

The numbers in Column A range from 10 to 30 with intermediate values of 15, 20, and 25. Determine the intermediate numerical value in column B that would correspond with 15 in column A.

A	B
10	50
15	
20	
25	
30	100

First, in column A, determine the relationship of 15 to the range between 10 and 30 as follows:

$$\frac{15 - 10}{30 - 10} = \frac{5}{20} \text{ or } 1/4$$

It should be noted that 15 is 1/4 of the range between 10 and 30. Now determine 1/4 of the range of column B between 50 and 100 as follows:

$$100 - 50 = 50$$

$$1/4 \text{ of } 50 = 12.5$$

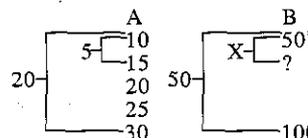
The answer 12.5 represents the number of units, but to arrive at the correct value, 12.5 must be added to the lower number in column B as follows:

$$50 + 12.5 = 62.5$$

The interpolation has been completed and 62.5 is the actual value which is 1/4 of the range of column B.

Another method of interpolation is shown below:

Using the same numbers as in the previous example, a proportion problem based on the relationship of the number can be set up.



$$\text{Proportion: } \frac{5}{20} = \frac{X}{50}$$

$$20X = 250$$

$$X = 12.5$$

The answer 12.5 must be added to 50 to arrive at the actual value of 62.5.

The following example illustrates the use of interpolation applied to a problem dealing with one aspect of airplane performance:

Temperature (°F)	Takeoff Distance (ft)
70	1,173
80	1,356

If a distance of 1,173 feet is required for takeoff when the temperature is 70 °F and 1,356 feet for 80 °F, what distance is required when the temperature is 75 °F? The solution to the problem can be determined as follows:

$$\begin{array}{r}
 10 \begin{array}{|l} \hline 5 \\ \hline \end{array} \begin{array}{|l} \hline 70^\circ \\ \hline 75^\circ \\ \hline 80^\circ \end{array} \\
 \hline
 \frac{5}{10} = \frac{X}{183} \\
 10X = 915 \\
 X = 91.5
 \end{array}
 \quad
 \begin{array}{r}
 50 \begin{array}{|l} \hline X \\ \hline \end{array} \begin{array}{|l} \hline 1,173 \\ \hline ? \\ \hline 1,356 \end{array}
 \end{array}$$

## Performance Charts

Following are descriptions of various performance charts. The information on these charts is not intended for operational use, but rather for familiarization and study. Because performance charts are developed for each specific make, model, and type of airplane, care must be exercised by the pilot to assure that the chart developed for the specific airplane flown is used when seeking performance data.

## Density Altitude Charts

Various methods can be used to determine density altitude, one of which is charts. Figure 4-8 illustrates a typical density altitude chart. The following is an example of a density altitude problem based on figure 4-8.

### Given:

Airport Elevation .....	2,545 ft
Outside Air Temperature .....	70 °F
Altimeter Setting .....	29.70 in. Hg.

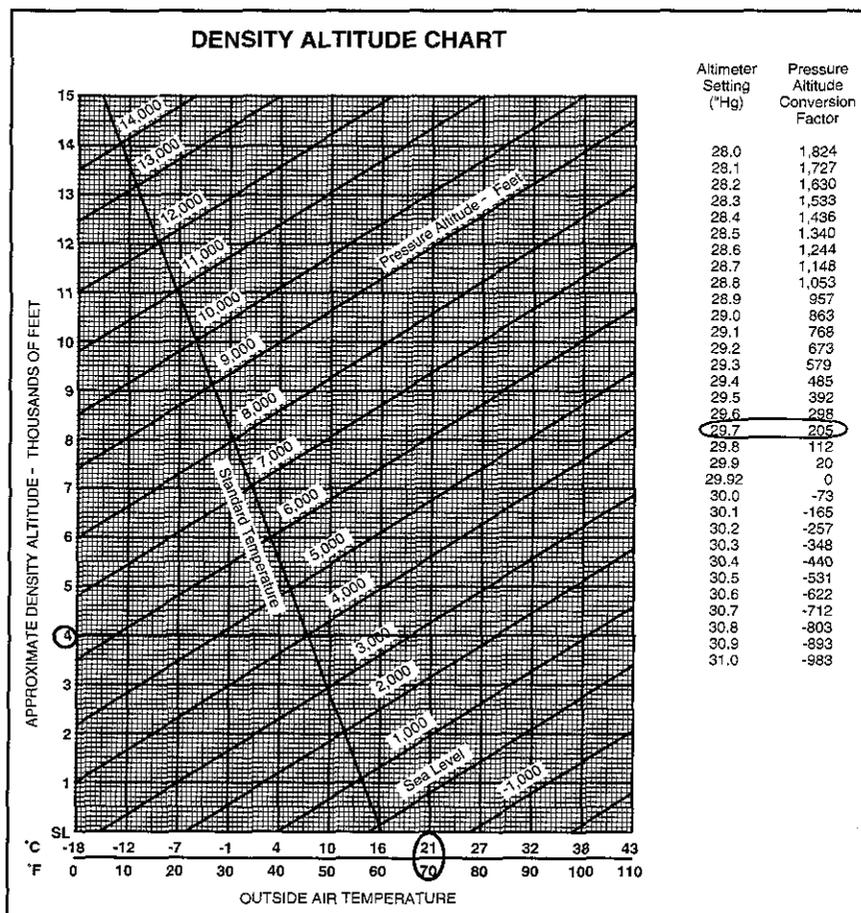


FIGURE 4-8.—Pressure altitude and density altitude chart.

**Step 1**—Find the pressure altitude by locating the altimeter setting of 29.70 in. Hg. and noting the pressure altitude conversion factor. The conversion factor is either added or subtracted from the airport elevation as indicated. In this case, the factor is 205 and should be added. The pressure altitude is 2,750 feet (2,545 + 205 = 2,750).

**Step 2**—Locate the outside air temperature of 70 °F at the bottom of the chart and draw a vertical line until it intersects with the pressure altitude of 2,750 feet. (The pressure altitude of 2,750 feet is located about three-fourths up between the 2,000 and 3,000-foot lines.)

**Step 3**—From where the temperature and pressure altitude lines intersect, draw a straight line to the left to determine the density altitude. The density altitude is 4,000 feet.

### Takeoff Data Charts

Takeoff data charts are found in many Airplane Flight Manuals or Pilot's Operating Handbooks. From this chart, the pilot can determine (1) the length of the takeoff ground run, and (2) the total distance required to clear a 50-foot obstacle under various airplane weights, headwinds, pressure altitudes, and temperatures. Chart formats will vary with manufacturers. Figure 4-9 shows one such chart.

The following is an example of a problem based on figure 4-9.

**Given:**

Gross Weight .....	2,200 lb
Pressure Altitude .....	1,000 ft
Temperature .....	20 °C
Headwind .....	18 kts

**Step 1**—Locate the gross weight of 2,200 pounds in the first column.

**Step 2**—Find the pressure altitude of 1,000 feet in the pressure altitude column corresponding to the weight of 2,200 pounds.

**Step 3**—Determine the ground roll by moving horizontally from the pressure altitude to the ground roll column corresponding to the temperature of 20 °C. The ground roll is 825 feet. To determine the total distance to clear a 50-foot obstacle, move to that column. The total distance would be 1,510 feet.

**Step 4**—In the notes above the chart, it states to decrease the distance by 10 percent for each 9 knots of headwind. With an 18-knot headwind, the takeoff roll would decrease by 20 percent (825 x 20% = 165; 825 - 165 = 660). The takeoff roll is 660 feet. The same would apply to the distance required to clear a 50-foot obstacle which would be 1,208 feet (1,510 x 20% = 302; 1,510 - 302 = 1,208).

TAKEOFF DISTANCE MAXIMUM WEIGHT 2400 LB													
CONDITIONS: Flaps 10° Full Throttle Prior to Brake Release Paved Level Runway Zero Wind													
SHORT FIELD													
NOTES: 1. Prior to takeoff from fields above 3000 feet elevation, the mixture should be leaned to give maximum RPM in a full throttle, static runup. 2. Decrease distances 10% for each 9 knots headwind. For operation with tailwind up to 10 knots, increase distances by 10% for each 2 knots. 3. For operation on a dry, grass runway, increase distances by 15% of the "ground roll" figure.													
WEIGHT LB	TAKEOFF SPEED KIAS		PRESS ALT FT	0 °C		10 °C		20 °C		30 °C		40 °C	
	LIFT OFF	AT 50 FT		GRND ROLL FT	TOTAL FT TO CLEAR 50 FT OBS								
2400	51	56	S.L.	795	1460	860	1570	925	1685	995	1810	1065	1945
			1000	875	1605	940	1725	1015	1860	1090	2000	1170	2155
			2000	960	1770	1035	1910	1115	2060	1200	2220	1290	2395
			3000	1055	1950	1140	2120	1230	2295	1325	2480	1425	2685
			4000	1165	2185	1260	2365	1355	2570	1465	2790	1575	3030
			5000	1285	2445	1390	2660	1500	2895	1620	3160	1745	3455
			6000	1425	2755	1540	3015	1685	3300	1800	3620	1940	3990
			8000	1755	3615	1905	4015	2060	4480	2200	4220	2420	5000
2200	49	54	S.L.	650	1195	700	1280	750	1375	805	1470	865	1575
			1000	710	1310	765	1405	825	1510	885	1615	950	1735
			2000	780	1440	840	1545	905	1660	975	1785	1045	1915
			3000	855	1585	925	1705	995	1835	1070	1975	1150	2130
			4000	945	1750	1020	1890	1100	2040	1180	2200	1270	2375
			5000	1040	1945	1125	2105	1210	2275	1305	2465	1405	2665
			6000	1150	2170	1240	2355	1340	2555	1445	2775	1555	3020
			8000	1470	2760	1525	3015	1685	3305	1805	3155	1730	3450
2000	46	51	S.L.	525	970	565	1035	605	1110	650	1185	695	1265
			1000	570	1080	615	1135	665	1215	710	1295	765	1385
			2000	625	1200	675	1240	725	1330	780	1425	840	1525
			3000	690	1370	740	1365	800	1465	860	1570	920	1685
			4000	755	1490	815	1500	880	1615	945	1735	1015	1865
			5000	830	1645	900	1680	970	1790	1045	1925	1120	2070
			6000	920	1830	990	1845	1070	1990	1145	2145	1235	2315
			8000	1015	2040	1095	2055	1180	2225	1245	2405	1370	2605
			1125	2125	1215	2305	1310	2500	1410	2715	1520	2950	

FIGURE 4-9.—Takeoff performance data chart.

**Step 5**—If the runway is dry grass, the notes state to increase the distance by 15 percent of the ground roll. In this problem, it would require adding 15 percent of 660 feet.

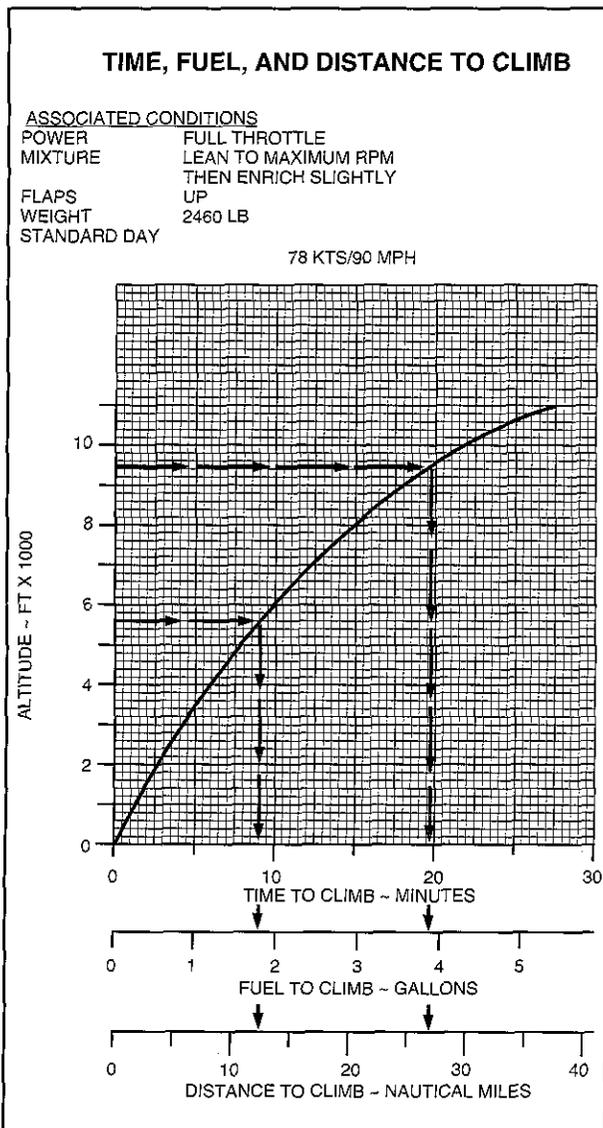
**Climb and Cruise Performance Data**

Climb and cruise performance are compiled from actual flight tests. This information is helpful in cross-country flight planning. Examples using different types of charts are provided as an example for determining climb performance and cruise performance.

Determine the time, fuel, and distance to climb using figure 4-10.

**Given:**

Airport Pressure Altitude ..... 5,650 ft  
 Cruise Altitude ..... 9,500 ft



**FIGURE 4-10.—Crosswind and headwind component charts.**

**Step 1**—Locate the airport pressure altitude of 5,650 feet on the chart, and draw a straight line until it intersects the curved line, then draw a line to the bottom of the chart.

**Step 2**—Using the scale at the bottom of the chart, note the time, fuel, and distance to climb (9 minutes; 1.9 gallons; 12 miles).

**Step 3**—Repeat steps 1 and 2 using the cruise altitude of 9,500 feet (20 minutes; 3.9 gallons; 27 miles).

**Step 4**—Subtract the information found in step 2 from that found in step 3 (Time to climb 20 - 9 = 11 minutes; fuel to climb 3.9 - 1.9 = 2 gallons; miles to climb 27 - 12 = 15 miles).

Determine the true airspeed and fuel consumption rate based on figure 4-11.

**Given:**

Pressure Altitude ..... 4,000 ft  
 Temperature ..... Standard  
 Power ..... 2,400 RPM

PRESSURE ALTITUDE FT	RPM	20 °C BELOW STANDARD TEMP			STANDARD TEMPERATURE			20 °C ABOVE STANDARD TEMP		
		% BHP	KTAS	GPH	% BHP	KTAS	GPH	% BHP	KTAS	GPH
2000	2500	---	---	---	76	114	8.5	72	114	8.1
	2400	72	110	8.1	69	109	7.7	65	108	7.3
	2300	65	104	7.3	62	103	6.9	59	102	6.6
	2200	58	99	6.6	55	97	6.3	53	96	6.1
	2100	52	92	6.0	50	91	5.8	48	89	5.7
4000	2550	---	---	---	76	117	8.5	72	116	8.1
	2500	77	115	8.6	73	114	8.1	69	113	7.7
	2400	69	109	7.8	65	108	7.3	62	107	7.0
	2300	62	104	7.0	59	102	6.6	57	101	6.4
	2200	56	98	6.3	54	96	6.1	51	94	5.9
6000	2600	---	---	---	77	119	8.6	72	118	8.1
	2500	73	114	8.2	69	113	7.8	66	112	7.4
	2400	66	108	7.4	63	107	7.0	60	106	6.7
	2300	60	103	6.7	57	101	6.4	55	99	6.2
	2200	54	96	6.1	52	95	5.9	50	92	5.8
8000	2650	---	---	---	77	121	8.6	73	120	8.1
	2600	77	119	8.7	73	118	8.2	69	117	7.8
	2500	70	113	7.8	66	112	7.4	63	111	7.1
	2400	63	108	7.1	60	106	6.7	58	104	6.6
	2300	57	101	6.4	55	100	6.2	53	97	6.0
10,000	2700	---	---	---	77	121	8.6	73	120	8.1
	2600	77	119	8.7	73	118	8.2	69	117	7.8
	2500	70	113	7.8	66	112	7.4	63	111	7.1
	2400	63	108	7.1	60	106	6.7	58	104	6.6
	2300	57	101	6.4	55	100	6.2	53	97	6.0
12,000	2750	---	---	---	77	121	8.6	73	120	8.1
	2600	77	119	8.7	73	118	8.2	69	117	7.8
	2500	70	113	7.8	66	112	7.4	63	111	7.1
	2400	63	108	7.1	60	106	6.7	58	104	6.6
	2300	57	101	6.4	55	100	6.2	53	97	6.0

**FIGURE 4-11.—Cruise performance chart.**

**Step 1**—Locate the pressure altitude of 4,000 feet on the chart.

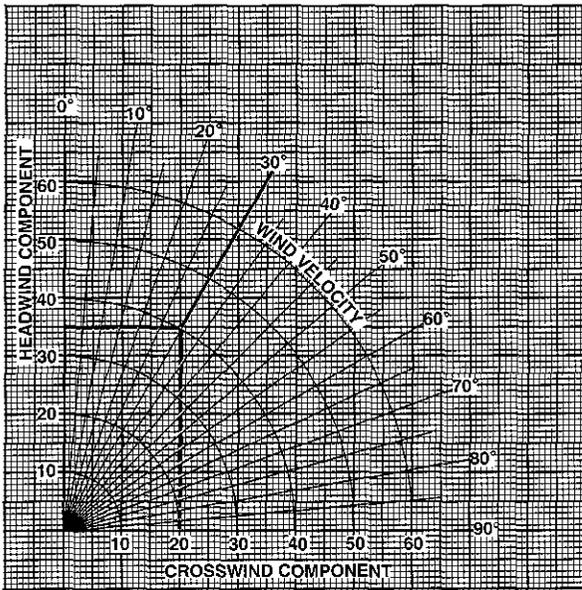
**Step 2**—Locate 2,400 RPM in the proper column.

**Step 3**—Move across the chart to the standard temperature column, and note the true airspeed and

fuel consumption rate (True airspeed, 108 knots; fuel consumption rate, 7.3 gallons per hour).

Takeoffs and landings in certain crosswind conditions are inadvisable or even dangerous. If the crosswind is strong enough to warrant an extreme drift correction, a hazardous landing condition may result. Therefore, always consider the takeoff or landing capabilities with respect to the reported surface wind conditions and the available landing directions.

Before an airplane is type certificated by the FAA, it must be flight tested to meet certain requirements. Among these is the demonstration of being satisfactorily controllable with no exceptional degree of skill or alertness on the part of the pilot in  $90^\circ$  crosswinds up to a velocity equal to  $0.2 V_{SO}$ . This means a windspeed of two-tenths of the airplane's stalling speed with power-off and gear and flaps down. (If the stalling speed is 60 knots, then the airplane must be capable of being landed in a 12 knot  $90^\circ$  crosswind.) To inform the pilot of the airplane's capability, regulations require that the demonstrated crosswind velocity be made available. Certain Airplane Owner's Manuals provide a chart for determining the maximum safe wind velocities for various degrees of crosswind for that particular airplane. The chart, with the example included, will familiarize pilots with a method of determining crosswind components. [Figure 4-12]



**FIGURE 4-12.—Crosswind and headwind component chart.**

Determine the headwind and crosswind component based on figure 4-12.

**Given:**

---

Runway .....	36
Wind .....	330° at 40 kts

---

**Step 1**—Subtract the runway heading from the wind direction to determine the wind angle ( $360-330 = 30$ ).

**Step 2**—Locate the  $30^\circ$  line and draw a line from that point until it intersects the wind velocity line of 40 knots.

**Step 3**—From where the wind angle line and wind velocity line intersect, draw a straight line across the chart to determine the headwind component and draw a line straight down the chart to determine the crosswind component (Headwind, 35 knots; crosswind, 20 knots).

**Landing Performance Data**

Variables similar to those affecting takeoff distance, also affect landing distances, although generally to a lesser extent. Consult your Aircraft Flight Manual or Pilot's Operating Handbook for landing distance data, recommended flap settings, and recommended approach airspeeds.

**Combined Graphs**

Some aircraft performance charts incorporate two or more graphs into one when an aircraft flight performance involves several conditions. A simple combination of graphs is illustrated in figure 4-13. It requires three functions to solve for takeoff distance with adjustments for air density, gross weight, and headwind conditions. The first function converts pressure altitude to density altitude. The right margin of this portion of the graph, even though it is not numbered, represents density altitude and starts the second function, the effect of gross weight on takeoff distance. The right margin of this section represents takeoff distance with no wind and starts the final phase of correcting for the effect of headwind.

Determine the ground roll and total landing distance to clear a 50-foot obstacle based on figure 4-13.

**Given:**

---

OAT .....	75 °F
Pressure Altitude .....	4,000 ft
Landing Weight .....	3,200 lb
Headwind .....	10 kts

---

**Step 1**—Locate the temperature at the bottom of the chart and draw a line up the chart until it intersects the pressure altitude. From where the temperature and pressure altitude lines intersect, draw a line across to the reference line.

**Step 2**—From the reference line, draw a line which parallels the other lines. Locate the weight at the bottom of the chart and draw a line upward until it intersects the parallel line just drawn. From that point, draw a straight line across to the next reference line.

**Step 3**—Repeat the same procedure as outlined in step 2 for applying the wind factor. The landing distance is 1,475 feet.

**Step 4**—The notes on the chart indicate the ground roll is 53 percent of the total landing distance (1,475 x .53 = 781.75 or 782 feet).

### NORMAL LANDING

ASSOCIATED CONDITIONS:

POWER AS REQUIRED TO MAINTAIN 800 FT/MIN DESCENT ON APPROACH  
 FLAPS DOWN  
 RUNWAY PAVED, LEVEL DRY SURFACE  
 APPROACH SPEED IAS AS TABULATED

NOTE: GROUND ROLL IS APPROX. 53% OF TOTAL LANDING DISTANCE OVER A 50 FT OBSTACLE.

EXAMPLE:

OAT 75° F  
 PRESSURE ALTITUDE 4000 FT  
 LANDING WEIGHT 3200 LB  
 HEADWIND 10 KNOTS

TOTAL LANDING DISTANCE OVER A 50 FT OBSTACLE 1475 FT  
 GROUND ROLL (53% OF 1475) 782 FT  
 IAS APPROACH SPEED 87 MPH IAS

WEIGHT POUNDS	IAS APPROACH SPEED (ASSUMES ZERO INSTR. ERROR)	
	MPH	KNOTS
3400	90	78
3200	87	76
3000	84	73
2800	81	70
2600	78	68
2400	75	65

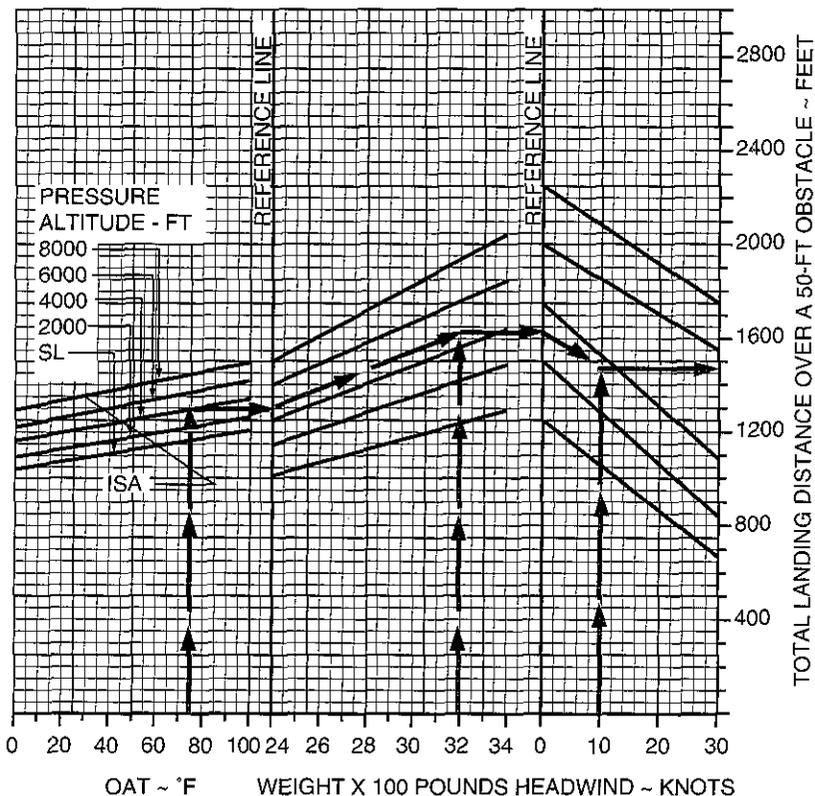


FIGURE 4-13.—Landing chart.