The Cost* of Your Airplane's Parasite Drag

(*as in what You pay at the pump)

and the Advantages of Airplane Drag Reduction

Some Points of Interest to

General Aviation Airplane Owners and Pilots

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Above all, I am very grateful to the Lord for allowing and enabling me to write the book during my eighth decade. He gave me everything I needed, physically, mentally, and spiritually.

A Voice From The Past on Airplane Parasite Drag

“Ever since I first began to study aeronautics I have been annoyed by the vast gap which has existed between the power actually expended on mechanical flight and the power ultimately necessary for flight in a correctly shaped aeroplane. This annoyance is aggravated by the effortless flight of birds and the correlated beauty and grace of their forms. We all possess a more or less clear ideal of what an aeroplane should look like, a kind of albatross with one or two pairs of wings.”

...“Apparently, large commercial airplanes of today would, were they ideally streamlined, either fly at present top speed for one-third of the present power, or alternatively, travel some sixty miles an hour faster for the same power.”

...“There is a natural tendency to decide on one day that the gain - say 20%, on the total drag, or 7%, on the speed, - to be had by spending endless trouble on improving the undercarriage design, is not worth the trouble; on the next day to come to a similar conclusion about the drag of the engine cooling apparatus; on the next day about the wires, struts, and minor excrescences, and on the next day about the pilot’s view; omitting to notice that if all the improvements were made at once the total gain would not be some insignificant percentage of the whole, but might reduce power consumption to a small fraction of its original value and so extend the range and usefulness of the aeroplane into realms which would be otherwise attainable.”

...“Reduction of drag will enable an aeroplane of a given power loading, either to cruise at higher speed or with a lower petrol consumption. This again will result in increased range or paying load, both factors of importance in aeronautical development.”

...“We all realize that the way to reduce (total parasite drag) is to attend very carefully to streamlining.”

...“It is, of course, well known that, unless bodies are carefully shaped, they do not necessarily generate streamline flow but shed streams of eddies from various parts of their surface. The generation of these eddies, which are continuously being carried away in the airstream, requires the expenditure of power additional to that required to overcome induced drag and skin friction.

...The power absorbed by these eddies may be, and often is, many times greater than the sum of the powers absorbed by skin friction and induced drag. The drag of a real aeroplane therefore exceeds the sum of the induced drag and skin friction by an amount which is a measure of defective (or lack of) streamlining.”

Professor B. Melville Jones, Professor of Aeronautical Engineering at Cambridge University, Great Britain. Some excerpts from a lecture before he gave to the British Royal Aeronautical Society in May of 1929.

Introduction

The Practical Value of the General Aviation Light Airplane.

The General Aviation light airplane is an efficient transportation vehicle for transporting four to eight people and a reasonable amount of luggage. At least 80 percent of general aviation flying is done for business or commercial purposes. Thus clearly our light airplanes are saving time and money for their owners and pilots. That's what especially business flying is about.

Higher Aerodynamic Efficiency = Cleaner Airplanes.

As the price of aviation gasoline goes up, aerodynamic efficiency plays an increasingly important part in operating costs of the light airplane. The more aerodynamically clean the airplane, and the smaller its frontal drag area, the more efficient it is in service. **There is plenty of scope here for improvement through better, more efficient aerodynamic design, construction, production-methods, and better maintenance and upkeep once the airplane is in service.**

Different Speed Regimes

Most of our cross-country light airplanes spend their flying-time cruising at 75 percent or less power at altitudes of between 4,000 and 11, 000 feet. Experience has shown that for different purposes there are different practical speed ranges.

1. The most economical is the 120 to 150 mph range. Airplanes flying at cruise-speed in this range can be practical, economical travelers. These airplanes today look and perform much as they did 20 or more years ago. **They also have several times more aerodynamic parasite drag than they should have.** Their speed-range is about the minimum necessary to get any advantages from the airplane.

2. To go even a little faster than 200 mph costs a lot more. Therefore, the 150 to 200 mph cruise-range is still what most owners/pilots settle for. There usually is enough additional power and speed to get to most places within 500 miles the same day. **These airplanes often also could, and certainly should, have a lot less drag.**

3. The next step is the 200 to 250 mph cruise-speed range. This is the range for the most expensive singles and twins. **This is also the class of airplane where streamlining and drag reduction are of utmost importance.**

More Speed Wanted.

When it comes to the improvement of the light airplane, increased cruise-speed is often THE main aim. Most private/business pilots want speedy (that is, faster) efficient airplanes suitable for business but also for family travel and business flying. Sheer speed and its attendant other performance advantages for both business and private flying is the new touchstone. However, higher cruise-speed is expensive. Higher speed costs money in the form of fuel burned. Thus we need to reach a higher performance level at the same or preferably less fuel cost. And that’s exactly where high parasite drag comes in.

The New Composite Airplanes

It will be very interesting to see how the appearance on the market of the various new composite airplanes will change the thinking and practices of the established airplane manufacturers in the United States and abroad. A lot will depend on how much pressure for low-drag airplanes there will be from you, the buyers, owners, and pilots. Market pressure, or market demand I believe it is called.

About This Book

In this book we’ll discuss parasite drag. We’ll look at where it comes from, and what it may be costing you on your airplane. We’ll also take a look at what drag-reduction can do for your and for any other airplane. We'll look into the money and time-savings possible with drag-reduction, and also important, the safety-aspects of drag-reduction.

While we do point out the "draggy" areas of your airplane, we are not going into how you can specifically decrease its the drag.

First, as owner of a certified airplane there is very little the FAA lets you get away with. However, there may well be a good deal of work you can do or have done in the way of regular upkeep and maintenance. A good look at the transient airplanes at the yearly Oshkosh Fly-In makes that very clear.

Second, there are many mod shops that offer a good number of well thought-out, well-designed, and certified modifications for decreasing your airplane's parasite drag. If you decide to accept their help, they are willing and able to tell and show you what is possible, and at what price. Then you can decide what to do.

Third, airplane owners can demand higher efficiency airplane's from the manufacturers.

"The increasing cost of flying is a significant threat to the long-term survival of General Aviation."

A meaningful statement from the October 11, 1999 issue, page 50, of AVIATION WEEK AND SPACE TECHNOLOGY magazine. Quoted by permission.

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Abbreviations Used, and Conversion Factors for Readers Overseas

Measurement	Abbr.	x	Gives	x	Gives
foot or feet	ft	0.3048	meters	3.281	feet
Feet + inches	ft in	---------	----------		
Feet per minute	fpm	0.3048	meter p. m	3.281	Feet per minute
Gallon or gallons (US)	gal	3.7854	liters	0.264	US gallon
Gallon per hour	gph	3.7854	liter/hour	0.264	US gallons per hour
Horsepower	hp	0.746	Kilowatt	1.34	horsepower
Inch	in	25.4	millimeter	0.0394	inch
Pound	lb	0.4536	Kilogram	2.205	pound
Pound per horsepower	lb/hp	0.4536	Kilogram/hp	2.205	lb/hp
Pound per hp/hour	lb/hp/hr	0.4536	Kg/hp/hr	2.205	l/hp/hr
Pound per square foot	lb/sf	4.8824	Kilogram/ sq m	10.765	lb/sf
Mile (land or stationary)	mi	1.6093	Kilometer	0.621	mile
Mile per US gallon	mpg	0.425	Km./liter	2.353	mpg
Mile per Imp. gallon	mpg	0.354	Kilometer/liter	2.825	mpg
Required	req	-------	--------		
Square foot or feet	sf	0.0929	square meter	10.765	sf
Sea Level	S.L.				

Section One

Your Airplane's

Parasite Drag

Causes and Costs

Chapter One

Your Airplane's Parasite Drag

As an airplane owner and pilot, perhaps you'd like to understand more about your airplane's parasite drag. What it does, what it is, what it means, and especially what it's costing you. All this drag that not only slows up your airplane, but also requires the expenditure of power, and thus fuel, and therefore your money, to overcome it. As you pay for your airplane's drag, you might as well know what it is you are paying for. Therefore, our purpose is to look into the causes and effects of your airplane's parasite drag, and give you a better understanding of what your airplane's parasite aerodynamic drag may be costing you.

Your Airplane's Total Parasite Drag. Your airplane's total parasite drag depends on several basic factors, such as

1. The density of the air. The more dense the air flowing past your airplane, the more parasite drag.

2. The viscosity of the air, or what we call its stickiness.

3. Your airplane's flying speed. As its flying speed increases, the amount of parasite drag increases with the square of the speed increase.

4. The shape of your airplane. The more streamlined your airplane is, the less is its parasite drag.

5. The "frontal drag area" or "Equivalent Flat Plate Area" (EFPA) of your airplane. The larger the size of your airplane, the higher probably its parasite drag area.

6. The nature of the exposed surfaces of your airplane. Are they smooth, irregular, or dirty?

Where Does Your Airplane's Drag Come From? The problems of airflow and the existence of the airplane's aerodynamic drag all result from the air's viscosity or stickiness. This viscosity or stickiness creates the parasite drag force. The resistance met by your airplane while flying through the air is of two types. One kind, the skin-friction drag, is due to the frictional force caused by the forward motion of your airplane and of the sticky air flowing aft over and along it.

The other kind is due to the inertia of the air, which keeps it moving after your airplane has passed. This also involves its density and the resulting velocity changes, which create pressure variations around the airplane's contours. Whatever kinds of parasite drag we will be dealing with are all wholly or partly based on skin-friction drag and turbulent-flow drag, which is also called pressure drag or form drag.

Where It All Starts From. Let's say you have parked your airplane on your airport's ramp, ready to go. The atmospheric pressure is the same all around it. The airport is practically at sea level, and it is on a standard no-wind day. So there is a pressure-force equal to about 14.7 pound per square inch (lb/in^2) pushing on your airplane everywhere, inside and outside. There's no net force either up or down, forward or backward.

However, as soon as you start your airplane rolling, higher pressures develop on the front. While pressure differences develop in its boundary layer, and regions of low-pressure air form behind it, skin-friction from the boundary-layer air flow sliding over its surfaces also starts to play its part. Both the boundary layer's skin friction drag and the body-shape determine your airplane's drag characteristics. The actual drag-force also is influenced a good bit by three-dimensional effects, especially on the fuselage and landing gear. Here's a list of the most important kinds and causes of parasite drag on your airplane, somewhat in order of importance:

1. Wing profile drag, especially in the form of turbulent boundary-layer flow drag.

2. Fuselage drag, including internal-flow drag caused by the ventilation inlets and outlets taking care of the cabin ventilation..

3. Landing Gear drag. This also often makes up a large percentage of the total drag

4. Engine drag, resulting from engine-intake and -cooling drag. This is going on all the time the airplane is flying. It often creates a large percentage of your airplane's total drag.

5. Empennage drag, which is part profile drag and part interference drag.

6. Maneuvering drag. Caused by the movement of the control surfaces in flight.

7. Trim drag. Caused by the permanent application of control-surfaces either directly or through trim tabs.

8. Slip-stream drag.

9. Interference drag. Caused by the interference of the boundary layer flows of two parts or assemblies connected with or close to each other.

10. Component Drag. Drag of various parts sticking out here and there, all by themselves, all over your airplane. This is mostly form drag.

Your Airplane's Form Drag. Your airplane's parasite form drag is made up out of the resistance offered by the main assemblies, plus a host of smaller parts. Things like antennas, control-hinges, control fittings, inspection plates, fasteners, tail- wheel and a lot of others. The parasite drag of these parts especially takes money out of your pocket without giving you anything in return.

Drag Requires Thrust. Because your airplane's drag continuously slows it down, you must provide a thrust equal to the drag force. This thrust comes from your airplane's engine and propeller. To provide this thrust, you burn aviation fuel. The average general aviation propeller-driven airplane has a lot more drag and therefore needs a lot more power than it should. The higher the drag of your airplane, the larger the thrust needed and therefore the bigger the engine must be. So, the more of your costly avgas it consumes. When your airplane needs a stronger engine than it should, it is not efficient. When it comes to drag, less is more! Consider this:

- A stronger engine means a bigger engine.
- A bigger engine means a heavier engine.
- A heavier engine means a stronger fuselage.
- A stronger fuselage means a heavier fuselage.
- A heavier fuselage means a heavier, bigger landing gear, tail surfaces, etc.

Therefore it will need a larger wing. Unfortunately,

- A larger wing means a heavier wing.
- A larger wing has more drag.
- It requires a stronger engine.

This means a heavier engine, ad infinitum. In contrast, the well-streamlined airplane, designed for the same cruise-speed will have:

- A smaller, lighter engine.
- A smaller, lighter fuselage.
- A smaller, lighter wing.
- A smaller, lighter landing gear.
- A smaller, lighter set of tail-surfaces.

Drag Increases with the Speed Squared. Because parasite drag increases with the square of the speed, if your airplane is flying at 200 mph its drag is 2 x 2 = 4 times as high as at 100 mph. At 300 mph the drag is 3 x 3 = 9 times as high. However, the horsepower required increases with the cube, or the third power, of the speed increase. Thus at 200 mph your airplane needs 2 x 2 x 2 = 8 times the horsepower it requires at 100 mph. At 300 mph it would need 3 x 3 x 3 = 27 times the horsepower.

Appendix 1 clearly shows how fast the cost of each pound of drag goes up with increased flying speed. The Table is based on a specific fuel consumption (SFC) of 0.50 pounds per hour per horsepower (lb/hr/hp), an 80-percent propeller-efficiency ("eta factor"), and a fuel-price of US $2.00 per US gallon. Most airplane owners and pilots in foreign countries will have to multiply the cost figures by a factor of three or four.

Horsepower Equals Fuel Dollars. Your airplane's total drag determines the horsepower required. Thus it directly affects how big your airplane's engine(s) must be and, therefore, your fuel bills. Thus we can only conclude: a high-drag airplane wastes horsepower, and therefore fuel, and lots of your fuel dollars.

As you know too well, fuel costs account for a sizable percentage of the total operating expenses of your airplane. As fuel prices climb, your airplane's efficiency and thus its fuel economy take on increasing importance. So one thing is clear: drag is the enemy of flight, therefore, ideally, the drag of every part of your airplane ought to be reduced to a minimum.

The More Efficient Airplane. An airplane with minimum drag is more efficient and thus more economical in operation. It also performs better. Drag reduction gives you either a direct saving in fuel, an increase in speed or in range. Or part of each as you decide. Low drag enables your airplane to carry the maximum payload for the least fuel consumption and reduces your operating costs.

The Ideal Airplane. The streamlined body is the foundation of the efficient airplane. Without streamlining, we cannot have efficient air transport. Therefore, further drag reduction is becoming more and more the dominant method of improving the airplane.

So how low should the parasite drag of a perfectly streamlined airplane be? Ideally, it should be no more than that caused by the friction of the air passing over its surfaces. Only pure skin-friction. For such an ideally streamlined airplane the skin-friction drag parallels the theoretical skin friction. Unfortunately, when your airplane disturbs the airstream, form or turbulence drag results. How much depends on the shape and surface-finish of your airplane. Thus the shape of your airplane and its external parts directly affects its form drag.

Horsepower Required. The horsepower your airplane needs to fly straight and level at your selected cruise-speed must overcome only your airplane's induced and parasite drag. On the other hand, on climb-out, the amount of engine-power required must equal the airplane's total drag plus the amount of power required for gaining altitude. Thus your airplane's rate of climb depends on the engine power in excess of the cruise-power required for climb-out speed. The more power required for going ahead, the less power available for going up. Thus reducing your airplane's total drag increases its rate of climb. This is a serious safety factor at every take-off and climb-out. And it works the other way for you when gliding with the power off, thus doubling the value of the Safety Factor.

Induced Drag. In ground school you learn there also is Induced Drag, caused by the wing creating lift. It is high at high angle-of-attack, as during takeoff and landing. With increased flying speed and thus decreased angle of attack it diminishes. For the airplane designer there are various ways to reduce it. On that point, therefore, you have to live with his design decisions. We will not be dealing with the induced drag.

Chapter Two

The Gross Equivalent Drag Area

Why We Use the Gross Equivalent Drag Area. For our purpose, there is a difficulty with the often-used formula for the so-called "Equivalent Flat Plate (Drag) Area (EFPA or EFPDA). When using the EFPA formula to get reliable figures for comparing two or more piston-engine propeller-driven airplanes, we need accurate figures for the propeller efficiency. However, normally we don't know this value; it may range from 0.65 to 0.85. It also change with an airplane's flying speed.

In any case, the engine does not know nor does it care how efficient or perhaps inefficient the propeller is. The engine consumes a certain amount of fuel, for which it gives a certain number of shaft-horsepower in return. What the propeller does with it makes no difference to the amount of fuel burned (and mostly wasted) by the engine, and thus to your fuel dollars. Therefore, for our purpose it is more practical to use the formula without the propeller efficiency figure.

Working It Out. The value we then get we call the Gross Equivalent Drag Area (GEDA). After all, that's the one you pay for at the avgas pump. We know that at $V_{max.}$ the engine's power output or thrust equals the drag. So first we calculate the airplane's gross drag at $V_{max.}$ (at Sea Level on a Standard Day). For this we use the simplified formula:

$$\text{Gross Drag} = (\text{Max. HP} \times 375) / V_{max.}\ (\text{mph})$$

Next we calculate or, for round mph-speeds, find in the air-pressure table the resistance per square foot (lb/sf) at the particular $V_{max.}$ Then we divide the drag figure over this value for q. That gives us the Gross Equivalent Drag Area. As 1 mph equals 1.46667 fps, we use

$$550 / 1.46667 = 375$$

For example, for an airplane having 100 hp and a maximum speed of 100 mph:

$$\text{Gross Drag} = (\text{HP} \times 375) / V_{max.}\ (\text{mph})$$

$$(100 \times 375) / 100 = 37500 / 100$$

$$= 375 \text{ lb}$$

375 / 25.5767 = 14.66 sf

Now a few real-life examples. For the Beechcraft Bonanza F33 , with 285 hp and a $V_{max.}$ @ sea level (S.L.) of 209 mph, our calculation works out to:

Drag = (285 x 375) / 209
= 106875 / 209
= 511.4 lb

At sea level, at 209 mph, air pressure q equals 111.72 lb/sf. Therefore

GEDA = 511.4 / 111.72
= 4.58 sf

In this way, we can directly compare the GEDA values of different piston-engine airplanes. No need to know or guess the value for the propeller efficiency. Let's work out the GEDA for a two other well-known light airplanes. First we take the 1978 Cessna Hawk XP. The numbers are:

Engine = 195 hp
Maximum speed @ S.L. = 153 mph

Drag = (195 x 375) / 153
= 73125 / 153
= 478 lb

Air pressure q @ 153 mph = 59.872 lb/sf

GEDA = 478 / 59.872
= 7.98 or say 8.0 sf

Now for the Piper 1982 PA-28 Cherokee. The figures are:

Engine = 160 hp
Maximum speed @ S.L. = 146 mph

Drag = (160 x 375) / 146
= 60000 / 146
= 410.96 or 411 lb

Air pressure q @ 146 mph = 54.52 lb/sf

GEDA = 411 / 54.52
= 7.54 sf

That's how easy it is to find the GEDA value for any piston-engine airplane if you know the maximum horsepower rating and the maximum speed at Sea Level (S.L.).

Chapter Three

Wing Profile Drag - Some Causes

The Wing Drag. While your airplane's wing creates the lift that makes your airplane fly, it also causes a good bit of fuel-consuming parasite profile drag. This wing's profile drag makes up a large portion of your airplane's total drag. It diminishes your airplane’s most important advantage: its cruise speed.

Wing Profile Drag. Drag, and especially wing drag, depends on the disturbed airflow caused by the retarded boundary layer. Wing profile drag consists of skin-friction drag and form drag. Skin-friction drag depends on the position of the point of transition from laminar to turbulent flow in the boundary layer, local boundary-layer surface velocities and pressure gradients, the degree of surface roughness, and the degree and scale of turbulence in the air-stream. All these factors are inter-related. They depend on profile shape and surface roughness.

Form drag is caused by the distortions of the boundary-layer airflow over the surfaces. The wing's form drag is a function of skin-friction drag, since it derives from the presence of the boundary layer and its effect on the wing's pressure distribution. For an airfoil or wing section it varies with the skin-friction drag when this is altered by changes in the boundary-layer transition point position.

Changes to the Airfoil Shape. The surface quality of a wing has a large effect on its profile drag. Some airfoil sections are extremely sensitive to small changes in their full-size shape on airplane wings. Many unintended small changes to the original airfoil shape may result in drag-increasing irregularities. The surface roughness causes the boundary-layer to become turbulent prematurely; the airfoil then no longer behaves like the smooth airfoil in the wind tunnel. Once the boundary layer is turbulent, it will stay turbulent. Because turbulence in the boundary layer is equivalent to an increase in airflow-velocity, the higher airspeed equals higher drag.

For low wing-drag, holding the accuracy of proper profile-shape in flight is very important. Unfortunately, wing profiles as built are not equal to the theoretical profile. This just can't be done with a thin-gauge metal wing.

Wing-surface Waviness. It is very difficult to produce an unbroken metal skin on both wing surfaces, with very small surface-waviness. Even in a highly polished metal wing-surface there are waves and humps in the skin. Often, these waves and bumps result from rivet-tension created by the spars and span-wise stiffeners on the inside. This usually causes premature transition to turbulent flow with increased profile drag.

First the boundary-layer airflow speeds up over a ridge, even one as small as 0.004 inch high. Then it slows down going into an equally tiny hollow. This constant speeding up and slowing down drains energy from the boundary layer, which then thickens and becomes turbulent. This, of course, makes it difficult to preserve laminar flow for more than a few inches, and then only near the wing's extreme leading edge. A very slight wave in the contour is sufficient to produce a local reversal of the pressure gradient and so cause transition to turbulent flow.

NACA Test Results. How important this is came out in NACA testing. When the waves covered only the rear two-thirds of both wing surfaces they increased the drag by only one percent. With the waves covering the rear 92 percent of the surfaces, drag increased by 10 percent. Thus the short chord-wise area from 8% to 33% produced 9% of the increased wing profile drag. A single wave at the 10.5-percent chord position on the top surface caused premature flow separation, with a 6-percent drag increase.

Achieving Minimum Drag. Thus to achieve minimum drag, the surface must be kept smooth all over. In one experiment, for drag-comparison, the whole surface of one wing was roughened all over, and only the back half of another wing. The roughness on the back half only gave only one-third of the drag increase on the wholly roughened wing, showing that the back part of the wing still is important.

Leading-edge Problems. Especially on the leading edge, any individual bit of surface roughness breaks up laminar boundary-layer flow. The disturbances then spread with an included angle of about 15-20 degrees. Dust adhering to the oil left by a human fingerprint will cause increased drag, as will scratches on the leading edge also. The actual drag depends on the nature of the surface-roughness.

Smooth Surface. A smooth wing is essential to the attainment of low wing drag. Freedom from any irregularity disturbing the boundary layer is especially important near the leading edge and on the upper surface forward of maximum thickness. Thus there should not be any waves or bumps on the first one-third of the wing. Surface roughness of 0.010 in. height will almost certainly create immediate transition. A dead insect, a raindrop, or an ice crystal will produce a turbulent wake with increased drag.

Sensitivity to Small Changes. Metal wings usually have a number of surface irregularities. Some are a direct result of the materials or construction technique used to build the airplane, usually all accidental. There are many ways an airfoil can become rough. The wing profile and the wing finish on each production airplane is not always exactly the same. Jogged laps, rivets, spot welding, poor contour-fairing, poorly matched skins or dents, produce a wing surface very much unlike the smooth wind-tunnel airfoil model. Each one causes increased drag for your airplane. Any decrease in performance results from *the total effect of many small factors.* Therefore your airplane's performance depends on attention to even the smallest details, right down from design to manufacturing, workmanship, maintenance, and upkeep.

Bare Metal Finish. Even a bare metal surface finish or a well rubbed-down paint increases skin-friction drag. Figure on about 5% for a bare-metal finish and 10% for a very good paint-finish. In tests, a very slight roughening of the surface with emery cloth increased drag by about 20 percent. Thus wing surface smoothness is essential. Especially the first 30-35 percent should be free from any kind of plate joints or ripples in the plating.

The Metal Airplane Wing. Instead of on the rather low stress levels, the skin-thickness of most light airplane wings often depends on the minimum gauge requirements. Therefore a wing-skin consists of the thinnest aluminum sheet that will hold its shape reasonably well and resist denting.

Such thin sheet-metal skins in many cases will easily oil-can span-wise under flight loads. This gives chord-wise bumps and shallow creases in the shape of the airfoil. These in turn will cause a turbulent boundary-layer to grow more rapidly, with an increase in the wing's profile drag. Oil-canning or buckling of metal skin always disrupts airflow over the wing. Thus it cuts down your airplane's performance in cruise-flight.

Upper-surface Problems. Small protuberances on the upper surface also produce large profile drag increases at low cruise-flight angles-of-attack. Although the effect varies with protuberance height and location, the additional drag is rather drastic in comparison with the basic airfoil drag.

Airfoil Model Tests. Wind-tunnel tests on an 8-inch chord airfoil-model at a Reynolds Number of 7 million showed that excrescences on the surface of about 0.0004 in. gave 32 percent more drag over that of a perfectly smooth airfoil surface, while of 0.001 in. gave an increase of 70 percent. This corresponds to excrescences of 0.004 and 0.01 inch respectively on a full-scale wing of about 7 feet chord, not much rougher than a fabric surface. At a Reynolds Number of ten million, on an 8-feet chord wing, the excrescences must not exceed 0.001 inch.

NACA did a series of tests on the drag increase caused by protuberances of different height on a 23012 airfoil. Drag increases are over the basic profile drag at Cl = 0.30 at various chord positions. Values are approximate. First for the upper surface:

Table No. 1. Protuberance Drag.

Upper Surface

	Protuberance height			
	0.001	0.002	0.005	0.0125
Location % chord	Drag Increase - Percent			
0.15	14	59	128	582
0.30	12	37	100	393
0.65	-----	34	114	233

Lower Surface

	Protuberance height			
Location	0.001	0.002	0.005	0.0125
% chord	Drag Increase - Percent			
0.30	-----	27	64	195
0.65	-----	20	42	162

These test-results clearly show that small protuberances have an important effect on the wing's profile drag. Manufacturing irregularities such as bulges and wrinkles increased drag by 8 percent of the smooth-wing drag. This was in addition to the drag caused by rivets and laps.

Drag of Finishes Test. NACA also tested the drag of various finishes often used on metal light airplane wings, to find their contribution to wing drag. The test results, for 100 mph are:

Table No. 2. Drag of Finishes Test

Finish	Drag Coeff.	Drag lb/sf
Smooth, polished	0.0060	0.1535
Wavy smooth metal	0.0112	0.2865
Production sheet metal	0.0160	0.4092
Smooth paint	0.0250	0.6394

This table shows the drag increase in percent for the lower three finishes as respectively being. 87, 167, and 317 percent.

Rivet-head Disturbances. All-metal riveted wings usually have problems with the disturbance of the airflow over the wing by rivet heads. The rows of rivets and the several lap joints in a metal wing produce a surface far from the original smooth airfoil outline.

A protruding rivet in the laminar region will bring the transition right up to the position of that rivet. The airflow separates on the aft-portion of each rivet, trailing a wake of turbulent airflow over the wing skin aft of the rivet.

Each of these little zones of disturbed air adds its own little bit of wing-profile drag. The turbulence caused by the rivet heads makes the flow over the wing more likely to become turbulent. On one airplane, small mushroom-headed rivets 0.038 in. high gave a one-percent speed loss, and larger rivets of 0.087 inch high gave a 6.6 percent speed reduction. On top of this, the forward movement of the boundary-layer transition point gave another 3-percent speed-reduction. So the larger rivets plus the earlier transition together gave almost ten percent slower flying speed. The penalty for using snap-head rivets also is severe.

NACA Tests on Rivets. NACA also tested a five-foot chord wing with rivets spaced 3/4 in. apart in 13 span-wise rows on both sides. For flush rivets the drag increased by 6 percent. For 3/32 in. brazier-head rivets this increased to 27 percent. About 70 percent of this drag came from the rivets on the forward 30 percent of the airfoil.

In other tests, on one 200-mph airplane, replacing flush rivets with snap-head rivets increased the wing drag by 8.5 percent. Also, the maximum speed decreased by more than 18 mph.

Much testing was done on the exposed rivet heads common in metal wing construction, with butt-jointed skins on a 6 by 36 feet airfoil model. First with simulated rivet heads placed in a single row at various chord positions. Then nine rows on the upper, next nine rows on both surfaces. A single span-wise row at the 5 percent chord position increased the minimum drag by 19 percent. This first row created a strongly turbulent boundary-layer flow over the rest of the wing. Nine rows on the upper surface from 5 to 85 percent chord positions increased the minimum drag by 21 percent.

NACA's Findings:

1. A single row of rivets at 5 percent chord on the upper surface gave increased minimum drag, more than at any other position.
2. Rivets added on the upper surface back of the first row at 5 percent chord had little effect on drag.
3. Nine rows of rivets on the lower surface increased drag less than one-third compared to the rivets on the upper surface.

NACA's Final Conclusion: Exposed rivet heads have a large detrimental effect on the fuel consumption at an airplane's cruise-speed.

Flush-riveting. Flush-riveting greatly reduces the effect of the rivets on the wing's boundary-layer airflow. However, for the manufacturer it is much cheaper to build metal structures with regular protruding rivets. After all, they have to make a profit on the airplane. Cost is the reason not all production airplanes are flush-riveted. Usually, manufacturers will flush-rivet their more expensive, high-performance airplanes only where it has the most effect.

With flush riveting, the maximum advantage is not obtained unless care is taken to ensure that the indentations in the riveting do not cause the boundary-layer transition-point to move forward. Unless the indentations are filled and polished, they might pull the transition point forward to 5 or 10 percent of the leading edge, with greatly increased drag.

Painted Wing Surfaces. The painted wing finish on production airplanes is not always exactly the same. Depending on the painter, his equipment, and atmospheric conditions, there may be over-spray. There are various other factors, like the care taken in handling the aircraft. Unless carefully rubbed down, paint lines may cause transition and increase the wing's profile drag. In one NACA test, the roughness due to bad spray painting increased drag by 14 percent.

Skin Joints. On most airplane wings, the top and bottom surfaces suffer from things like overlapping skin joints. Forward-facing lap joints especially are great drag-producers, about just as bad as snap-head rivets. This depends, of course, much on the skill with which the surface is manufactured. Unless a filler is used, there always is some loss. Each of the discontinuities will result in a slight increase in form drag.

NACA tests showed that six jogged lap joints on each surface increased drag by 4 percent. For plain laps it was 9 percent. The next test was with a down-wind step or lap of 0.012 in. on the leading edge. This increased minimum skin-friction drag by 13 percent. Plate laps at right angles to the airflow have about 60 times the drag as a lap lined up with the airflow.

Gaps. Surface conditions are not the only potential boundary-layer hazards. Another frequent cause of boundary-layer disturbance is the presence of air leaking through gaps, especially at control-surface slots in the wing surface. As air emerges from the gap in the wing surface it squirts out at 60-90 degrees to the wing's surface.

This jet of leaking air is not going in the same direction as the main air-low. When they mix, the flow becomes very turbulent. The thickness of the turbulent boundary layer increases, and so does the drag. The more load the airfoil carries on its aft part, the worse the problem of control-gap air leakage. Deflected flaps also have a gap at each inboard-end. Often they do not meet the wing-root fillet cleanly, causing interference drag in cruise-flight.

Fuel-filler Cap and Hinge brackets. Fuel filler caps often project above the wing surface, usually quite close to the leading edge. Located at the thickest part of the wing, they cause flow-separation over the wing area behind them. This, of course, creates a large area of unnecessary turbulent boundary-layer drag. Aileron and flap-hinge brackets also cause high-drag turbulent flow.

Various other causes of wing drag. High wing drag also comes from items like damaged seal strips, miss-rigged flaps and doors. And from patches, miss-matched skin sections, dents in the skin, paint-stripes, inspection-panels, and fuel-vent pipes.

Wing-walks sometimes have their rough surface carried all the way to the leading edge, resulting in extra high drag. Wing-tip tanks result in a loss in performance due to the increase in wetted area. All openings in the wing surface not properly sealed will increase the profile drag. Panels, access cover plates, etc. may sometimes open up partly when the wing structure is subject to high air-loads.

Author's Note: After Chapters 3, 5, 7, 9, and 11 there are some photographs shown dealing with the subject of the Chapter. No captions are included for the simple reason that you will be very familiar with the things shown in the individual photographs.

Chapter Four

Wing Drag - The Cost

Our Four Example Airplanes. In the various sections on the parasite drag of your airplane's main assemblies, we will base our drag calculations on four types of manufacturer's General Aviation light airplanes:

1. A 2400-pound four-seat airplane.
   It is powered by a 160-HP engine and a fixed-pitch propeller; n = 0.75.
   Maximum speed at sea level is 123 knots or 141.5 mph.
   Cruise-speed = 129 mph. Air-pressure q = 42.562 lb/sf.
   Nominal wing area is 160 sf. Our calculated effective wing area Se = 148 sf.

2. A 2800-pound four-to-five seat airplane with retractable landing-gear.
   It is powered by a 200-HP engine with a constant-speed propeller; n = 0.83.
   Maximum speed at sea level is 156 knots or 180 mph.
   Cruise-speed = 164 mph. Air-pressure q = 68.79 lb/sf.
   Nominal wing area is 188 sf, Se = 167 sf.

3. A 3400-pound four-to-five seat airplane single-engine retractable.
   It is powered by a 285-HP engine with a constant-speed propeller; n = 0.83.
   Maximum speed at sea level is 182.5 knots or 210 mph.
   Cruise-speed = 191 mph. Air-pressure q = 93.3064 lb/sf.
   Nominal wing area is 188 sf, Se = 167 sf.

4. A 5500-pound twin retractable.
   It is powered by two 285-HP engines with constant-speed propellers; n = 0.83.
   Maximum speed at sea level is 207 knots or 238 mph.
   Cruise-speed = 217 mph. Air-pressure q = 120.4382 lb-sf.
   Nominal wing area is 179 sf, Se = 158 sf.

Profile-drag values. The basic minimum zero-lift section profile-drag coefficient (Cdo) for the wind-tunnel model section usually lies between 0.0050 and 0.0100, usually at a test Reynolds Number between 6 and 10 million. A very smooth, clean metal light airplane wing may have about twice the minimum profile-section drag value.

Wing Profile-drag Calculations. For our four example airplanes we will first work out the wing profile-drag based on a range of practical drag-coefficients. Then, in Table No. 2, we'll look into what it all may come to in Aviation-gasoline dollars. For each example we start with the calculations for the section-profile model at a reasonably practical value.

How we are going to tackle this. We want to see the results of our considerations and calculations in practical, real-world figures. Therefore we do not work with the regular nominal values for wing areas. This fully takes in the area covered by the fuselage and, on twins, by the engine-nacelles. Instead, we work with the calculated net wing area figure.

For each of the four airplane sections in Table No. 1, we will work out the net profile drag in pounds for the effective wing area.

A. First we multiply the cruise-speed value of the air-pressure q by the estimated effective wing area "Se." This gives us our Factor (1).

B. We multiply the selected range of profile drag-coefficient figures by this Factor (1) in Table No. 1.

C. The result of our calculation gives us the wing profile drag in pounds for each profile drag coefficient in our Table.

D. Dividing these drag values over the net airplane drag gives us the percentages of net wing-profile drag over net airplane drag for each percentage value in our Cd-range.

In Table No. 2 we take the net profile-drag values from Table No. 1, and work out:

1. The gross horsepower required, based on the applicable (assumed) propeller-efficiency factor "n" for the airplane.

2. The fuel-consumption in number of U.S. gallons of fuel per hour, based on 0.5 lb/hp/hr.

3. The cost in US dollars, at $2.00 per U.S. gallon.

Next, as a check, for each airplane we work the drag values in pounds for the airplane against the NACA wing-drag values we find in Table No. 1 shown below for the various profile thicknesses. The NACA data below is for minimum profile drag per square foot for metal riveted wing-surfaces as seen in planform, at 100 mph.

Table No. 1. Thickness and Drag

Thickness/Chord Ratio	Drag lb/sf
9%	0.242
12%	0.264
15%	0.297
18%	0.330

For flying speeds over 100 mph we must multiply these values by the "Multiplication Factor" (M.F.) for the actual cruise-speed. For each of our four example airplanes we will also look at what these figures work out to in percentages of total airplane drag. We work it out for the 75% cruise-speed, and check where the resulting drag figures put the drag values in the wing's Cd-range.

Working it Out for Airplane No. 1

We assume a cruise-flight airplane weight half way between maximum take-off weight and +empty weight. In this case this gives us 1950 pounds. The lift-coefficient then works out to

Cl = Airplane Weight / (Air-pressure q x effective wing area).

For the airspeed of 129 mph the air-pressure table gives a value of 42.562 lb/sf. Thus

$$\begin{aligned} Cl &= 1950 / (42.562 \times 148) \\ &= 1950 / 6298.88 = 0.31 \end{aligned}$$

The wing-profile section used is the 12% thick NACA section 2412. For this lift-coefficient the NACA/NASA data the minimum drag at a Reynolds Number of 5-6 million is Cdo = 0.0065. The airplane's 75-percent cruise-Reynolds Number is about 5.86 million.

Factor (1), (air-pressure q times the estimated wing area) comes to

$$42.562 \times 148 = 6299.18$$

The number 6299.18 (Factor 1) we use In Table No. 2 to work out the wing's profile drag.

Note: One aerodynamicist-author estimated the wing profile drag for a Piper Cherokee (in regular service) as 0.0093. To this he adds 50% for roughness. This gives an upper range of 0.01395, just under 0.0140. We want to see what the 50-percent higher Cd figures come down to at the pump. Therefore, we extend our calculations for airplane No. one to Cd = 0.0140.

We work out the profile drag from the value of 0.0100 up to 0.0140 in steps of 0.0005, or 5 counts. One count is 0.0001.

$$\begin{aligned} \text{Wing Profile Drag } D &= Cd \times (q \times \text{Effective Wing Area}) \\ &= Cd \times (42.562 \times 148) \\ &= Cd \times 6299.18 \text{ lb} \end{aligned}$$

Next we first work out the value for the net airplane drag for the cruise-flight condition. This lets us directly work out the percentage of the wing's net profile-drag over the airplane's net total drag for each step. The net airplane drag at 75-percent cruise works out to

$$\begin{aligned} D &= (((HP \times 0.75) \times (n) \times (375) / V \\ &= (((160 \times 0.75) \times (0.75) \times (375) / 129 \\ &= ((120 \times .75) \times (375) / 129 \\ &= (90 \times 375) / 129 \\ &= 33750 / 129 \\ &= 261.63 \text{ lb} \end{aligned}$$

Table No. 2.

Airplane No. 1. Net Profile Drag @ Cruise speed and percentage of total airplane drag.

	Cd		Factor (q x Se) (1)		Wing Drag lb		Total Drag lb		Percent of A/P Drag
1.	0.0100	x	6299.18	=	62.99	/	261.63	=	24.08
2.	0.0105	x	6299.18	=	66.14	/	261.63	=	25.28
3.	0.0110	x	6299.18	=	69.29	/	261.63	=	26.48
4.	0.0115	x	6299.18	=	72.44	/	261.63	=	27.69
5.	0.0120	x	6299.18	=	75.59	/	261.63	=	28.89
6.	0.0125	x	6299.18	=	78.74	/	261.63	=	30.10
7.	0.0130	x	6299.18	=	81.89	/	261.63	=	31.30
8.	0.0135	x	6299.18	=	85.04	/	261.63	=	32.63
9.	0.0140	x	6299.18	=	88.19	/	261.63	=	33.84

For Table No. 2 we now work out gross horsepower required, and cost at the pump. This time we put the propeller-efficiency factor "n" in our equation.

Gross HP required = (Drag x Speed) / (n x 375)
= Drag x (129 / (0.75 x 375))
= Drag x (129 / 281.25)
= Drag x 0.45867

The number 0.45867 is our Factor (2). For the gross horsepower required we multiply the drag-values from Table No. 1 by Factor (2). We now have the cost per hour of flying for the range of profile-drag values from Cd = 0.0100 to 0.0140.

Table No. 3.
Airplane No. 1. Wing Drag, HP, Fuel-Consumption, and Fuel-Cost, per hour.

	Drag lb		Factor (2)	HP req total	Fuel gal.	$
1.	62.99	x	0.45867	28.90	2.41	4.82
2.	66.14	x	0.45867	30.34	2.53	5.06
3.	69.29	x	0.45867	31.79	2.65	5.30
4.	72.44	x	0.45867	33.23	2.77	5.54
5.	75.59	x	0.45867	34.67	2.89	5.78
6.	78.74	x	0.45867	36.12	3.01	6.02
7.	81.89	x	0.45867	37.56	3.13	6.26
8.	85.04	x	0.45867	39.00	3.25	6.50
9.	88.19	x	0.45867	40.45	3.37	6.74

Wing drag according to the NACA Figures. Let's look at the total wing profile-drag and the likely drag-coefficient level based on the NACA drag figures. The wing thickness is 12 percent. For the cruise speed of 129 mph, the multiplication factor is

1.29 x 1.29 = 1.664

For 12% t/c ratio, NACA's minimum profile-drag per square foot of wing area = 0.264 lb

Drag per square foot = 1.664 x 0.264
= 0.439 lb/sf
148 x 0.439 = 64.97 lb

This would fit the wing with a Cd of just over 0.0103 and shows a wing drag/airplane drag ratio of about 25 percent, for a rather smooth wing surface, most likely often the wing profile drag, and thus the percentage value, will be a good deal higher.

The net wing profile drag of 88.19 lb we calculated in Table No. 1, for a Cd of 0.0140, over the net total airplane drag of 261.63 lb, would give a 33.71 percent drag figure for the wing. Could well be within the ballpark.

Working it out for Airplane No. 2.

We estimate the airplane's cruise-weight at 2300 pounds. For a cruise-speed of 164 mph, the lift-coefficient works out to

Cl = Weight / (Air-pressure q x effective wing area)
= 2300 / (68.79 x 163)
= 2300 / 11212.77
= 0.205

This airplane has a wing with two NACA laminar airfoils, 16 percent thick at the root and 12 percent thick at the tip. This gives an average profile-thickness at 14.0 percent. The wind tunnel Reynolds Number is 5.36 million, and the airplane's cruise Reynolds Number is about 7.51 million, which is better. The average drag-coefficient at Cl = 0.205 for the smooth laminar-flow model-section is 0.0046. However, laminar flow on an airplane wing is an elusive thing. Many authors advise not to count on it for a wing in service. So we will make our table for Cd = 0.70 to Cd = 0.0115.

The nominal wing area is 188 square feet and our estimated effective wing area comes to about 163 square feet. At a cruise-speed of 164 mph, Factor (1) works out to

q x Se = 68.79 x 163 = 11212.77

Net airplane drag D = (((HP x 0.75) x (n)) x (375) / V
= (((180 x 0.75) x (0.83)) x (375) / 164
= ((135 x 0.83) x (375) / 164
= (112.05 x 375) / 164
= 42018.75 / 164
= 256.21 lb

Table No. 4
Airplane No. 2. Net Wing Profile Drag,
and Percentage of Total Net Airplane Drag.

	Cd		Factor (q x Se) (1)		Drag lb		Total Drag	Percent Drag
1.	0.0070	x	11212.77	=	78.49	/	256.21	30.62
2.	0.0075	x	11212.77	=	84.10	/	256.21	32.82
3.	0.0080	x	11212.77	=	89.70	/	256.21	35.01
4.	0.0085	x	11212.77	=	95.31	/	256.21	37.20
5.	0.0090	x	11212.77	=	100.91	/	256.21	39.39
6.	0.0092	x	11212.77	=	103.16	/	256.21	40.26
7.	0.0095	x	11212.77	=	106.52	/	256.21	41.58
8.	0.0100	x	11212.77	=	112.13	/	256.21	43.76
9.	0.0105	x	11212,77	=	117.73	/	256.21	45.95
10.	0.1100	x	11212.77	=	123.34	/	256.21	48.14
11.	0.0115	x	11212.77	=	128.95	/	256.21	50.33

We'll now work out the figures for Gross Horsepower required, the fuel-consumption, and the fuel-cost. Our Factor (2) comes to

Gross HP required = (D x V) / (n x 375)
= D x (V / (0.83 x 375))
= D x (V / 311.25))
= D x (164 / 311.25)
= D x 0.5269

Table No. 5.
Airplane No. 2. Drag, Gross Horsepower required,
Fuel-consumption, and Fuel-Cost, per hour.

	Drag lb		Factor (2)	HP total	Fuel Gal.	$
1.	78.49	x	0.5269	41.36	3.45	6.90
2.	84.10	x	0.5269	44.31	3.69	7.39
3.	89.70	x	0.5269	47.26	3.94	7.88
4.	95.31	x	0.5269	50.22	4.18	8.37
5.	100.91	x	0.5269	53.17	4.43	8.86
6.	103.16	x	0.5269	54.36	4.53	9.06
7.	106.52	x	0.5269	56.13	4.68	9.35
8.	112.13	x	0.5269	59.08	4.92	9.85
9.	117.73	x	0.5269	62.03	5.17	10.34
10.	123.34	x	0.5269	64.99	5.42	10.83
11.	128.95	x	0.5269	67.94	5.66	11.32

Now let's check the NACA figures for the profile drag per square foot for our effective wing-area at our 164 mph cruise-speed. The average wing-thickness is

$$(12 + 15) / 2 = 13.5 \text{ percent.}$$

For our 164-mph cruise speed, the factor for multiplication works out to:

$$1.64 \times 1.64 = 2.69$$

For 12% t/c D = 2.69 x 0.264 = 0.710 lb/sf
For 15% t/c D = 2.69 x 0.297 = 0.799 lb/sf
For 13.5 percent,

D = (0.264 + 0.297) = 0.562
= 0.562 / 2
= 0.281 lb/sf

Therefore, for 13.5% t/c

D = 0.281 x 2.67 = 0.75
= 0.75 x 163

= 122.29 lb/sf

Our calculations show that this would fit the wing with a drag-coefficient of about 0.0109. A net wing-profile drag of 128.95 pounds comes to 47.97 percent of the total net airplane drag. This looks realistic for this kind of airplane. On an airplane with retractable landing gear, the wing drag always is apt to be a larger percentage of the total airplane drag.

Working It Out For Airplane No. 3.

Airplane No. 3 has with a combination of two NACA airfoils, 23016 at the fuselage and 23012 at the tip. For an airplane weight of 2700 lb, the lift-coefficient at the 191 mph cruise-speed works out to

Cl = Weight / (Air-pressure q x effective wing area)
Cl = 2700 / (93.3064 x 167)
= 2700 / 15582.168
= 0.173

The average minimum Cdo for the two profiles is 0.0064 for the smooth wind-tunnel section at R. N. = 10 million, the same as the airplane's cruise R. N. The estimated effective wing area Se is 167 square feet out of 188 square feet. For a cruise speed of 191 mph the air-pressure table gives 93.3064 pounds per square foot. Multiplying this by the effective wing-area we get

93.3064 x 167 = 15582.17

This is our Factor (1). The net airplane drag works out to

D = (((HP x 0.75) x (n) x (375) / V
= (((285 x 0.75) x (0.83)) x (375) / 191
= ((213.75 x 0.83) x (375) / 191
= (177.413 x 375) / 191
= 66529.69 / 191
= 348.32 lb

Table No. 6.
Airplane No. 3. Net Wing Profile Drag and Percentage of Total Drag.

Cd Drag		Factor (q x S_e) (1)		Drag lb / Total Drag	Percent
1. 0.0100	x	15582.17	=	155.82 / 348.32	44.73
2. 0.0105	x	15582.17	=	163.61 / 348.32	46.97
3. 0.0110	x	15582.17	=	171.40 / 348.32	49.21
4. 0.0115	x	15582.17	=	179.20 / 348.32	51.45

5.	0.0120	x	15582.17	=	186.99 / 348.32	53.68
6.	0.0125	x	15582.17	=	194.78 / 348.32	55.92
7.	0.0130	x	15582.17	=	202.57 / 348.32	58.16

For Table No. 2 we now work out the gross horsepower required and what it comes down to at the fuel pump. Our factor (2) comes to

Gross HP required = (D x V) / (n x 375)
= D x (191 / (0.83 x 375))
= D x (191 / 311.25)
= D x 0.6137

We multiply the drag-values from Table No. 1 by Factor (2) of 0.6137. The pump figures we work out in columns 5 and 6.

Table No. 7.
Airplane No. 3. Net Drag, Net HP, Gross HP, Fuel-Consumption, and Fuel-Cost, per hour.

	Drag lb		Factor (2)	HP gross	Fuel Gal.	$
1.	155.82	x	0.6137	95.67	7.97	15.95
2.	163.61	x	0.6137	100.46	8.37	16.74
3.	171.40	x	0.6137	105.24	8.77	17.54
4.	179.20	x	0.6137	110.03	9.17	18.34
5.	186.99	x	0.6137	114.81	9.57	19.13
6.	194.78	x	0.6137	119.60	9.97	19.93
7.	202.57	x	0.6137	124.31	10.36	20.72

According to the NACA figures, for 12% t/c, drag = 0.264, for 16% t/c, drag = 0.308.

Therefore, for 14.0 percent, the drag per square foot =

D = (0.264 + 0.308) = 0.572
= 0.572 / 2
= 0.286 lb

Cruise speed is 191 mph, so the speed-multiplication factor comes to 1.91 x 1.91 = 3.648 Multiplying by this factor we get

0.286 x 3.648 = 1.043

net profile-drag per square foot. For the effective wing-area we get

167 x 1.043 = 174.18 lb

of wing profile-drag. This time our calculations show that with a Cd of 0.0112, or 72 percent over the minimum drag-coefficient value. The net wing profile drag comes to 174.52 lb, or 50 percent of the total airplane drag.

The net wing profile drag of 202.57 lb over a net total airplane-drag of 348.32 pounds from Table No. 1 would give a 58.16 percent drag-figure for the wing. So we'll say that the actual value most probably lies somewhere in the middle.

Working it Out for Airplane No. 4.

In this case we have two wide engine-nacelles taking up a good deal of wing area, leaving us with an estimated net wing-area of 58 effective square feet out of a nominal 179 square feet. The half-way cruise-weight is 4400 pounds, the cruise lift-coefficient for the effective wing area is 0.23. The Reynolds Number at cruise-speed is 9.83 million, very close to the test Reynolds Number of 10 m.

The wing profile sections are NACA 23018 and NACA 2309, so the average thickness is 13.5 percent. Drag coefficients are 0.0062 for the 9% section and 0.0068 for the 18% section, which gives an average profile drag-coefficient of

(0.0062 + 0.0068) / 2
= 0.0130 / 2
= 0.0065

The 75-percent power cruise speed is 217 mph, therefore: Factor (1) comes to

q x Effective Area
= 120.4382 x 158
= 19029.236 (= Factor 1)

Profile Drag D = Cd x 19029.236, and the total net airplane drag comes to

D = (((HP x 0.75) x (n) x (375) / V
= (((570 x 0.75 x (0.83) x (375) / 217
= ((427.50 x 0.83) x (375) / 217
= (354.825 x 375) / 217
= 133059.375 / 217 = 613.18 lb

Table No. 8.
Airplane No. 4. Net Wing Profile Drag and percentage of total drag.

	Cd Drag		Factor (q x Se) (1)		Drag lb		Total Drag		Percent
1.	0.0100	x	19029.236	=	190.29	/	613.18	=	31.03
2.	0.0105	x	19029.236	=	199.81	/	613.18	=	32.59
3.	0.0110	x	19029.236	=	209.32	/	613.18	=	34.14
4.	0.0115	x	19029.236	=	218.84	/	613.18	=	35.69
5.	0.0120	x	19029.236	=	228.35	/	613.18	=	37.24
6.	0.0125	x	19029.236	=	237.87	/	613.18	=	38.79
7.	0.0130	x	19029.236	=	247.38	/	613.18	=	40.34

Now we'll work out the figures for Gross Horsepower required, fuel-consumption, and the fuel-cost. Our factor (2) comes to:

Gross HP required = (D x V) / (n x 375)
= (D x (217 / (0.83 x 375))
= D x (217 / 311.25)
= D x 0.6972

For the gross horsepower we multiply the drag-values from Table No. 1 by Factor (2). The fuel-pump figures we get in columns 5 and 6.

Table No. 9.
Airplane No. 4. Net Drag, Net HP req., Gross HP req., Fuel-Consumption and Cost.

	Drag lb	Factor (2)	Total HP	Fuel Gal.	$
1.	190.29	0.6972	132.67	11.06	22.11
2.	199.81	0.6972	139.31	11.61	23.22
3.	209.32	0.6972	145.94	12.16	24.32
4.	218.84	0.6972	152.57	12.71	25.43
5.	228.35	0.6972	159.20	13.27	26.53
6.	237.87	0.6972	165.84	13.82	27.64
7.	247.38	0.6972	172.47	14.37	28.75

For this airplane, we'll assume that the two engine nacelles will give us five percent interference drag. There is also the slip-stream of the two propellers. So we'll make another simple table for this, to get at the final figures for the horsepower required and fuel-consumption.

Table No. 10.
Airplane No. 4. Gross HP and total cost for five-percent additional interference drag.

	Drag		Factor		Drag	Gal.	Cost
1.	132.67	x	1.05	=	139.30	11.61	3.22
2.	139.31	x	1.05	=	146.28	12.19	4.38
3.	145.94	x	1.05	=	153.24	12.77	5.54
4.	152.57	x	1.05	=	160.20	13.35	6.70
5.	159.20	x	1.05	=	167.16	13.93	7.86
6.	165.84	x	1.05	=	174.13	14.51	9.02
7.	172.47	x	1.05	=	181.09	15.09	0.18

Now we'll check our figures against the NACA figures for the profile drag at 100 mph. First we work out the average figure for the two profiles of 9 and 18 percent thick. Cruise speed is 217 mph, so the speed factor comes to

2.17 x 2.17 = 4.71

For 9% t/c: 0.2421 x 4.71 = 1.139
For 18% t/c: 0.3300 x 4.71 = 1.554
For 13.5 t/c: 0.2860 x 4.71 = 1.347

1.347 x 158 = 212.83 lb net wing profile drag.

Our calculations show that this would fit the wing with a drag-coefficient Cd of 0.0112 or about 34.75 percent of total airplane drag. According to the table, a net wing profile drag of 247.38 pounds would make up

247.48 / 613.18 = 40.34 percent of the total net airplane drag.

For this airplane, we have a relatively small wing area, so in this case the second figure seems more realistic.

Chapter Five

Fuselage Drag - Some Causes

Airplane Drag. The total drag of your airplane's fuselage assembly depends mostly on the turbulent drag of its parts and on their mutual interference. That is where their form or pressure-drag comes in. In this case, form-drag is due mainly to the disturbance or wake created by the fuselage. as a whole. Important factors are its main cross-sectional area and longitudinal fairing lines.

Some Causes of Fuselage Drag. Now we'll take a look at some smaller individual causes of fuselage drag. When taking a good look at your airplane's fuselage you'll probably be able to recognize some of them.

Interference Drag. This type of drag results from the breakdown of the boundary-layer airflow especially at items like exposed bolt-heads and -nuts, drain-fittings, and radio antennas. Often, this turbulent air flows over other protuberances, causing additional drag. And even if you fair these other protuberances, there will still be an interference-drag effect.

Fuselage Wetted Area and Skin-friction Drag. One important factor for the fuselage here is its wetted area. The larger the wetted area in direct contact with the turbulent boundary-layer airflow, the more skin-friction drag. On a square-sided fuselage, the additional boundary-layer separation at the corners causes much higher drag. If the corner is large or sharp, or its radius too small, the flow will separate and cause much extra drag. Typical fuselage-areas where separation also may develop are sharp breaks and discontinuities, at antennas, air-scoops, and various other protrusions and protuberances.

Propeller Blockage. This refers to the effect of the interference of the fuselage or a nacelle on the propeller efficiency. The propeller slipstream is slowed down by the fuselage or nacelle body around which it is forced to go. This causes extra drag, which includes form drag plus the effect of the propeller slipstream on the local pressure and boundary layer.

Windshield. While a flat-wrapped windshield makes for easier fabrication, and may prevent optical distortion, unfortunately, a flat-wrapped windshield joining a flat-wrapped cabin roof forms a sharp corner. Such a sharp corner causes separation and thus significantly increases drag. A windshield slope of less than 45 degree from the vertical also acts a an effective drag-raiser. On a smoothly-faired fuselage shape, even an efficient windshield-cabin combination may add (40) about 6 percent drag. Windshield drag also may account for 15 percent of total airplane drag! Windshield retainers with a good number of screws cause extra turbulent drag.

Fuselage Rear-end Shape. The fuselage rear-end shape often gives more drag than the nose. If the flow will not stay attached up to the end of the tail cone, it will cause flow- separations. This usually happens on the after-body of a short or upswept fuselage, giving about 20 percent extra base drag. Several General Aviation light airplanes have such a rather high-drag aft-fuselage shape.

Paint Job. Sharp paint-edges, -projections, and -corners will produce disturbances in the boundary layer airflow. Thus a complicated paint job can cost you a few miles per hour in cruise-speed as well. Paint may be damaged by scratches and marks from tools, and rocks and debris thrown up by the wheels. Ultraviolet light from the sun degrades protective coatings, while trapped moisture may cause corrosion and pitted metal surfaces.

Surface Skin Roughness. As on the wing, a lot of unnecessary drag on the fuselage of your airplane results from rough surface areas. The lapping of sheets, for example, causes an irregularity amounting to a protuberance. Skin-plating and skin-lapping increase boundary-layer airflow separation and skin-friction drag. Such a lap, critically located, will cause a 10-15 percent increase in local fuselage skin-friction drag.

Protrusions. Looking at airplane fuselages at any airfield you will see the most extreme variety of protrusions and protuberances. Even a basically efficient fuselage often still has several drag-creating protuberances sticking out into the airstream. Your airplane's fuselage drag goes up quickly when you add items like antennas, strobe lights, and OAT probes.

Every protuberance sticking out of your airplane's fuselage is a separate body. It disturbs the airflow over the downstream surface and causes parasite drag. Depending on the position of the protuberance, the flow will differ from that of the normal boundary-layer airs-flow. Therefore it has its own friction- and pressure-drag, and perhaps its own separation drag.

With higher pressure against the front than at the rear, we get a drag-force in the stream-wise direction. A protrusion changes the skin-friction characteristics of the surface, and leaves a turbulent wake behind it. While they may look negligible individually. together they will add a lot of drag. Though often they are the result of the manufacturer's need to keep cost and complexity down, they do create a lot of unnecessary drag.

Unfortunately, anything sticking out of your airplane adds drag, costing you mph and gasoline. And so the cost is still there, only you now are paying it in the extra fuel costs they take out of your wallet. In many cases, not all of these parasite drag producers may be necessary anyway.

Sheet-metal Construction. With sheet-metal construction of our light airplanes, they often have straight skins simply bent or wrapped into shape. Unfortunately, rivets of various sorts are playing a major role in fuselage sheet-metal airplane construction. Thousands of rivets on a typical light airplane, just for the aluminum sheeting and the frames.

On many a twin's nose we see hundreds of draggy rivets, ahead of the windshield, and in the fuselage-wing area. These rivets, plus several protuberances, create much turbulence, with high skin-friction drag.

Doors. Cabin doors often are big offenders in that they let air leak out. Also, some baggage-compartment doors sit right beside the wing's trailing edge, with their bottom edge seal very close to the wing surface. Because of their location, they offer a good potential for air leakage to the outside. Besides reducing your airplane's speed, they also create unwanted noise. Older Bellanca Cruisair airplanes are reported be 20 mph slower because doors don't close tight, the cowling has gaps and waves at its edges, and the wings have rough areas.

Hinges. Exposed hinges and door handles on airplanes create much more drag than those found on today's late-model highly-streamlined automobiles.

Outside Air Temperature Probe. This is a simple, appropriate, and very visible protuberance example. On many light airplanes the outside air temperature (OAT) probe sticks out perpendicular to the surface of the windshield or fuselage. Right in the high-speed airflow over the top created by the angle of the windshield. On a single-engine airplane we also have the propeller's slipstream effect. At this location, any protuberance has from 2 to 5 times the normal flat-plate drag. So, while this may well be the handiest position for the pilot, it puts the high-drag probe where its drag is very high.

Boarding Steps. Many light airplanes have a fixed boarding step, or steps, often a step mounted on a piece of tubing. Such a step installation creates as much parasite drag as several feet of your airplane's wing. It may cost you four or five mph in cruise-speed. Hour after pleasant hour.

Antennas. Radio antennas also produce considerable drag. And often there's a good number of them, all contributing their parasite drag.

Gaps. Gaps in the skin are an important cause of extra airplane drag. They allow air to leak through and disrupt the surface airflow, creating a lot of extra turbulent boundary-layer drag. The high flow-speed of the boundary-layer air creates a strong sucking effect at even the smallest leakage point. It also creates boundary layer skin-friction drag.

First, by flowing in through holes and gaps in high-pressure area. Second, by flowing out again at the low-pressure areas. The momentum loss of the inhaled and exhaled air adds directly to the drag over the entire area of downstream skin area. It may well cause premature flow separation, which increases drag even more. Because of the decreased density of the outside air, the leaks will increase at the higher cruise-flight altitudes.

Patches. Patches, access- and inspection doors and cover-plates, pieces of broken or damaged seal strips, are also high-drag items.

Ventilation Drag. Because if you let air in you have to let it flow out again, the air taken in for cabin ventilation is a problem. As it results from momentum- or energy-losses experienced by the internal flow, it is a function of the internal flow circuit configuration. The heating- and ventilating air flowing through your airplane's cabin space forms a part of your airplane's total parasite drag. Fresh-air vents and vanes sticking out into the slipstream cause extra drag.
On the dorsal fin they create interference drag.

Leakage Drag. For a production propeller-driven light airplane, leaks may add about 5% of drag. Even small gaps can cause reduced performance. A 1/8th-inch by 48-inch gap causes as much drag as a metal strip 1/8th-inch high by 48-inch long. Let's work out some figures.

$$\text{Area} = 0.125 \times 48.0 = 6.0 \text{ sq. in.} = 0.04167 \text{ sf}$$

At 100 mph and 80.0 percent propeller efficiency, the drag works out to

$$\text{Drag} = 0.04167 \times 25.5767 = 1.066 \text{ lb}$$

Horsepower required HP required = $HP = (D \times V) / 375$

HP = (1.066 x 100) / 375
= 106.6 / 375 = 0.355.

For our four airplanes at their cruise-speeds, we get

Airplane No. 1., V = 129 mph. HP = 0.59.
Airplane No. 2., V = 164 mph. HP = 0.955.
Airplane No. 3., V = 191 mph. HP = 1.295.
Airplane No. 4., V = 217 mph. HP = 1.672.

An Interesting Note on Leakage Tests. Tests done on the "Hurricane" fighter in 1938 showed that leakage air was responsible for at least up to 10% of total parasite drag.

Hurricane prototype: HP = 990, $V_{max.}$ = 315 mph @ 16,200 feet
HP @ 75% = say 750
V @ 75% = .91 x 315 = 287 mph

Ten percent of 750 HP = 75 HP for air leakage only. And that for a fighter plane which needed every single horsepower against the German Me109! The extra 75 HP would have given it an extra 3 percent or 9 mph in top speed.

Fastener Drag

Here's an interesting Table showing the differences in drag created by various types of fasteners used in airplane construction. The figures are from NACA, for three-dimensional effects.

Table No. 1. Fastener Drag.

	Cd	% Drag Increase
Flush rivet	0.02	
Flat-headed screw	0.02	
Flat-headed rivet	0.04	100%
Round-headed rivet	0.32	1600%
Bolt head, round	0.42	2100%
Bolt head	0.76	3800%
Round pin	0.80	4000%
Bolt head with washer	0.80	4000%

During the 1940's tests on a Mustang fighter gave these interesting results:

Table No. 2. Drag Test on North American Mustang Fighter

Surface condition	Speed	% speed difference
Airplane as received from the Service	306.5 knots	
With camouflage finish, wax polished	330.9 knots	+8 %
Smooth camouflage finish, carefully applied	330.0 knots	+7 %
Special night finish, careful application	292.7 knots	-4.5 %
Special night finish, normal application	285.7 knots	-6.7 %

Thus the general cleaning-up of the airplane from a regular service condition gave 24.3 knot or 8 percent increase in the airplane's cruise-speed. The special night finish gave a 45.2 knot or 14.75 percent decrease. The difference between the service condition and the smoothed conditions indicates the extreme seriousness of allowing a painted airplane to deteriorate in operation. Other tests on the Mustang showed that once a critical roughness of 0.0005 inch has been exceeded, the drag increases faster than theory would suggest.

Protrusions and protuberances include in themselves often insignificant-looking small items. Below is of list of often-seen items. They are true parasites, feeding off your engine's power and off your wallet.

Access doors mismatched
Access doors not fully closed.
ADF blades
Air Leaks
Antennas (wire type)
Antenna wires from fuselage to stabilizer
Blisters of any type
Boarding steps
Bolt heads
Brackets of various kinds
Broken or damaged seal strips.
Cabin and baggage area door locks
Cabin ventilation vents.
Clevis pins
Control balances
Control hinges
Control horns
Dents in skin plating
DME blades
Door handles (exposed)
Door hinges (exposed)
Doors at equipment inside fuselage.
Door reinforcement plates
Doors, cabin or access not fully closed
Doors, miss-rigged
Doors, poorly fitting
Drain tubes
Exhaust pipes
Fairing studs
Fittings, exposed
Fuselage tail tie-down bracket.
Gaps, various kinds at various places
Grommets, damaged or missing (around drain tubes for example)
Handholds at doors
Hinges, especially those big cabin door ones, and on clamshell type doors
Humps and bumps in the skin plating
Inspection covers disturbing the airflow
Latches
Lights, navigation and other
Locks on access doors, esp. when not fitting properly
Outside-Air Temperature Probe
Patches, especially if riveted-on
Paint job, poorly done or worn
Paint stripes
Rivets, protruding.
Skin panels, with rough corners, sharp-edged
Skin dents.

Skin laps at joints
Skin panels, misaligned
Struts
Steps on fuselage for checking fuel on high-wing airplanes
Surface-skin roughness
Transponder blades
Ventilation air scoops
Vent pipes, tubes and air scoops
Ventral fins on fuselage
VHF blades
VOR blades
Wing-strut fittings on lower fuselage
Window frames, with draggy edges
Windshield de-icer tubes.
Wires

Chapter Six

Fuselage Drag - the Cost

Compared to the wing drag, the fuselage drag is a lot harder to pin down with any accuracy. When looking at the parked airplanes at the Wittman Field at Oshkosh you will see the most extreme variety of shapes and sections, surface finishes, protrusions and protuberances on the fuselages of these mostly older airplanes.

One thing is sure: The fineness-ratio of your airplane's fuselage is higher than that for minimum drag. With a fixed cross-section, drag would be the minimum with the shortest shape which avoided separation of flow from the tail. Any increase in length increases the drag since the surface area is increased. The optimum fineness-ratio is about 3. Your airplane probably has a ratio of from 7 to 9, with consequently higher skin-friction drag. Also, there's more room for all kinds of protrusions and protuberances of any and all kinds.

Some NACA Figures. NACA once came up with some interesting general figures on airplane fuselage drag. Based on the drag in pounds per square foot of cross-sectional area:

Table No. 1.
NACA Figures on Fuselage Drag, at 100 mph.

Fuselage type	Drag in lb/sf
Very well designed and aerodynamically clean	3.0
Average	4.09 to 4.5
Rectangular section	6.09
Square section with protuberances	7.0 to 8.0

So first we'll look into what the NACA figures mean to the fuselages of our four airplanes. Because NACA's figures are for 100 mph, to get the right drag values per square foot of fuselage cross-sectional area, here too we have to use the multiplication factor

For airplanes No. 1, No. 2, and No. 3, there's an engine in front, which we deal with separately. So we subtract 0.25 percent from the fuselage cross-sectional area figures. Our four airplanes have these cross-sectional areas:

Table No. 2.

Cross-sectional Areas of the four airplanes.

Airplane No. 1.	13.0 sf
Airplane No. 2.	14.8 sf
Airplane No. 3.	14.6 sf
Airplane No. 4.	15.0 sf

Airplane No. 1

Cross-sectional area = 0.75 x 13.0 = 9.75 sf.
Cruise-speed = 129 mph.
Multiplication Factor = 1.664.
Total Airplane Drag @ Cruise-speed = 261.63 lb

Table No. 3.
Airplane No. 1. Fuselage Drag.

Fuselage Condition No.	Fuselage Drag lb	Percent of Total drag
1.	9.75 x 3.0 = 29.25 x 1.664 = 48.68	18.60
2a.	9.75 x 4.0 = 39.00 x 1.664 = 64.90	24.81
2b.	9.75 x 4.5 = 43.88 x 1.664 = 73.00	27.90
3.	9.75 x 6.0 = 58.50 x 1.664 = 97.34	37.21
4a.	9.75 x 7.0 = 68.25 x 1.664 = 113.57	43.41
4b.	9.75 x 8.0 = 78.00 x 1.664 = 129.79	49.61

For this airplane, where the landing-gear drag may take up as much as twenty-five percent or more of the total airplane drag, conditions No. 4 and 4a are too far out. At least for the average airplane of this group. It could be more than for Case 2 though. We'll make the Table for the range of from 20 to 40 percent of total airplane drag..

Airplane No. 2.

Cross-sectional Area = 0.75 x 14.8 = 11.1 sf
Cruise-speed = 164 mph
Multiplication Factor = 2.69
Total airplane drag @ cruise-speed = 256.21 lb

Table No. 4.
Airplane No. 2. Fuselage Drag.

Condition No.	Fuselage Drag lb	Percent of Total Drag
1	11.1 x 3.0 = 33.30 x 2.69 = 88.77	34.65
2a.	11.1 x 4.0 = 44.40 x 2.69 = 119.44	46.62
2b.	11.1 x 4.5 = 49.95 x 2.69 = 134.35	52.44
3.	11.1 x 6.0 = 66.60 x 2.69 = 179.13	69.92

It is clear that No. 3 fuselage condition is too far out for this airplane. Even No. 2b is too much, even for this airplane with retracted landing gear. In this case, we'll make the table 25 to 45 percent of total airplane drag.

Airplane No. 3.

Cross-sectional Area = 0.75 x 14.60 = 10.95 sf.
Cruise-speed = 191.0 mph.
Multiplication Factor = 3.65.
Total airplane drag = 348.32 lb

Table No. 5.
Airplane No. 3. Fuselage Drag.

Condition No.	Fuselage Drag lb	Percent of Total Drag
1.	10.95 x 3.0 = 32.85 x 3.65 = 119.90	34.42
2a.	10.95 x 4.0 = 43.80 x 3.65 = 159.87	45.90
2b.	10.95 x 4.5 = 49.28 x 3.65 = 179.85	51.63
3.	10.95 x 6.0 = 65.70 x 3.65 = 239.81	68.85

Somewhere between Case No. 1 and Case No. 2 might be right. We'll make the table for from 25 to 50 percent.

Airplane No. 4.
Twin engine
Cross-sectional Area = 15.00 sf

Cruise-speed = 217 mph
Multiplication Factor = 4.8
Total airplane drag = 613.18 lb

The two nacelles on this airplane produce extra drag.

Table No. 6.
Airplane No. 4. **Fuselage Drag.**

Condition No.	Fuselage Drag lb	Fuselage Percent of Total Drag
1.	15.0 x 3.0 = 45.00 x 4.8 = 220.50	35.96
2a.	15.0 x 4.0 = 60.00 x 4.8 = 288.00	46.97
2b.	15.0 x 4.5 = 67.50 x 4.8 = 324.00	52.84

Same as for airplane No. 3. So the Table will be for from 25 to 45 percent.

Working It Out

Now we'll look into the results we'll get from working out the fuselage drag over a range of percentages of the total airplane drag, in fuel-cost for each percentage step.

Table No. 7.
Airplane No. 1.
Fuselage Drag from 20 to 40 percent. of total airplane drag.
Fuel-cost per hour.

%	Drag lb	HP	Fuel gal	Cost $
20	52.33	24.0	2.0	4.00
21	54.94	25.2	2.1	4.20
22	57.56	26.4	2.2	4.40
23	60.18	27.6	2.3	4.60
24	62.79	28.8	2.4	4.80
25	65.41	30.0	2.5	5.00
26	68.02	31.2	2.6	5.20
27	70.64	32.4	2.7	5.40
28	73.26	33.6	2.8	5.60
29	75.87	34.8	2.9	5.80
30	78.49	36.0	3.0	6.00
31	81.11	37.2	3.1	6.20
32	83.72	38.4	3.2	6.40
33	86.34	39.6	3.3	6.60
34	88.95	40.8	3.4	6.80
35	91.57	42.0	3.5	7.00
36	94.19	43.2	3.6	7.20
37	96.80	44.4	3.7	7.40

38	99.42	45.6	3.8	7.60
39	102.04	46.8	3.9	7.80
40	104.65	48.0	4.0	8.00

Table No. 8.
Airplane No. 2.
Fuselage drag from 25 to 45 percent of total airplane drag.
Fuel-cost per hour.

%	Drag lb	HP	Fuel gal	Cost $
25	64.05	33.75	2.81	5.63
26	66.62	35.10	2.93	5.85
27	69.18	36.45	3.04	6.08
28	71.74	37.80	3.15	6.30
29	74.30	39.15	3.26	6.53
30	76.86	40.50	3.38	6.75
31	79.43	41.85	3.49	6.98
32	81.99	43.20	3.60	7.20
33	84.55	44.55	3.71	7.43
34	87.11	45.90	3.83	7.65
35	89.67	47.25	3.94	7.88
36	92.24	48.60	4.05	8.10
37	94.80	49.95	4.16	8.33
38	97.36	51.30	4.28	8.55
39	99.92	52.65	4.39	8.78
40	102.48	54.00	4.50	9.00
41	105.05	55.35	4.61	9.23
42	107.61	56.70	4.73	9.45
43	110.17	58.05	4.84	9.68

44	112.73	59.40	4.95	9.90
45	115.29	60.75	5.06	10.13

Table No. 9.
Airplane No. 3.
Fuselage drag from 25 to 50 percent of total airplane drag.
Fuel-cost per hour.

%	Drag lb	HP	Fuel Gal.	Cost $
25	87.08	53.438	4.45	8.90
26	90.56	55.575	4.63	9.26
27	94.05	57.713	4.81	9.62
28	97.53	59.850	4.99	9.98
29	101.01	61.990	5.17	10.34
30	104.50	64.125	5.34	10.68
31	107.98	66.263	5.52	11.04
32	111.46	68.400	5.70	11.40
33	114.95	70.538	5.88	11.76
34	118.43	72.675	6.06	12.12
35	121.91	74.813	6.23	12.46
36	125.40	76.950	6.41	12.82
37	128.88	79.088	6.59	13.18
38	132.36	81.225	6.77	13.54
39	135.84	83.363	6.95	13.90
40	139.33	85.500	7.13	14.26
41	142.81	87.638	7.30	14.60
42	146.29	89.775	7.48	14.96
43	149.78	91.913	7.66	15.32

44	153.26	96.188	7.84	15.68
45	156.74	96.188	8.02	16.04

Table No. 10.
Airplane No. 4.
Fuselage drag from 20 to 45 percent of total airplane drag. Fuel-cost per hour.

%	Drag lb	HP	Fuel Gal.	Cost $
20	148.20	85.500	7.125	14.25
21	155.61	89.775	7.481	14.96
22	163.02	94.050	7.838	15.68
23	170.43	98.325	8.194	16.39
24	177.84	102.600	8.550	17.10
25	185.25	106.875	8.906	17.81
26	192.66	111.150	9.263	18.53
27	200.07	115.425	9.619	19.24
28	207.48	119.700	9.975	19.95
29	214.89	123.975	10.331	20.66
30	222.30	128.250	10.688	21.38
31	229.71	132.525	11.044	22.00
32	237.12	136.800	11.400	22.80
33	244.53	141.075	11.756	23.51
34	251.94	145.350	12.113	24.23
35	259.35	149.625	12.469	24.94
36	266.76	153.900	12.825	25.65
37	274.17	158.175	13.181	26.36
38	281.58	162.450	13.538	27.08

39	288.99	166.725	13.894	27.79
40	296.40	171.000	14.250	28.50
41	203.81	175.275	14.606	29.21
42	311.22	179.550	14.963	29.93
43	318.63	183.825	15.319	30.64
44	326.04	188.100	15.675	31.35
45	333.45	192.375	16.031	32.06

Chapter Seven

Landing Gear Drag - Some Causes

The Conventional Landing Gear. The conventional fixed non-streamlined tricycle landing gear, protruding into the air-stream as it does, creates a lot of parasite drag. As this parasite drag makes up a surprisingly large of part of your airplane's total drag, it greatly influences its performance and cost.

The landing gear differs from the airplane's other main assemblies, wing, fuselage, tail, and engine: they all contribute to safe and successful flight (if the pilot cooperates). While in flight, the landing gear serves no useful purpose, it takes considerable horsepower to overcome its drag. Every pound of landing-gear drag requires an extra pound of thrust from the propeller and increases your airplane's fuel-consumption. With no positive returns.

Landing-gear Drag. In the fixed landing gear, the drag is made up of the resistance of:

1. The wheels;
2. The struts or legs;
3. The wheel-pants, if installed;
4. The mutual interference created by
    a. the struts and wheels or wheel-fairings,
    b. the wing for low-wing airplanes, and the fuselage for high-wing airplanes.

The Wheels. Obviously, the element which is common to all types is the wheel. A wheel has a high drag-coefficient.

The Struts. Because tubing of circular cross-section is not an aerodynamically "clean" form, a good deal of landing gear drag often is due to round struts. When an airstream meets a round strut, at first it parts smoothly. At the back, however, a low-pressure area develops which creates wake drag. A poorly-faired main gear strut on a low-wing airplane will also create a large amount of both form- and interference drag.

The Legs. The spring-steel (or plastic) gear leg often used as a strut represents the simple type of landing gear. As installed on many Cessna models, it is rugged and virtually maintenance free. The steel or (sometimes fiberglass) strut/spring also carries the brake line. Because landing-gear springs create interference drag on the fuselage and at their outer ends they are high-drag items. Sharp angles on the corners of the flat bar increase the interference drag.

Often a drag-creating step is welded onto the steel spring, allowing ease getting in and out of the airplane. If a landing-gear leg or strut doesn't intersect the wheel pants at about a 90 degree angle, that intersection will generate quite a bit of turbulence and interference drag. Curving the lower end of the gear-spring away from the wheel reduces interference drag between the leg and the wheel.

Fixed-gear Drag. Fixed-gear aircraft also develop large amounts of interference drag between the various gear members, which accounts for a high percentage of the total landing-gear drag. The gear leg, wheel and tire, and brake systems, all cause their own drag, and in their interaction with each other. Especially the brakes and the axle-fittings on the inside of the wheel create high form and interference drag. Sharp angles at the points of interference increase the drag The average fitting-plus-interference drag of common landing gears is given as about 14 percent of their total drag.

The Wheel-fairings. The drag of the wheels depends on the manner of shrouding or fairing employed. The apparently poor effect of the wheel pants alone is due to the interference between the airflow over the leg and the wheel-pant. Then there is the part of the wheel protruding below the lower ledge of the wheel-pant body. This part of the wheel accounts for a surprisingly large part of the landing-gear drag.

Wheel-pant Drag. Many wheel pant installations have some sort of a strut or axle sticking out of the inboard side of the pants. If not covered by an effective fairing, this will cause high interference drag. The interference drag between a single strut alongside of a wheel and the wheel generally increase as the included angle between the two parts is decreased. Even if your airplane has a decent set of fairings on its three wheels, there will still be a good deal of form- and interference drag on the struts or legs where they carry the wheels. Plus, often, a high-drag brake assembly installation.

Nose-wheel Interference Drag. Even with a streamlined wheel-pant, the wake of the nose-wheel ruins the airflow over and along the fuselage bottom. The conventional nose-wheel, installation, complete with springing and shock-absorbing devices, steering gear and controls, and a landing-light, has a considerable amount of drag.

Wheel-doors and Wheel-well Drag. To be fully effective, the retractable landing-gear must retract flush into the wing. Wheel-doors should close hermetically, thus preventing any unwanted flow into or out of the well. If the wheel wells are in area where the wing should have a somewhat smooth boundary-layer airflow, extra drag will result. Open gear wells can easily create a good amount of drag.

At cruise speed, with the air-pressure in the well higher than the boundary-layer pressure, the doors tend to be sucked outwards and into the boundary layer air-stream, with air flowing in and out through the wells. Thus these doors may undo some part of the drag-decreasing effect of the retract installation. In NACA tests, the open wheel-well cost 6 mph in speed. Partly sealed wheel-wells cost 3 mph.

Removal of seals from the edge of full-length fairing over retracted landing gear on the plane increased the drag coefficient, indicating that air was leaking through 1/8 inch cracks at these points. This kind of drag is due both to air-leakage and the airflow disturbance of the exposed parts. These results show the importance of completely sealing the wheel well opening.

Landing Gear Drag - Some Causes

Chapter Eight

Landing-Gear Drag - the Cost

Fixed Landing Gear Drag. The fixed landing gear creates up to approximately 30 to 40 percent of the total airplane drag. For a design study, for landing gear without fairings, the percentage of total airplane drag was assumed to be 38 percent. For the faired gear it was 14 percent. One author gave a Cdo of 0.022 for the Cardinal RG (based on wing area S and at zero-lift coefficient) and 0.033 for the basic Cardinal.

This is a 50-percent difference! He also gave a general value of basic zero-lift drag Cdo = 0.025 for airplanes with retracted gear and 0.035 for airplanes with non-retracted gear, a 40-percent increase in total airplane drag.

Similar Models show the Cost. Among single-engine airplanes are a number of fairly similar models with both fixed and retractable gear versions which offer some interesting comparisons. So we will look into that now. What we are mostly interested in is: how much more total drag is created by a fixed-gear installation compared to the same airplane with retracted gear.

Retractable Landing Gear - The Drag Difference. We will take a detailed look at the difference in total airplane drag in GEDA values between ten sets of comparable airplanes available with either fixed or retractable landing gear. This will give us some figures on the percentage of landing gear drag vs. total airplane drag. Here's a list of the 20 normally-aspirated airplanes:

Table No. 1.
List of fixed-gear and retract-gear airplanes.

1a	Beech Sundowner	142 mph on 180 HP	GEDA = 9.22 sf
1b	Beech Sierra RG	163 mph on 200 HP	GEDA = 6.77 sf
2a	Cessna C-172	143 mph on 160 HP	GEDA = 8.02 sf
2b	Cessna Cutlass RG	167 mph on 180 HP	GEDA = 5.67 sf
3a	Mooney Mk	147 mph on 180 HP	GEDA = 8.31 sf
3b	Mooney Mark 21	185 mph on 180 HP	GEDA = 4.17 sf
4a	Piper Cherokee 180	152 mph on 180 HP	GEDA = 7.52 sf
4b	Piper Cherokee 180 RG	170 mph on 180 HP	GEDA = 5.37 sf
5a	Piper Archer Ⅲ	143 mph on 180 HP	GEDA = 8.14 sf
5b	Piper Arrow RG	175 mph on 200 HP	GEDA = 5.47 sf
6a	Cessna C-177 Cardinal	150 mph on 180 HP	GEDA = 8.02 sf
6b	Cessna C-177 Cardinal RG	180 mph. on 200 HP	GEDA = 5.03 sf
7a	Cessna C-182 Skylane	168 mph on 230 HP	GEDA = 7.11 sf
7b	Cessna C-182 Skylane RG	180 mph on 235 HP	GEDA = 5.91 sf
8a	Piper Saratoga	175 mph on 300 HP	GEDA = 8.21 sf
8b	Piper Saratoga RG	188.8 mph on 300 HP	GEDA = 6.54 sf
9a	Cessna C-182 Skylane	168 mph on 230 HP	GEDA = 7.11 sf
9b	Cessna C-210	198 mph on 260 HP	GEDA = 4.91 sf
10a	Cessna 336 Loadmaster	182 mph on 420 HP	GEDA = 10.20 sf
10b	Cessna 336 Loadmaster	200 mph on 420 HP	GEDA = 7.70 sf

Working It Out. To show how we go about getting our figures, we'll work out the complete set of calculations for the first set of airplanes, the Beech Sundowner and the Sierra. . First we will work out the total drag and the GEDA for the Sundowner.

$HP_{max.} = 180.$ $V_{max.} = 142$
Air-pressure q @ 142 mph = 51.57 lb/sf

$$\begin{aligned} \text{Drag } D &= (HP \times 375) / V \\ &= (180 \times 375) / 142 \\ &= 67500 / 142 \\ &= 475.35 \text{ lb} \end{aligned}$$

Gross Equivalent Flat Plate Area GEFPA = D / q

$$= 475.35 / 51.57 = 9.22 \text{ sf}$$

which is rather high even for this type of airplane, due to the un-faired wheels 142-mph breeze. Now we'll do the same for the Sierra.

$HP_{max.} = 200.$
$V_{max.} = 163.0$ mph.
Air-pressure q @ 163 mph = 67.96 lb/sf

$$\begin{aligned} \text{Drag } D &= (HP \times 375) / V \\ &= (200 \times 375) / 163 \\ &= 75000 / 163 \\ &= 460{,}12 \text{ lb} \end{aligned}$$

$$\text{GEDA} = 460.12 / 67.96 = 6.77 \text{ sf}$$

Therefore the GEDA difference between the two airplanes is

$$9.22 - 6.77 = 2.45 \text{ sf}$$

As a percentage:

$$6.77 / 9.22 = 0.734 = 73.4 \text{ percent.}$$

Or, 9.2 / 6.77 = 1.36.

Which shows that the drag of the fixed gear Sundowner is 36.2 percent higher than the drag of the retract-gear Sierra. So we see that while the nominal speed difference is only 21.4 mph, the drag percentage is 36.2 percent higher for the Sundowner.

At 163 mph, D = GEDA x q = 9.22 x 67.96 = 626.6 lb

Table No. 2.
Drag difference of fixed-gear airplanes and their retract-gear model.

No.	HP	$V_{max.}$ mph	GEDA	% Drag diff'ce
1a.	180	142	9.22	+36.20
1b.	200	163	6.77	-26.57
2a.	160	143	8.02	+41.45
2b.	180	167	5.67	-29.30
3a.	180	147	8.31	+99.28
3b.	180	185	4.17	-49.82
4a.	180	152	7.52	+40.00
4b.	180	170	5.37	-21.59
5a.	180	148	8.14	+48.81
5b.	200	175	5.47	-32.80
6a.	180	150	8.02	+59.44
6b.	200	180	5.03	-37.28
7a.	230	168	7.11	+20.30
7b.	235	180	5.91	-16.88
8a.	300	175	8.21	+25.54
8b.	300	189	6.54	-20.34
9a.	230	168	7.11	+44.81

9b.	260	198	4.91	-30.94
10a.	420	182	10.2	+32.50
10b.	420	200	7.7	-24.51

Retracted-gear airplane at (lower) fixed-gear flying speed. There is another side to this: how much horsepower will the Sundowner need to fly at 163 mph? That's what we will work out next. As we know, power required increases with the third power of the speed increase.

163 / 142 = 1.148
1.148 x 1.148 x 1.148 = 1.513

1.513 x 180 = 272.35 HP

Say 272 HP. Now 272 - 180.0 = 92 HP which is 51.1 percent of 180 HP extra. This shows that to just say "Oh it only goes 18 miles per hour faster", for example, is not the whole story. The real difference lies in the answer to the question: how many percent extra horsepower would it take for the fixed-gear airplane to fly at the same speed as its retractable cousin? Next we'll see what the figures are for our eight fixed-gear airplanes.

Table No. 3.
Extra hp required for fixed-gear airplanes to fly at retract model's higher maximum speeds.

No.	Max. HP	V1	V2	V1/V2	% HP extra	HP req extra
1a.	180	142	163	1.148	51.10	92.00
2a.	160	143	167	1.168	15.39	24.62
3a.	180	147	185	1.259	99.32	178.86
4a.	180	152	170	1.118	39.90	71.82
5a.	180	148	175	1.182	65.31	117.55
6a.	180	150	180	1.200	72.80	131.04
7a.	230	168	180	1.071	23.00	52.87
8a.	300	175	188	1.079	25.49	76.48
9a.	230	168	198	1.179	44.80	146.42

10a.	420	182	191	1.050	32.50	136.55

Fast airplanes flying at slower speeds and less horsepower. We can make another interesting comparison here: how much less horsepower would the RG models need to fly at the fixed-gear models' slower speed. Let's look into that now. To find the numbers, we make this simple calculation:

HP = (D x V) / 375

D = GEFPA x q

So, for the Sierra, at the Sundowner's lower 142 mph speed,

D = 6.77 x 51.57 = 349.13

Therefore, HPreq = (349.13 x 141.6) / 375 = 49576.46 / 375 = 132.20

Thus the Sierra would need only 132.20 / 200 = 66.10 percent of its power to fly at the Sundowner's maximum speed. That means it could easily do it with a 140 HP engine. Now we will work out the figures for table No. 3 on this.

Table No. 4.

Horsepower Savings for Retractable Airplanes

No.	Lower speed	Present HP	New HP	Saving percent	Saving HP
1b.	142	200	132.2	33.90	67.8
2b.	143	180	113.0	37.22	67.0
3b.	147	180	90.0	49.80	89.7
4b.	152	180	128.6	28.56	51.3
5b.	148	200	129.9	35.05	70.1
6b.	150	200	112.9	43.55	87.1
7b.	168	235	191.0	18.67	44.0
8b.	168	260	158.8	38.90	101.2
9b.	175	300	239.0	20.31	60.9
10b.	182	420	316.6	25.62	103.4

The table shows that the percentage of gear-drag for this set of comparable airplanes ranges from a low of 18.67 to a high of 49.80 percent. The average comes to 331.58 / 10 = 33.16 percent. Thus the authors coming up with 30 - 40 percent seem to have it right.

Lower Maximum speeds for Retract Airplanes. **A**ccording to flight-reports in the aviation press, owners of airplanes with tuck'em-up landing gear often seem to say they feel they are not getting the manufacturer's official high speed listed in the Pilots Operating Handbook or the specifications. So, to satisfy everyone concerned we'll work out still another table. This time for each retract model we'll take one-half of the gain and work out the HP required for the now lower base-model's V2. Taking the Sierra again for an example, we get:

Sierra RG. vs. Sundowner =

163.0 - 142 = 21 mph
21 / 2 = 10.5 mph
142 + 10.5 = 152.5 mph

So that's our new (lower) V2 for the Sundowner.

Again, D = GEDA x q (for V2).
Q = $(152.5 \times 1.46667)^2 \times 0.001189$ = 59.53 lb/sf
So D = 9.3 x 59.53 = 553.65 lb

Now for the table. First we work out the new V2 speed for the complete set.

Table 5.
Slower Speeds for Retract Airplanes. (mph)

1a. + 1b. (142 + 163) / 2 = 305 / 2 = 152.5
2a. + 2b. (143 + 167) / 2 = 310 / 2 = 155
3a. + 3b. (147 + 185) / 2 = 332 / 2 = 166
4a. + 4b. (152 + 170) / 2 = 322 / 2 = 161
5a. + 5b. (148 + 175) / 2 = 323 / 2 = 161.5

6a. + 6b. (150 + 180) / 2 = 330 / 2 = 165
7a. + 7b. (168 + 180) / 2 = 348 / 2 = 174
8a. + 8b. (168 + 198) / 2 = 366 / 2 = 183
9a. + 9b. (175 + 188) / 2 = 363 / 2 = 181.5
10a + 10b. (182 + 200) / 2 = 382 / 2 = 191

Next we work out the horsepower required for the fixed-gear airplanes to fly at these more moderately new higher speeds. We use the same formulas we used for the first case. To show how we find the numbers, we work out the following sample for the Beech Sundowner:

HP = D x V / 375
V2 = 152.5
q = 59.53 lb/sf

So, D = 9.22 x 59.53 = 553.65 lb
HP = (553.65 x 152.5) / 375
= 84431.07 / 375
= 225.15= 1.2508 or 25.08 percent extra
= 225.15- 180 = 45.15 HP extra.

Here are the numbers for all the retract airplanes.

Table 6.
New Medium Faster Speeds for
Fixed-Gear Airplanes.

No.	Max. HP	V1	V2	V1/V2	% HP extra	HP req extra
1a.	180	142	152.5	1.074	25.08	45.15
2a.	160	143	155.0	1.084	27.35	43.75
3a.	180	147	166.0	1.129	44.00	79.21
4a.	180	152	161.0	1.059	18.84	33.90
5a.	180	148	161.5	1.091	29.93	53.89
6a.	180	150	165.0	1.100	33.10	59.58
7a.	230	168	174.0	1.036	11.10	25.53
8a.	230	168	183.0	1.089	29.25	67.27
9a.	300	175	181.5	1.037	11.56	36.69
10a.	420	182	191.0	1.050	15.58	65.44

Drag- and Fuel-Cost Data for our four Example Airplanes.

Now we've finally come down to the money level. For airplane No. 1 we just work it out on the basis of the cruise-drag figures used in the other Chapters. As our sample airplanes Nos. 2, 3, and 4 used in the other Chapters don't have the gear hanging down at cruise-speed, we cannot very well work out tables showing the fuel-cost for the gear-drag. Not to let you off so easily, however, we'll play it differently this time. We'll do like we have a gear hanging down and suppose it creates an average amount of landing gear drag based on the above calculations in Table No. 4b. We do this just to make clear how expensive it would be to have a fixed gear on a high-performance airplane.

Assuming airplanes Nos. 2 - 4 would have well-designed, low-drag landing gear, we'll make the tables for the range of 20 to 40 percent for airplane No. 2, 10 to 30 percent for airplane No. 3, and 20 to 35 percent for airplane No. 4.

Table No. 7.
Airplane No. 1.
Landing-gear drag from
20 to 40 percent of total
airplane drag.
Cruise-speed = 129 mph.

%	Drag lb	HP	Fuel Gal.	$
20	70.0	24.0	2.0	4.00
21	73.5	25.2	2.1	4.20
22	77.0	26.4	2.2	4.40
23	80.5	27.6	2.3	4.60
24	84.0	28.8	2.4	4.80
25	87.5	30.0	2.5	5.00
26	91.0	31.2	2.6	5.20
27	94.5	32.4	2.7	5.40
28	98.0	33.6	2.8	5.60
29	101.5	34.8	2.9	5.80
30	105.0	36.0	3.0	6.00
31	108.5	37.2	3.1	6.20
32	112.0	38.4	3.2	6.40
33	115.5	39.6	3.3	6.60

34	119.0	40.8	3.4	6.80
35	122.5	42.0	3.5	7.00
36	126.0	43.2	3.6	7.20
37	129.5	44.4	3.7	7.40
38	133.0	45.6	3.8	7.60
39	136.5	46.8	3.9	7.80
40	149.0	48.0	4.0	8.00

Airplane No. 2.

For airplane No. 2 the drag of the basic airplane with gear retracted, at 164 mph cruise-speed, comes to

Drag = (HP x 375) / Vcr
= (((200 x 0.75) x)375) / 164
= (150 x 375) / 164
= 56250 / 164 = 343 lb

We want get a total drag value about 37 percent higher than 343 pound for this airplane with a fixed gear. That means that the 343-pound figure will have to become about 63 percent of the new, increased total drag figure.

343 / 63 = 5.44 lb
100 x 5.44 = 544 lb
343 / 544 = 0.6305,

so the difference is about 100 - 63.05 = 36.95 percent.

We'll make the table for 20 to 40 percent, to get some idea of what a fixed-gear airplane might costs in horsepower and consequently in fuel at the 164 mph cruise-speed.

Table No. 8.
Airplane No. 2.
Landing-gear drag from
20 to 40 percent of total
higher airplane drag.
Vcruise = 164 mph.

%	Drag lb	HP	Fuel Gal.	$
20	110.0	48.0	4.0	8.00
21	115.5	50.4	4.2	8.40
22	121.0	52.8	4.4	8.80
23	126.5	55.2	4.6	9.20
24	132.0	57.6	4.8	9.60
25	137.5	60.0	5.0	10.00
26	143.0	62.4	5.2	10.40
27	148.5	64.8	5.4	10.80
28	154.0	67.2	5.6	11.20
29	159.5	69.6	5.8	11.60
30	165.0	72.0	6.0	12.00
31	170.5	74.4	6.2	12.40
32	176.0	76.8	6.4	12.80
33	181.5	79.2	6.6	13.20
34	187.0	81.6	6.8	13.60
35	192.5	84.0	7.0	14.00
36	198.0	86.4	7.2	14.40

37	203.5	88.8	7.4	14.80
38	209.0	91.2	7.6	15.20
39	214.5	93.6	7.8	15.60
40	220.0	96.0	8.0	16.00

Airplane No. 3. We start out with a basic drag of 420 pound at a cruise-speed of 191 mph. We again add 25 percent extra drag for the fixed gear. So, 420 becomes 75 percent. We'll make the table for 10 to 30 percent.

420 / 75 = 5.6 lb
100 x 5.6 = 560 lb
420 / 560 = 0.75

Table No. 9.

Airplane No. 3.
Landing-gear drag from 10 to 30 percent of total airplane drag.
Cruise-speed = 191 mph.

%	Drag lb	HP	Fuel Gal.	$
10	56.0	28.50	2.375	4.75
11	61.6	31.35	2.613	5.23
12	67.2	34.20	2.850	5.70
13	72.8	37.05	3.088	6.18
14	78.4	39.90	3.325	6.65
15	84.0	42.75	3.563	7.13
16	89.6	45.60	3.800	7.60
17	95.2	48.45	4.038	8.08
18	100.2	51.30	4.275	8.55
19	106.4	54.15	4.513	9.03
20	112.0	57.00	4.750	9.50
21	117.6	59.85	4.988	9.98
22	123.2	62.70	5.225	10.45
23	128.8	65.55	5.463	10.93
24	134.4	68.40	5.700	11.40

25	140.0	71.25	5.938	11.98
26	145.6	74.10	6.175	12.35
27	151.2	76.95	6.413	12.83
28	156.8	79.80	6.650	13.30
29	162.4	82.65	6.888	13.78
30	168.0	85.50	7.125	14.25

Airplane No. 4. We start out with a basic airplane drag of 738.8 lb Here we also want to add 25 percent, therefore:

738.8 /75 = 9.85 lb
100 x 9.85 = 985 lb
738.8 / 985 = 0.75

Table No. 10.
Airplane No. 4.
Landing-gear drag from 20 to 35 percent of total airplane drag.
Cruise-speed = 217 mph.

%	Drag lb	HP	Fuel Gal.	$
20	197.00	114.0	9.500	19.00
21	206.85	119.7	9.975	19.95
22	216.70	125.4	10.450	20.90
23	226.55	131.1	10.925	21.85
24	236.40	136.8	11.400	22.80
25	246.25	142.5	11.875	23.75
26	256.10	148.2	12.350	24.70
27	265.90	153.9	12.825	25.65
28	275.80	159.6	13.300	26.60
29	285.65	165.3	13.775	27.55
30	295.50	171.0	14.250	28.50
31	305.35	176.7	14.725	29.45
32	315.20	182.4	15.200	30.40
33	325.05	188.1	15.675	31.35
34	334.90	193.8	16.150	32.30
35	344.75	199.5	16.625	33.25

Chapter Nine

Engine Drag - Some Causes

Cooling and Cowling Drag. The purpose of your airplane's cooling system is to carry off the heat developed by the engine with the minimum possible loss in engine power. while maintaining the required engine temperature under all flight conditions. Transferring the engine's heat to the cooling-air (even if through a radiator on a liquid-cooled engine) always requires a portion of the engine's horsepower. There are many reasons for this power loss. For starters, engine makers put the front cylinders as close to the propeller plane as possible, which makes for a blunt nose cowl. This may take 5 to 10 percent of engine power.

When cooling-air rams into the inlet, it continues to move in the same direction as the airplane. By being slowed down, however, it picks up some energy from the airplane, costing you some momentum drag. The cooling system's effectiveness also depends much on external- and internal cowling design. This includes baffling and exits or cowl flaps. Like outside drag, inside cowling drag also slows down your airplane.

The internal flow drag of the cooling system basically consists of

1) inlet drag;
2) upper plenum drag;
3) cylinder-finning drag;
4) baffle drag;
5) lower plenum drag;
6) drag of the various ducts;
7) outlet drag,
8) exhaust drag.

Friction and Pressure Drag. While the cooling-air passes over the engine, it creates considerable frictional and pressure drag. Unnecessary airflow means extra drag. There's friction on the cylinder-finning, plenum walls, duct walls and bends, and perhaps turbulence from improper duct-expansion. Poorly-shaped conduits or ducts, with complicated bends creating disturbance cause much drag. Usually, exhaust-pipes, nose-wheel legs, various controls, engine mounts, and other drag-creating items pass through the lower cowling. There is also the interference-drag effect these parts impose on each other.

Cooling-Air Inlets. With the shape of your airplane's cowling somewhat streamlined, it still must have openings to let in the cooling- and induction air. No single fixed inlet can be ideal for the airplane's full range of angles-of-attack and flying speeds. However, for minimum drag the inlet should have the smallest area that maintains adequate cooling during climb. If the inlet openings are too large, the oncoming air will spill over and create turbulent-flow drag. The total of these inlet drag-losses often is a lot higher than really necessary.

With the cylinders right behind the inlet opening, there are no internal diffuser walls to give high internal pressure-recovery. This means we have high inlet losses right at the inlet opening. Lack of pressure recovery at the inlets decreases the effective inlet size.

Baffling- and Baffle Drag. One NACA report shows that conventional baffling systems leak about 50 percent of the cooling air taken in through the inlets. All this air leaking around the baffles causes unnecessary drag. Often, the worst leakage is at the flexible seal between the removable cowling at the top and the diaphragm baffle. High pressure here may cause the cowling to bulge upwards, away from the baffles, allowing the cooling-air to escape.

Leaks also often occur at the baffle attachments or joints. All leaks in the baffle area mean unneeded air flowing through the cowling-inlet and -outlet, with extra power used. Each baffle depends upon the other baffles.

Cowling Outlets. Because the heated, expanded cooling air should get out of the cowling with minimum drag, the exit area should be bigger than the intake area. However, an oversized exit area will pull too much air through the cowling and also cause unnecessary drag. Thus a fixed-geometry system specifically designed to cool the engine during the climb will give high drag in cruise-flight, and lower overall performance.

A fixed cowling outlet will decrease the airplane's cruise- speed by six to ten mph. If the cooling-air's exit velocity is higher than the speed of the boundary-layer, the friction-drag losses on the fuselage behind it also are higher. If the air leaves the cowling's exit openings at an angle, there will be turbulence in the boundary layer. Any items obstructing the air flow in the lower cowling area also create turbulence in the exiting air.

Cowling Flaps. Minimum cooling-drag in cruise flight requires closed cowling-flaps. On the Mooney 231, cowl flaps cause a loss of five knots in cruise in the trail position and 14 knots fully open.

Nacelle Drag on Twins. High nacelle drag on twins results from their blunt shape and sharp corners in front. This causes an increase in boundary-layer thickness resulting in flow separation around the inlet and behind the nacelle. On nacelles with side cooling-air exits, flow separation gives increased drag over the rear nacelle.

Accessory Cooling Air. Your airplane's engine also needs cooling-air for cooling the various engine accessories, like inter-coolers, and cabin-air heaters. There's many a pound of drag caused by less-than-efficient systems here.

Engine Induction Air. If the induction airflow is not smooth and unrestricted, there will be extra drag. This is especially important for high-speed airplanes. While the intake should take in dust-free air, air-filters often provide a poor flow-path, with a large pressure-loss. Thus on many single-engine light airplanes, when using the air-filter there's a small performance penalty of up to 5 percent. Abrupt changes in duct size, shape, or cross-section and leakage create high duct losses. With high airflow velocities, friction on the duct-walls slows the air down. Corrugated ducts, with corrugations perpendicular to the airflow, give extra high skin-friction.

Oil-cooler Air. Your airplane's engine needs an oil cooler to help keep the oil temperature within the proper recommended temperature limits. Any excess air going through the oil cooler causes extra drag; a badly designed oil-cooler installation may cause a lot of drag, and cost you some cruise-speed. Light airplanes often have very poor oil-cooler installations with multiple turns in the inlet duct.

Exhaust Drag. Many airplanes dump the exhaust gas overboard through one or more stub stacks. This stream of hot exhaust gases exiting at right angles or more or less backwards to the outside airflow angle creates high-drag turbulence. Especially since the straight round exhaust stacks are very high-drag bodies; a 3" dia. x 6" long round pipe has 3.2 lb of drag at 100 mph.

Here are some interesting figures:

Table No. 1.
Exhaust Drag

Speed	q	Drag	
mph	lb/sf	one pipe	two pipes
140	50.00	6.27	12.54
150	57.55	7.19	14.38
160	65.48	8.19	16.37
170	73.92	9.24	18.48
180	82.87	10.36	20.72
190	92.33	11.54	23.08
200	102.31	12.79	25.58

For an airplane cruising at 140 mph and a GEDA of 8 sf., this works out to respectively 3.12 percent for two pipes. For an airplane cruising at 170 mph and a GEDA of 6 sf., it works out to 4.17 percent. For an airplane cruising at 200 mph and a GEDA of 4 sf. it works out to 6.25 percent of the total airplane drag..

Chapter Ten

Engine Drag --- the Cost

Cowling- and Nacelle Shape. Your airplane's engine cowling(s) and nacelle(s) are far from the low-drag forms we like to see on our light airplanes. Even the best shapes of engine-cowling and -nacelles make up a large part of the total airplane drag. Putting in bigger engines to increase flying speed only makes things worse. As an airplane's engine's total engine-installation drag always requires a good percentage of its horsepower output, your airplane's cruise-flight performance depends a good deal on its total engine-drag. Especially if you are flying a fast, low-drag airplane, cooling drag is a significant factor.

The cleaner the airplane behind it, the larger percentage the engine drag becomes, comparatively. The proper cowling can show as much as 15 mph difference in top speed. In cooling an airplane engine, the power required increases as the cube of the flying speed. This is not too bad for airplane speeds of up to about 150 mph, but above this speed the power required starts to become prohibitive. No doubt on many light airplanes the engine installation creates too much of the total airplane parasite drag.

Some Figures. There seems to be agreement that, on the low side, for an ideal installation it may be as low as five percent. Looking at light airplane engine installations at Oshkosh, many must be creating a whole lot more drag than five percent. While an efficient light-airplane engine installation is said to take about eight to twelve percent of the rated power available, NACA found on average about 13 percent. A 20 percent power loss is more typical for light airplanes. According to Roy LoPresti, on the older Comanches, 30% of the airplane's drag occurs inside the cowling. So let's just say it can range from five percent for a very efficient system to at least thirty percent for a very poor installation. So what we'll do here is to make our cost-calculations for the full range from 5 percent to 30 percent for our four airplanes. Perhaps this chapter will give you some idea of what you may be paying for your engine's drag. Whatever the percentage, it comes out of your pocket.

First Some Simple Calculations. According to some sources, the average drag coefficient of a nacelle or cowling is CD = 0.20, based on frontal area. This comes to about 5.0 lb/ft^2 at 100 mph. The drag of a pure streamline form would be about 1.0 lb/ft^2. A clean form may be 3.0 lb/sf at 100 mph. For a basic rectangular cowling of say 45 in. high and 36 in. high at the end of the cowling, the area is 11.25 sf. With a CD of 0.20, this gives us 2.25 sf of GEDA. Taking the (area x q) at 100 mph, this gives a drag of 2.25 x 25.5767 = 57.55 lb

At 140 mph we get

$$(1.4 \times 1.4) \times 57.55 \quad = 1.96 \times 55.55 \quad = 112.79 \text{ lb}$$

On an airplane with a GEDA of 8 sf and a total drag of 401.04 lb this is

$$112.78 / 401.04 = 28.125 \text{ percent.}$$

For the average not-too-good installation, that may be not too far off. Now for the full range of numbers and the cost in your money.

Table No. 1.
Airplane No. 1.
Engine drag from 5 to 30 percent of total airplane drag.
Cruise-speed = 129 mph

%	Drag lb	HP	Fuel gal.	$
5	17.5	6.0	0.50	1.00
6	21.0	7.2	0.60	1.20
7	24.5	8.4	0.70	1.40
8	28.0	9.6	0.80	1.60
9	31.5	10.8	0.90	1.80
10	35.0	12.0	1.00	2.00
11	38.5	13.2	1.10	2.20
12	42.0	14.4	1.20	2.40
13	45.5	15.6	1.30	2.60
14	49.0	16.8	1.40	2.80
15	52.5	18.0	1.50	3.00
16	56.0	19.2	1.60	3.20
17	59.5	20.4	1.70	3.40
18	63.0	21.6	1.80	3.60
19	66.5	22.8	1.90	3.80
20	70.0	24.0	2.00	4.00
21	73.5	25.2	2.10	4.20
22	77.0	26.4	2.20	4.40
23	80.5	27.6	2.30	4.60
24	84.0	28.8	2.40	4.80
25	87.5	30.0	2.50	5.00
26	91.0	31.2	2.60	5.20
27	94.5	32.4	2.70	5.40
28	98.0	33.6	2.80	5.60
29	101.5	34.8	2.90	5.80
30	105.0	36.0	3.00	6.00

Table No. 2.
Airplane No. 2.
Engine drag from 5 to 30 percent of total airplane drag.
Cruise-speed = 164 mph

%	Drag lb	HP	Fuel Gal.	$
5	17.20	7.50	0.63	1.25
6	20.64	9.00	0.75	1.50
7	24.08	10.50	0.88	1.75
8	27.52	12.00	1.00	2.00
9	30.96	13.50	1.13	2.25
10	34.40	15.00	1.25	2.50
11	37.84	16.50	1.38	2.75
12	41.28	18.00	1.50	3.00
13	44.72	19.50	1.63	3.25
14	48.16	21.00	1.75	3.50
15	51.60	22.50	1.88	3.75
16	55.04	24.00	2.00	4.00
17	58.48	25.50	2.13	4.25
18	61.92	27.00	2.25	4.50
19	65.36	28.50	2.38	4.75
20	68.80	30.00	2.50	5.00
21	72.24	31.50	2.63	5.25
22	75.68	33.00	2.75	5.50
23	79.12	34.50	2.88	5.75
24	82.56	36.00	3.00	6.00
25	86.00	37.50	3.13	6.25
26	89.44	39.00	3.25	6.50
27	92.88	40.50	3.38	6.75
28	96.32	42.00	3.50	7.00
29	99.76	43.50	3.63	7.25
30	103.20	45.00	3.75	7.50

Table No. 3.
Airplane No. 3.
Engine drag from 5 to 30 percent of total airplane drag.
Cruise-speed = 191 mph

%	Drag lb	HP	Fuel Gal.	$
5	21.0	10.688	0.89	1.78
6	25.2	12.825	1.07	2.14
7	29.4	14.963	1.25	2.49
8	33.6	17.100	1.43	2.85
9	37.8	19.238	1.60	3.21
10	42.0	21.375	1.78	3.56
11	46.2	23.513	1.96	3.92
12	50.4	25.650	2.14	4.27
13	54.6	27.788	2.32	4.63
14	58.8	29.925	2.49	4.99
15	63.0	32.063	2.67	5.34
16	67.2	34.200	2.85	5.70
17	71.4	36.338	3.92	6.06
18	75.6	38.475	3.21	6.41
19	79.8	40.613	3.38	6.77
20	84.0	42.750	3.56	7.12
21	88.2	44.888	3.74	7.48
22	92.4	47.025	3.92	7.84
23	96.6	49.163	4.10	8.19
24	100.8	51.300	4.28	8.55
25	105.0	53.438	4.45	8.90
26	109.2	55.575	4.63	9.26
27	113.4	57.713	4.81	9.62
28	117.6	59.850	4.99	9.98
29	121.8	61.990	5.17	10.34
30	126.0	64.125	5.34	10.68

Table No. 4
Airplane No. 4.
Engine drag from 5 to 30 percent
of total airplane drag.
Cruise-speed = 217 mph

%	Drag lb	HP	Fuel Gal.	$
5	37.05	21.375	1.78	3.56
6	44.46	25.650	2.14	4.28
7	51.87	29.925	2.49	4.99
8	59.28	34.200	2.85	5.70
9	66.69	38.475	3.21	6.41
10	74.10	42.750	3.56	7.13
11	81.51	47.025	3.92	7.84
12	88.92	51.300	4.28	8.55
13	96.33	55.575	4.63	9.26
14	103.74	59.850	4 99	9.98
15	111.15	64.125	5.34	10.69
16	118.56	68.400	5.70	11.40
17	125.97	72.675	6.06	12.11
18	133.38	76.950	6.41	12.83
19	140.79	81.225	6.77	13.54
20	148.20	85.500	7.13	14.25
21	155.61	89.775	7.48	14.96
22	163.02	94.050	7.84	15.68
23	170.43	98.325	8.19	16.38
24	177.84	102.600	8.55	17.10
25	185.25	106.875	8.91	17.81
26	192.66	111.150	9.26	18.53
27	200.07	115.425	9.62	19.24
28	207.48	119.700	9.98	19.95
29	214.89	123.975	10.33	20.33
30	222.30	128.250	10.69	21.38

Chapter Eleven

Tail Drag - Some Causes

The Practical Causes. While our interest is strictly in the practical causes, and the cost of the tail-drag in your aviation-gas dollars, the drag of the tail-surfaces depend on various important aerodynamic and design factors. For example, a big engine needs big tail surfaces. So do twins.

Fuselage is Like an Airfoil. A fuselage, for example, is like an airfoil section with a large nose overhang. That means, the area of the fuselage forward of the c.g. is like the area in front of the hinge on a control-surface, and is equally destabilizing, i.e. it tends to over-balance. The sharper the nose-shape, the less over-balance. Both weight and drag of the tail-surfaces can be saved by a clean fuselage nose.

Thus the shape of the fuselage front-end also has a large influence on the size and efficiency of the tail-surfaces. In general, the smoother the airflow around the fuselage nose, the better the stability will be and the lower the drag.

The Fuselage Rear End. At moderate and higher speeds, the shape of the fuselage rear end is especially important. A suitably tapered fuselage after-body is as important as the shape of the nose. If possible, the rear portion of a fuselage should narrow down rather gradually. The fuselage tail-section produces a basic skin-friction drag roughly proportional to its "wetted area" and thus to its cross-sectional circumference and its length.

Various Influences. For cruise-flight speeds the effect of the propeller on the average wing down-wash is small. Of course, the propeller slipstream, the wing wake, and the fuselage boundary-layer all do influence the airflow in the region of the tail. The wing-fuselage interference has a direct influence on the size and effectiveness of the tail-surfaces. The size of the tail is highly influenced by fuselage shape and dimensions, and also by the position of the wing on the fuselage.

The Turbulent Profile Airflow. The main source of drag on the tail-surfaces is due to the rather turbulent profile drag coming off the wing. The wing's boundary-layer airflow sweeps down off the wing's trailing edge as a turbulent air-stream we call the wake. This turbulent wake influences the air, both above and below itself, in a downward direction called "down-wash." Therefore the tail surfaces of a conventional airplane always operate in a disturbed atmosphere.

The Wing-position Influence. A low-wing airplane needs 20 to 30 percent less fin and rudder area than does a high-wing airplane, all because of its higher efficiency. On a high-wing airplane, the effectiveness of the normal fin is reduced, while on a low-wing airplane the effectiveness of a normal type of fin is not reduced but may be increased. All this has to do with the fuselage side-wash. This is why dorsal or ventral fins are often used for reducing the fuselage's unstable yawing-moment.

The Tail-volume Coefficient. If the area of a geometrically similar wing is halved, thus doubling the airplane's wing-loading, the tail-volume coefficient is nearly trebled (2 x the root of 2, or 2 x 1.414 = 2.828). To this is added the destabilizing influence of the fuselage. Thus, airplanes with a higher wing-loading require larger tail areas, which in turn create increased drag.

Gap Drag. Gaps at stabilizers, stabilators, elevators, and rudders all cause tail drag. So do poorly sealed control-surface gaps. Gaps between the tail and the fuselage add form- and interference drag. The drag of even small gaps can cause rather large reductions in your airplane's performance. Thus, the less gap, the better your airplane will fly. Then there's the drag of the gaps at the moving surfaces.

The variable-incidence tail. A disadvantage of the variable-incidence tail is the gap between the movable horizontal surface and the fuselage. These gaps allow air to leak through and disrupt the airflow, creating turbulent boundary layer drag. Any gap here remakes the horizontal tail into two short-span small wings. Sealing this gap can be difficult, especially at curved fuselage areas.

Interference drag of a T-tail is theoretically less than that of a conventional or a cruciform tail.

The V-Tail. In theory, some reduction of total tail drag should result from reducing the three tail-surfaces to two. A good example is the old Beech Bonanza's V-tail. However, in practice, the total area for a V-tail may be more. Also, the V-tail has interference drag owing to the inboard sections of the two surfaces being close together.

Drag of Control Horns and Hinges. NACA data shows that the drag of external control-horns is up to about 2.0 lb each at 100 mph. Control horns with fairing can be 0.875 lb/sf. Because a protrusion on the upper surface acts like a small spoiler, there's 100% extra for interference in that case.

Chapter Twelve

Tail Drag - The Cost.

Tail Drag Cost for the Four Airplanes. Here is some NACA data, based on tail surface area outside the fuselage, with no tail-lift provided. Profile drag per square foot, at 100 mph, in plan-view or side-view, including interference drag, at 100 mph, is roughly

0.380 lb for 9 percent thickness
0.425 lb for 12 percent thickness.

On this basis, we take the average normal drag of the tail surfaces, at 0.40 lb per sf. at 100 mph. The total drag of the tail surfaces will be

Total Drag = Total Area x 0.40 lb

So now we'll look into the cost of the tail drag of each of our four airplanes.

Airplane No. 1.

This airplane has a total tail-surface area of 55 sf., which works out to

55 / 171 = 0.3216

= 32.16 percent of the nominal wing area. The cruise speed at 75 percent power is 129 mph, and the air-pressure q at 129 mph = 42.56 lb/sf. First we work out the value of 0.40 lb/sf drag value at 100 mph for the cruise speed of 129 mph. Drag per square foot at 129 mph is

D = (1.29 x 1.29) x 0.40 = 0.66 lb/sf

So the total drag for the tail-surfaces comes to

55 x 0.66 = 36.3 lb

The total airplane drag at the 129 mph cruise speed is (GEDA x q)

= 8.3 x 42.56 = 353.25 lb

Therefore the tail-drag percentage works out to

$$36.3 / 353.25 = 10.276$$

or 10.28 percent of total airplane drag. The tail drag percentage for light airplanes can range from about five to twenty-five percent of total airplane drag. We use a range of ten percent. from about five percent lower to five percent higher than the result of our calculations. Therefore, for airplane No. 1 we will work it out in our table for 5 to 15 percent of total airplane drag.

Table No. 1.
Airplane No. 1.
Tail drag from 5 to 15
percent of total airplane drag.
Cruise-speed = 129 mph

%	Drag lb	HP	Fuel Gal.	$
5	17.5	6.0	0.5	1.00
6	21.0	7.2	0.6	1.20
7	24.5	8.4	0.7	1.40
8	28.0	9.6	0.8	1.60
9	31.5	10.8	0.9	1.80
10	35.0	12.0	1.0	2.00
11	38.5	13.2	1.1	2.20
12	42.0	14.4	1.2	2.40
13	45.5	15.6	1.3	2.60
14	49.0	16.8	1.4	2.80
15	52.5	18.0	1.5	3.00

Airplane No. 2.

The tail-area is 53.0 sf., 30.14 percent of the nominal wing area of 174 sf. The cruise speed is 163.5 mph, and q at that speed is 68.41 lb/sf. The tail drag per square foot works out to

$$(0.635 \times 1.635) \times 0.40$$

= 2.67 x 0.40 = 1.07 lb/sf

So total tail drag is 53 x 1.07 = 56.71 lb

The total airplane drag at the cruise speed of 163.5 mph works out to

5.03 x 68.41 = 344.10 lb

Thus the percentage tail drag is

56.71 / 344.10 = 16.48 percent.

We make the table for from 12 to 21 percent of total airplane drag.

Table No. 2.
Airplane No. 2.
Tail drag from 12 to 21 percent
of total airplane drag.
Cruise-speed = 164 mph

%	Drag lb	HP	Fuel Gal.	$
12	41.28	18.00	1.50	3.00
13	44.72	19.50	1.63	3.25
14	48.16	21.00	1.75	3.50
15	51.60	22.50	1.88	3.75
16	55.04	24.00	2.00	4.00
17	58.48	25.50	2.13	4.25
18	61.92	27.00	2.25	4.50
19	65.36	28.50	2.38	4.75
20	68.80	30.00	2.50	5.00
21	72.24	31.50	2.63	5.25

Airplane No. 3. The tail area is 52.0 sf, which is 28.73 percent of the nominal wing area of 181 sf. The cruise speed is 190.8 mph, which gives a value for q of 93.11 lb/sf. The drag per sf. works out to

(1.908 x 1.908) x 0.40 = 3.64 x 0.40 = 1.46 lb/sf

The total tail drag is 52 x 1.46 = 75.9 lb. The percentage of tail drag works out to

75.9 / (4.53 x 93.11) = 75.9/421.8 = 18 percent.

Table No. 3.
Airplane No. 3.
Tail drag from 13 to 30 percent
of total airplane drag.
Cruise-speed = 191 mph

%	Drag lb	HP	Fuel Gal.	$
13	54.6	27.788	2.32	4.63
14	58.8	29.925	2.49	4.99
15	63.0	32.063	2.67	5.34
16	67.2	34.200	2.85	5.70
17	71.4	36.338	3.92	6.06
18	75.6	38.475	3.21	6.41
19	79.8	40.613	3.38	6.77
20	84.0	42.750	3.56	7.12
21	88.2	44.888	3.74	7.48
22	92.4	47.025	3.92	7.84
23	96.6	49.163	4.10	8.19

Airplane No. 4.

Tail area is 81.0 sf, which is 45.25 percent of the nominal wing area of 179 sf. For fast airplanes and twins the tail is always much larger than for slower single-engine airplanes.
Cruise speed is 216 mph., q is 119.6 lb/sf. The drag per square foot works out to

(2.16 x 2.16) x .40 = 1.87 lb/sf

Total tail drag works out to

81.0 x 1.87 = 151.47 lb

For the percentage of tail drag to total airplane drag, this works out to

= 151.47 / 741.52
= 0.2043 or 20.43 percent.

That gives us a spread from 15 to 25 percent for the table.

Table No. 4.
Airplane No. 4.
Tail drag from 15 to 25 percent of total airplane drag.
Cruise-speed = 216 mph

%	Drag lb .	HP	Fuel Gal.	$
15	111.15	64.125	5.34	10.69
16	118.56	68.400	5.70	11.40
17	125.97	72.675	6.06	12.11
18	133.38	76.950	6.41	12.83
19	140.79	81.225	6.77	13.54
20	148.20	85.500	7.13	14.25
21	155.61	89.775	7.48	14.96
22	163.02	94.050	7.84	15.68
23	170.43	98.325	8.19	16.38
24	177.84	102.600	8.55	17.10
25	185.25	106.875	8.91	17.81

Now let's see how the figures for our four airplanes compare.

Table No. 5.
Tail Drag Comparison.

Airplane	Tail Area sf	Percentage % sf	Tail Drag lb	Percentage %
No. 1	55.0	32.16	36.3	10.28
No. 2	53.0	30.14	56.71	16.48
No. 3	52.0	28.73	75.90	18.00
No. 4	81.0	45.06	151.47	20.43

Airplanes No. 2, 3, and 4 have retractable landing gear. Thus we can expect the tail drag to be a comparatively higher percentage of the total airplane drag.

There is some information on tail-drag coefficients in the older NACA Reports:

Parasite Drag added by Tail Surfaces, at zero-lift. (Cd)

Single-engine low-wing monoplane	0.0085	to	0.0120
Multi-engine low-wing monoplane	0.0060	to	0.0110
High-wing monoplane	0.0120	to	0.0180

These values have a lot of scatter due to the very different amounts of fuselage-and wing interference on the tail for various airplane design types. Thus they are mostly interesting for the orders of magnitude they show.

Chapter Thirteen

Maneuvering Drag

Control Surfaces. A good percentage of your airplane's total drag comes from the deflection of the control surfaces during cruise flight. When you deflect the control surfaces from their neutral position, they cause a definite addition to the total airplane drag.

First, the increased drag is parasite drag due to the less-streamlined shape of the deflected control surface. Second, we get some induced drag due to the extra lift since work is being done. You notice the extra drag especially when applying the ailerons. Deflecting an aileron to increase the amount of lift on that wing, you also increase that wing's drag.

Both the deflection and the chord-dimension of the ailerons help determine their control power. As the control surface area shrinks, the deflection required to make the turn gets larger and larger, and drag goes up steeply.

NACA Tests. NACA investigated the effects of varying the depth (percent of chord) of the control surfaces and came up with the following conclusions for ailerons.

15 percent	Limited control power, higher drag at large deflections.
20 to 25 percent	Highest power and minimum drag.
30 percent	Good power but much more drag.
40 percent	Good power but over a reduced range of deflections, with higher drag outside the most efficient range.

Elevator Deflection. While you deflect the elevator, the angle of attack of the stabilizer changes. For an assumed resultant lift coefficient equal to zero, the drag-coefficient value is some nine times the basic section-drag coefficient. This clearly shows the high drag increase. At reasonably large deflections of the rudder or elevator, the tail surfaces cause a very large drag. Increasing deflection beyond that gains little more control power but creates significant higher drag.

Continuous deflection of control surfaces in flight may account for an estimated average of 5 percent of your airplane's total parasite drag. To you, that's five cents out of every fuel dollar. Because large rudder deflections multiply control-surface drag, the way you fly can have a large impact on your airplane's maneuvering drag.

Wind Tunnel Results. Wind tunnel results show an average basic drag coefficient of tail surfaces within the range (positive or negative) of CL = 0.2. in the order of Cds = 0.01. This is for deflection angles within 5 degrees either way. With the flap deflected beyond about 5 degrees, drag builds up quickly beyond that.

Between 12 and 15 degrees elevator or rudder deflection, the flow remains fully attached. Between 15 and 18 degrees, flow separates from the suction side of elevator or rudder. Beyond some 19 degree, drag continues to increase with further deflection of the elevator or rudder. Then, at some 30 degrees elevator (or rudder) angle, for a lift-coefficient = + 0.2, we get still more flow separation and increased drag.

Rudder Drag. The highest influence on the drag comes from rudder deflection, especially for balanced systems. Keeping the centerline of the airplane aligned with the direction of flight in a turn takes a cambered fin airfoil-section. You camber it more when you apply rudder into a turn.

With the fin and rudder, we have a low-aspect-ratio surface. Thus we can actually increase the width of the control surface to about 30 to 40 percent. For a vertical tail with an aspect-ratio of 2:1 and a rudder area of 40 percent of the total vertical tail area, the relative drag value for a deflection of about 20 degree comes to roughly four to six times the drag of the solid drag value. And for a rudder area of 60 percent and about 15 percent deflection it is about two to two and one-half times the basic value.

Table No. 1.
Airplane No. 1.
Maneuvering drag from 1 to 10 percent of total airplane drag.
Cruise-speed = 129 mph

%	Drag lb	HP	Fuel gal.	$
1	3.5	1.2	0.10	0.20
2	7.0	2.4	0.20	0.40
3	10.5	3.6	0.30	0.60
4	14.0	4.8	0.40	0.80
5	17.5	6.0	0.50	1.00
6	21.0	7.2	0.60	1.20
7	24.5	8.4	0.70	1.40
8	28.0	9.6	0.80	1.60
9	31.5	10.8	0.90	1.80
10	35.0	12.0	1.00	2.00

Table No. 2.
Airplane No. 2.
Maneuvering drag from 1 to 10 percent of total airplane drag.
Cruise-speed = 164 mph

%	Drag lb	HP	Fuel gal.	$
1	3.44	1.50	0.13	0.25
2	6.88	3.00	0.25	0.50
3	10.32	4.50	0.38	0.75
4	13.76	6.00	0.50	1.00
5	17.20	7.50	0.63	1.25
6	20.64	9.00	0.75	1.50
7	24.08	10.50	0.88	1.75
8	27.52	12.00	1.00	2.00
9	30.96	13.50	1.13	2.25
10	34.40	15.00	1.25	2.50

Table No. 3.
Airplane No. 3.
Maneuvering drag from 1 to 10 percent of total airplane drag.
Cruise-speed = 191 mph

%	Drag lb	HP	Fuel gal.	$
1	4.2	2.14	0.18	0.36
2	8.4	4.28	0.36	0.71
3	12.6	6.413	0.53	1.07
4	16.8	8.550	0.71	1.42
5	21.0	10.688	0.89	1.78
6	25.2	12.825	1.07	2.14
7	29.4	14.963	1.25	2.49
8	33.6	17.100	1.43	2.85
9	37.8	19.238	1.60	3.21
10	42.0	21.375	1.78	3.56

Table No. 4.
Airplane No. 4.
Maneuvering drag from 1 to 10 percent of total airplane drag.
Cruise-speed = 217 mph

%	Drag lb	HP	Fuel gal.	$
1	7.41	4.28	0.36	0.71
2	14.82	8.55	0.71	1.42
3	22.23	12.83	1.07	2,14
4	29.64	17.10	1.43	2.86
5	37.05	21.375	1.78	3.56
6	44.46	25.650	2.14	4.28
7	51.87	29.925	2.49	4.99
8	59.28	34.200	2.85	5.70
9	66.69	38.475	3.21	6.41
10	74.10	42.750	3.56	7.13

Chapter Fourteen

Trim Drag - Causes and Cost

Many General Aviation light airplanes come with pitch, roll, or yaw trim control in the form of trim tabs at the control-surface trailing edge. Each use of trim-control causes trim drag. We'll look at this in some detail below.

Longitudinal Trim. Your airplane's longitudinal stability requires that the Center of Gravity or C.G. is ahead of the airplane's (not just the wing's) aerodynamic center. For a well-trimmed airplane the Moment around the Center of Gravity (C.G.) is Zero. The farther forward your airplane's Center of Gravity, the more downward trim-force the tail must provide.

The pitching moment (Cm) of the wing is the torque acting around the quarter-chord or "C/4" position. It is the upward force (force x arm) produced by the resultant of the lift on the aft part of wing. This aerodynamic force, acting aft of and around the Center of Gravity is what makes the airplane's nose want to go down.

The Airplane's Center of Pressure is the aerodynamic center of the complete airplane. On many airfoils, at increasing flying speeds, Center of Pressure (C.P.) of the wing's total lift increasingly moves aft, away from the quarter chord (C/4) position. As a result, the pitching moment increases and the wing increasingly wants to pitch nose-down. The rearward-moving C.P. travel (and thus the Cm) is larger on some airfoils (high camber, aft loaded) than on others.

Overcoming The Pitching Moment. The horizontal tail must overcome the chord-wise pitching-moment. As the pilot, you take care of this by trimming the airplane around its Center of Gravity. Of course, a higher wing pitching-moment means more trim drag. During the cruise-phase, the main purpose of longitudinal aerodynamic trim is to keep the airplane in balanced horizontal flight. It then needs only to cope with a small portion of the available control-force range.

Each wing lift-coefficient requires a different down-load and therefore a different stabilizer or elevator position to keep the airplane balanced. Thus trim drag also includes the extra lift required of the wing to counter the down-load on the horizontal stabilizer. This practical effect of the wing moment-coefficient Cm on your airplane's longitudinal stability means extra trim drag.

The additional lift required to counter-act the down-load also produces an increase in the induced drag of wing and stabilizer. This also is part of your airplane's total trim drag. Thus your airplane's loading configuration, or load and balance has a large influence on its trim drag. Longitudinal trim may make up the largest part of your airplane's total trim drag.

The more you must deflect a trim tab to overcome an unbalanced flight-condition, the more drag you create. The larger the trim tab, the smaller the tab-deflection needed to get the desired trimming effect for the cruise-condition.

Off-set of the Vertical Stabilizer. Because of the propeller slipstream's rotation, the vertical stabilizer or fin is often offset a few degrees to correct for this in straight and level flight. The extra drag this creates is actually part of the trim drag. With clockwise propeller rotation as viewed from behind the propeller, the vertical stabilizer or fin offset is to the left. Vertical (rudder) trim is similar to the horizontal tail situation, and the same principles apply.

Also included in the total trim drag is the drag from trimmed ailerons, either through trim tabs or direct. Because of the many and varied factors (often with assumed values) involved in trying to come up with practical values, we will not go into this complicated subject here. Rather we'll work out some figures for total trim drag.

Trim Drag: Horsepower Required and Cost in Fuel. According to the literature on this subject, trim drag will not be more than five percent of total airplane drag. Therefore, the Tables below show the horsepower required and the cost in fuel for total trim drag of 3, 4, and 5 percent of total airplane drag.

Table No. 1.
Airplane No. 1.
Trim drag from 3 to 5 percent of total airplane drag.
Cruise-speed = 129 mph

%	Drag lb	HP	Fuel gal.	$
3	10.5	3.6	0.30	0.60
4	14.0	4.8	0.40	0.80
5	17.5	6.0	0.50	1.00

Table No. 2.
Airplane No. 2.
Trim drag from 3 to 5 percent of total airplane drag.
Cruise-speed = 164 mph

%	Drag lb	HP	Fuel gal.	$
3	10.3	4.5	0.38	0.75
4	13.8	6.0	0.50	1.00
5	17.2	7.5	0.63	1.25

Table No. 3.
Airplane No. 3.
Trim drag from 3 to 5 percent of total airplane drag.
Cruise-speed = 191 mph

%	Drag lb	HP	Fuel gal.	$
3	12.6	6.4	0.53	1.07
4	16.8	8.6	0.71	1.42
5	21.0	10.7	0.89	1.78

Table No. 4.
Airplane No. 4.
Trim drag from 3 to 5 percent of total airplane drag.
Cruise-speed = 217 mph

%	Drag lb	HP	Fuel gal.	$
3	22.2	12.8	1.07	2.14
4	29.6	17.1	1.43	2.86
5	37.0	21.4	1.78	3.56

Chapter Fifteen

Slip-stream Effects and Drag

Your Airplane's Slipstream. Your airplane's propeller-slipstream consists of the accelerated mass of air thrust backward by the propeller. It is roughly the size of a cylinder of the same diameter as the propeller. This accelerated speed of the slipstream gives your airplane the thrust required for its forward flight. The slipstream is an air mass with a higher velocity than the airplane's flying speed. However, the air inside the slipstream does not travel down the fuselage exactly in the same direction the airplane is flying. It is deflected and strikes the fuselage at an angle, thus spoiling the flow over and around it.

When leaving the propeller, the slipstream rotates in the same direction the propeller is turning. This results in a helical motion of the air around the fuselage. While at first the slipstream is highly turbulent, it soon loses some of its violent character.

Slipstream Effects. Because of the slipstream's increased speed, the local airflow speed over any airplane part in the slipstream is higher than the flying speed of the airplane; both the local dynamic pressure will be increased, and the turbulence will induce premature transition in the local boundary-layer airflow.

As the fuselage and all of its appendages and protrusions are located within the propeller's slipstream, they are subject to an increase in local dynamic pressure which increases the total fuselage drag. This increases the drag of the part or protrusion by the square of the local airflow speed increase. At cruise speed the velocity of the air flowing over those parts that are in the slipstream is from 10 to 20 percent higher than the airplane's flying speed. This varies with throttle setting and with the angle of attack of the propeller.

Considering that this effects at least the whole fuselage and tail end, you could end up with perhaps a good ten percent increase in total airplane drag. But it all varies a lot with different airplanes, of course.

Extra Parasite Drag Means Extra Horsepower. This high-velocity stream of air flowing over the fuselage and pushing against all its protrusions absorbs a lot of your airplane engine's horsepower. While the drag penalty is much larger when the speeded-up slipstream flows over high-drag bluff objects, on relatively well-faired components of your airplane such as the fuselage sides the propeller wake will in any case increase the skin-friction drag.

Because even on a streamline body, turbulence in the fuselage boundary layer flow influences the drag considerably, if you fly a conventional airplane it is very important to reduce the drag in the region of the propeller slipstream to the very minimum practical and possible. If you can fly a cleaner airplane with a reduced number and size of various protrusions located in the propeller slipstream, you will decreases the drag-increasing and horsepower-absorbing influence of the slipstream. After all, Drag = Horsepower = Avgas = $$. Your $$.

Other Slipstream Effects. With a single-engine airplane, besides the fuselage, the slipstream affects the wing roots, tail plane, fin, rudder and part of a fixed landing gear. If you fly any conventional airplane configuration, whether high-wing or low-wing, the tractor propeller sends the slipstream over the central part of your airplane's wing. While the propeller diameter is usually not large enough to ruin much of the wing flow, even if your airplane has a perfectly smooth wing with a laminar airfoil, you'll have no laminar flow in the region reached by the turbulent propeller slipstream.

Slip-stream Drag of Landing Gear. On many airplanes at least part of the fixed landing gear is exposed to the slipstream, especially nose-wheels and un-faired nose-wheel struts located close to the propeller. Because fuselage-mounted main landing-gear struts located in the accelerated propeller-slipstream are also significant drag producers, on a low-wing airplane wing-mounting the main landing-gear struts outboard of the slipstream will cut down on fixed main-gear drag.

Balance Problems. Because the slipstream's helical motion spiraling around your airplane affects one side only of the fin and rudder, it somewhat affects the directional and lateral balance of your airplane. To balance the airplane for normal cruising flight the fin is probably offset at least two or three degrees. Of course, when engine power is changed above or below cruise power settings this balance is upset.

BEDE DESIGN No. 18. Slipstream Velocities. Interesting data relating to the velocity of the propeller slipstream for various forward speeds of the BD-4 airplane is given by the Bede Aircraft Company's BEDE DESIGN book. These values were obtained from actual flight tests on a BD-4 aircraft equipped with a 180 HP Lycoming engine swinging a 74" diameter propeller, a combination found on a good number of light airplanes. It shows that on start of take-off, the slipstream velocity is relatively high, 110 mph vs. 60 mph airspeed. At 120 mph flying speed it was 150 mph, and at 180 mph the slipstream speed was 195 mph, still 15 mph faster. These values can be good approximations for many light airplane engine/propeller combinations.

Because those components of the airplane inside the slipstream are exposed to a high-speed airflow compared to those outside, their drag is higher. The drag increase on affected areas at cruise-speed due to slipstream may be somewhere from 10-20 percent, depending on percentage of power used and the resulting flying speed. Since the fuselage drag increases as the square of the speed, when flying at, say 180 mph, when the air pressure value q equals 82.87 lb/sf, the fuselage may actually be flying at, say 195 mph, when q equals 69.63 lb/sf. This gives

(82.87 / 69.63) = 1.19% = 19.0 % increase in local air-pressure.

For the Drag Tables, from 5 to 15 percent, on the four airplanes, please refer to Chapter Twelve on the Tail Drag.

Chapter Sixteen

Interference Drag
Causes and Cost

Interference Drag - Causes. In the airflow around or over an airplane part, the combination of an increasing pressure and the inward curvature causes a turbulent boundary layer. To keep the airflow interference low, the boundary-layer flow around each part must match closely. The aerodynamic pressure-distributions and boundary-layers of two shapes intersecting or placed near each other always interact. The result is an extra net drag which we call the interference drag. It is due to the change of the boundary layer airflow of one part by the interfering part. In doing so, it causes the boundary-layer airflow to become turbulent. Thus interference drag is the increase in the drag of the various airplane parts, which makes the total airplane drag higher than the total of the separate drags.

Interference drag happens where the flow can't follow the shape of a surface moving away from the direction of the airflow. For example, on the rear portion of the wing's upper surface, past the wing's maximum-thickness point, especially when the fuselage also begins narrowing just ahead of the wing's trailing edge. Or on the inside of air-scoops and inlet-ducts, when the channel area begins to expand too quickly. Also when an un-faired projection or protuberance sticks out into the airstream.

Interference Points. Interference points are all over the airplane. The worst ones are the wing-fuselage junction, strut-intersections with the wings, and the landing-gear with its struts and wheels. Then there are parts such as wires, fittings, engine cowlings and nacelles, and perhaps radiators.

Smaller items are door hinges and handles, tail-brace struts, wires, exposed bolt heads and nuts, drain fittings, radio antennas, rivet heads, overlapped metal skin, and poorly painted surfaces. The disturbances produced by these different types of small projections and protuberances affects the flow about the wing and fuselage.

The drag of a fitting including its interference drag comes to about twice that of its projected flat plate area. This includes diverse non-streamlined projecting parts. Below we'll take a look at some of them.

The interference drag often represents a large portion of the total airplane drag.

Gaps. A most sneaky form of interference drag results from air leaks at gaps. Because air is invisible, there are no visible signs of air flowing through gaps, though sometimes you can hear it, or feel the cold draft. Moveable control-surfaces also cause interference drag. Some of these may be inherent in the design, and some affected by the pilot when maneuvering the airplane. Sealing the control-surface gaps reduces interference drag. Leaks through the wing are especially devastating. They cause boundary-layer separation and turbulence over a good area of the wing's upper surface, increasing local drag.

Cabin Ventilation. Pressure variations along a fuselage may cause air flow into and out of the fuselage. This will interfere with the normal airflow and cause disturbances. A serious problem here is sealing the fuselage to prevent random airflow in or out of the airplane. Because pilots and their passengers must have cooling air or ventilation, some form of "controlled air leaks" into and out of the cabin is a must. An efficient ventilation system takes in outside air without messing up the fuselage boundary-layer air-low. After diffusing through the cabin, the air exhausts at the boundary- layer airflow-velocity at the tail-cone. This produces the minimum possible interference drag. But where do you find such an efficient system?

Engine-nacelles on the Wing. Favorable airflow interaction requires proper shaping of forward parts of nacelles. The interference effect of an engine-nacelle on a wing is somewhat comparable to the case of a fuselage-wing combination.

The normal type of nacelle shape consists of a three-dimensional somewhat streamlined form placed partly within the wing, with the presence of the wing implying a two-dimensional flow. At and near the location of the nacelles, the shape of the wing sections then differs considerably from that of the principal profile. Superimposing a three-dimensional flow around a nacelle on the two-dimensional wing flow results in unfavorable interaction.

Slipstream. The propeller slipstream also produces interference effects. This propeller interference effect may be considerable, and often extends well behind the fuselage tail- surfaces. It can be quite serious.

The Wing Tip. In the case of wing-tip mounted fuel tanks, the interaction of airflow over various parts may be favorable enough to decrease drag, with the resulting reduction in reduced drag offsetting the increased form drag of the fuel tanks.

Winglets. Winglets are a good example of favorable interference. Because it decreases induced drag, a properly designed wing/winglet combination is more efficient than a wing alone.

The Wing-fuselage junction. Interference effects depend on the shape of the fuselage, the airfoil section, and the relative position of the fuselage. Proper location of the wing on the fuselage will increase of the airplane's efficiency factor. Especially on low-wing airplanes, the shape of the fuselage in the area of the wing-root has a big effect on airflow over the wing root.

On many light airplanes, the sides of the fuselage start to pull inward ahead of the wing's trailing edge. Unfortunately, this often is where the wing-surface slopes downward. With the boundary-layer flow not being able to follow the contours of the wing- and fuselage junction, the flow becomes turbulent, and perhaps separates, causing extra drag.

An important factor is also the airfoil shape of the wing at the root area. The airflow over the upper surface of a wing is very sensitive. Any irregular changes here in direction in the high-velocity boundary layer airflow always leads to turbulence. If it does, wing efficiency is low and drag high.

The variation of the angle of wing-incidence also affects the interference and drag of the wing-fuselage junction. It does so mainly by varying the attitude of the fuselage to the relative wind for any given angle of attack of the airplane. The shape of the fuselage front part leading up to and at the wing position also is very important. The airflow over the front fuselage may break away before reaching the wing-fuselage junction. The longer the fuselage in front of the wing, the more important fore-body shape becomes.

High-wing Airplanes. The high-wing configuration has the least interference drag, and is the most efficient aerodynamic choice. High-wing airplanes often have better wing-to-fuselage junctions. A high wing with some dihedral is an example of a design with low interference drag. Also for the high-wing combination, the minimum drag-coefficient is lowest at a small positive angle of attack.

For a high-wing configuration, interference drag results mostly from the interaction of the fuselage boundary layer with that from the wing's lower surface. This latter layer is rather thin at positive angles of attack.

As the interference increases slowly with increasing angle of attack, an un-filleted fuselage-wing junction may sometimes show serious high interference drag here. Certain high-wing combinations with a very unsatisfactory fuselage-wing junction may have high drag in the high-speed range. In a well-designed high-wing airplane the wing/fuselage junction affects only the much less critical lower wing-surface. The fuselage does not interfere with the airflow over the upper side of the wing. Therefore, a properly-designed high-wing monoplane needs filleting on the under-surface.

The Low-Wing Airplane. On a low-wing airplane, interference drag is highest where an expanding area exists between the fuselage and the sloping-down rear part of the wing's upper-surface. In such a case, first the fuselage interferes with the boundary layer on the upper surface of a low wing. Second, the airflow over the upper surface of a wing is more sensitive to interference and premature separation. Also, because of its low pressure, the wing's upper-surface boundary-layer is appreciably thicker than the lower-surface boundary-layer.

To follow both the wing and the fuselage surfaces, the air-stream behind the wing's mid-chord point must expand. Therefore, on the upper surface of a wing behind the point of minimum pressure, there is an increase in pressure in the boundary-layer flow. After first overcoming this pressure increase, the airflow then must overcome that due to the geometrical sloping away of the wing- and fuselage surfaces.

With a high angle of divergence between the fuselage and the upper surface of the wing, the low-wing position involves strong diffusion of the mixed boundary layer flows. We have here conditions comparable with those existing in the outlet cone of a Venturi tube. If the angle of this "cone" is too large, the stream cannot expand fast enough to fill the cone. Thus the flow detaches itself from the walls.

The kinetic energy in the boundary layer is simply not high enough to overcome the increasing pressure accompanying the expansion in the cone. The flow detaches itself from the upper wing-surface and also, usually, from the adjacent portion of the fuselage surface. Thus the junctions on the upper surface of a wing are much more critical than those on the bottom.

On the under surface of the wing the pressure always is positive. This somewhat helps the flow to adhere to the surfaces. Also, the divergence of the fuselage surface from the lower wing surface is less than from the upper wing-surface.

The Interference Zone. Especially on a low-wing airplane, the wing-root the zone of interference effects may extend at least a chord length or more out from the fuselage. On a longer fuselage, with any taper more gradual, the divergence usually is much less than on a short fuselage. Therefore the airflow can better follow the more gradual area expansion.

Skin-friction slows down the air flowing in a corner between two surfaces, causing more drag and perhaps early separation. This is even more important if fuselage- and wing surfaces meet at an angle of less than 90 degree. Like on a low-wing airplane with a rounded fuselage cross-section and dihedral in the wing. Therefore there must never be an acute angle between two intersecting surfaces. Fillets are required in such areas.

The Interference Drag Factor. For a modern light airplane interference drag is an increasingly important part of its total drag, ranging from about six to ten percent. Working out the interference between the various elements of the airplane is difficult. There simply are too many factors involved. Without model tests, it is common to add some 10 to as much as 25 percent to the total drag. The average interference drag factor varies according to the aerodynamic finesse of the airplane.

For a cantilever monoplane with the wing roots carefully faired into the fuselage, ten percent may be a fair average value. Even for a very clean modern design it rarely is less than five or six percent. It always is important to reduce the interference drag to the practical minimum figure.

For the drag tables for the four airplanes, from 5 to 15 percent, please again refer to Chapter Twelve, on the Tail Drag.

SECTION TWO

Drag Reduction

Possible Savings

Chapter Seventeen

Flying-time Savings from Drag Reduction

Time-savings for 1 to 1000 hours of cruise flight.

Just to show you how we get the figures for Tables No. 3, 4, and 5, we work out the time-savings made possible by drag reduction. As before, from 95% drag down to 50% drag in steps of 5%. For any ratio of lower drag over original (100%) drag, the resulting third-root figure is always the same. Therefore, for our calculations we do not need to know the actual flying speeds. All we need to know are the drag-reduction ratios. We first calculate after how much time the airplane has gone the distance equal to V1. This depends on the third root of the ratio of D2 over D1 (D2 / D1). Then we subtract the resulting value from one hour. This gives us the amount of time saved. The example below will make this clear.

The Calculations. How we do this: First we calculate the third-root value for D2 over D1 (D2 / D1). Thus for each drag-reduction step, we divide the lower drag, or D2, over the higher base drag, D1. Then we subtract the resulting number from 1.00, (which stands for 100% drag). Next we multiply the result we get by 3600, the number of seconds in one hour. This gives us the time saved per hour of flight, in seconds. This number of seconds we then divide over 60. Which gives us the number of minutes and seconds of flying time saved per one hour of flight. The table we get gives us a set of universally applicable time-savings figures. Thus these time-saved ratios apply to any airplane and to any speeds for which we use this method.

Example: For D = 75%. We divide D2, which in this example is 75 percent, over D1, which always is 100 percent.

75 / 100 = 0.75

Third root of 0.75 / 1.00 = 0.908560

1.00 - 0.908560 = 0.09144

One hour = 3600 seconds; 0.09144 x 3600 = 329.183 Seconds = 5 minutes and 29 seconds. Thus the time saved is 5 minutes and 29 seconds per hour of cruise flight.

Put neatly in a row, there are six steps.

1) For each 5% step we calculate the values for the lower drag percentage over base drag, given by (D2 / D1).

2) Next we work out the third-root value of the division in step 1.

3) We then subtract that (third-root) value from 1.0.

4) The resulting value gives us the fraction of the time saved per hour.

5) Multiplying that value by 3600 (seconds) gives us the total number of seconds saved per hour of flying.

6) Dividing over 60 gives us the time saved in minutes and seconds.

Table No. 1.

D % Rest	Third Root	Subtraction
0.95 =	0.983047572;	1.00 ––– 0.983047572 = 0.0169523
0.90 =	0.965489385;	1.00 ––– 0.096548939 = 0.0345106
0.85 =	0.947268237;	1.00 ––– 0.947268237 = 0.0527318
0.80 =	0.928317767;	1.00 ––– 0.928317767 = 0.0716822
0.75 =	0.908560296;	1.00 ––– 0.908560296 = 0.0914397
0.70 =	0.887904002;	1.00 ––– 0.887904002 = 0.112096
0.65 =	0.866239105;	1.00 ––– 0.866239105 = 0.1337609
0.60 =	0.843432665;	1.00 ––– 0.843432665 = 0.1565673
0.55 =	0.819321271;	1.00 ––– 0.819321271 = 0.1806787
0.50 =	0.793700526;	1.00 ––– 0.793700526 = 0.2062995

Table No. 2.

D %	Savings in seconds and in minutes
0.95	0.0169523 x 3600 = 61.028" = 1'-01"
0.90	0.0345106 x 3600 = 124.238" = 2'-24"
0.85	0.0527318 x 3600 = 189.835" = 3'-10"
0.80	0.0716822 x 3600 = 258.056" = 4'-19"
0.75	0.0914 x 3600 = 329.183" = 5'-29"
0.70	0.112096 x 3600 = 403.546" = 6'-44"
0.65	0.1337609 x 3600 = 481.539" = 8'-02"
0.60	0.1565673 x 3600 = 563.642" = 9'-24"
0.55	0.1806787 x 3600 = 650.443" = 10'-50"
0.50	0.2062995 x 3600 = 742.678" = 12'-23"

Tables 3, 4, and 5 list the time saved in three ways.

First Table No. 3, for 1, 2, 3 and so on to 10 hours of flight. These are good for working out the time-savings for a single flight, or total flying time for one day, for example. Table No. 4 shows the time-savings for 20, 30, 40, and so up to 100 hours. Good for flying times per month or a certain period.

Table No. 5 shows the time-savings for 200, 300, and up to 1,000 hours of flying time. Flying time, of course, here means straight and level cruise flight. No aerobatics allowed.

Table No. 3.
Time Savings for One to Ten Hours of Cruise Flight.
First in minutes and seconds, then in hours and minutes.

	Flying Hours									
D%	1	2	3	4	5	6	7	8	9	10
95	1-01	2-02	3-03	4-04	5-05	6-06	7-07	8-08	9-09	10-10
90	2-04	4-08	6-13	8-17	10-21	12-25	14-30	16-34	18-38	20-42
85	3-10	6-20	9-30	12-39	15-49	18-59	22-09	25-19	28-29	31-38
80	4-18	8-36	12-54	17-12	21-30	25-48	30-06	34-24	38-43	43-01
75	5-29	10-58	16-28	21-57	27-26	32-55	38-24	43-54	49-23	54-52

70	6-44	13-27	20-11	26-54	33-38	40-21	47-05	53-48	1:01	1:07
65	8-02	16-03	24-05	32-06	40-08	48-09	56-11	1:04	1:12	1:20
60	9-24	18-47	28-11	37-35	46-58	56-22	1:06	1:15	1:25	1:34
55	10-51	21-42	32-33	43-24	54-16	1:05	1:16	1:27	1:38	1:49
50	12-23	24-45	37-08	49-31	1:02	1:14	1:27	1:39	1:51	2:04

Table No. 4.
Time Savings for 20 to 100 Hours.
First in minutes and seconds, then in hours and minutes.

	Flying Hours								
D%	20	30	40	50	60	70	80	90	100
95	20-21	33-34	44-45	55-57	1:07	1:11	1:21	1:32	1:42
90	45-33	1:08	1:31	1:54	2:17	2:25	2:46	3:06	3:27
85	1:03	1:35	2:07	2:38	3:10	3:41	4:13	4:45	5:16
80	1:26	2:09	2:52	3:35	4:18	5:01	5:44	6:27	7:10
75	1:50	2:45	3:39	4:34	5:29	6:24	7:19	8:14	9:09
70	2:15	3:22	4:29	5:36	6:44	7:51	8:58	10:05	11:13
65	2:41	4:01	5:21	6:41	8:02	9:22	10:22	12:02	13:23
60	3:08	4:42	6:16	7:50	9:24	10:58	12:32	14:05	15:39
55	3:37	5:26	7:14	9:03	10:51	12:40	14:28	16:17	18:05
50	4:08	6:11	8:15	10:19	12:22	14:26	16:30	18:34	20:38

Table No. 5.
Time Savings for 200 to 1000 hours. In and hours and minutes.

	Flying Hours								
D%	200	300	400	500	600	700	800	900	1000
95	3:23	5:05	6:47	8:29	10;10	11:52	13:34	15:15	16:57
90	6:54	10:21	13:48	17:15	20:42	24:09	27:37	31:04	34:31
85	10:33	15:49	21:06	26:22	31:38	36:55	42:11	47:28	52:44
80	14:20	21:30	28:40	35:50	43:01	50:11	57:21	64:31	71:41
75	18:17	27:26	36:35	45:43	54:52	64:00	73:09	82:18	91:26
70	22:25	33:38	44:50	56:03	67:15	78:28	89:41	100:53	112:06
65	26:45	40:08	53:30	66:53	80:15	83:38	107:01	120 23	133:46
60	31:19	46:58	62:38	78:17	93:56	109:36	125:15	140:55	156:34
55	36:12	54:17	72:23	90:29	108:31	126:36	144:41	162:47	180:52
50	41:16	61:53	82:31	103:09	123:47	144:25	165:02	185:40	206:18

Chapter Eighteen

Savings in Fuel Costs Through Drag Reduction

Money saved on Fuel expenses. In this Chapter we work out the savings in fuel-costs we get from drag reduction on light airplanes. This time we will also use the factors we get from calculating the third root of D2/D1. We have a good, practical reason for this. With its drag reduced, your airplane covers a larger distance per hour. Your savings in fuel costs come from the reduced flight time required to cover the distance equal to the basic speed at 100% drag. The extra distance covered per hour is your saving.

Table No. 1.
Percentages of fuel-cost savings per amount spent
per hour or per flight per fuel-dollar.

Savings Savings

percent cts/$
D% Savings calculation 3d Root
Rest

95 1.0 – 0.98305 = 0.01695 = 1.695% = 1.70
90 1.0 – 0.96549 = 0.03451 = 3.451% = 3.45
85 1.0 – 0.94727 = 0.05273 = 5.273% = 5.27
80 1.0 – 0.92832 = 0.07168 = 7.168% = 7.17
75 1.0 – 0.90856 = 0.09144 = 9.144% = 9.14

70 1.0 – 0.88790 = 0.11210 = 11.210% = 11.21

65 1.0 – 0.86624 = 0.13376 = 13.376% = 13.38
60 1.0 – 0.84343 = 0.15657 = 15.657% = 15.66
55 1.0 – 0.81932 = 0.18068 = 18.068% = 18.07
50 1.0 – 0.79370 = 0.20630 = 20.630% = 20.63

Table No. 2.
Fuel cost savings in dollars per amount spent per hour or per flight.

D%	$10	$20	$30	$40	$50	$60	$70	$80	$90	$100
95	0.17	0.34	0.51	0.68	0.85	1.02	1,19	1.36	1.53	1.70
90	0.35	0.69	1.04	1.38	1.73	2.07	2.42	2.76	3.11	3.35
85	0.53	1.05	1.58	2.11	2.64	3.16	3.69	4.22	4.75	5.27
80	0.72	1.43	2.15	2.87	3.58	4.30	5.02	5.73	6.45	7.17
75	0.91	1.83	2.74	3.66	4.57	5.49	6.40	7.32	8.23	9.14
70	1.12	2.24	3.36	4.48	5.60	6.73	7.85	8.97	10.09	11.21
65	1.34	2.67	4.01	5.35	6.69	8.03	9.36	10.70	12.04	13.38
60	1.57	3.13	4.70	6.26	7.83	9.39	10.96	12.53	14.09	15.66
55	1.81	3.61	5.42	7.23	9.03	10.84	12.65	14.45	16.26	18.07
50	2.06	4.13	6.19	8.25	10.31	12.38	14.44	16.50	18.57	20.63

Table No. 3.
Fuel cost savings in dollars per amount spend per hour or per flight.

D%	$110	$120	$130	$140	$150	$160	$170	$180	$190	$200
95	1.86	2.03	2.20	2.37	2.54	2.71	2.88	3.05	3.22	3.39
90	3.80	4.14	4.49	4.83	5.18	5.52	5.87	6.21	6.56	6.90
85	5.80	6.33	6.86	7.38	7.91	8.94	8.96	9.49	10.02	10.55

80	7.89	8.60	9.32	10.04	10.75	11.47	12.19	12.90	13.62	14.34
75	10.06	10.97	11.89	12.80	13.72	14.63	15.54	16.46	17.37	18.09
70	12.33	13.45	14.57	15.69	16.81	17.94	19.06	20,18	21.30	22.42
65	14.71	16.05	17.39	18.73	20.06	21.40	22.74	24.08	25.41	26.75
60	17.22	18.79	20.35	21.92	23.49	25.05	26.62	28.18	29.75	31.31
55	19.87	21.68	23.49	25.30	27.10	28.91	30.72	32.52	34.33	36.14
50	22.69	24.76	26.82	28.88	30.94	33.01	35.07	37.13	39.20	41.26

Chapter Nineteen

The Effect of Drag-Reduction

Part 1.

The Effect of Your Airplane's Parasite Drag Reduction in Straight and Level Flight.

Parasite drag reduction gives benefits at both ends and at the middle of a flight. However, while the take-off and the landing phases take only a relatively short period of the flight time, the cruise-flight section may go on for from two to five hours. Thus any drag-reduction benefit will give the biggest pay-off in reduced fuel expenses during cruise flight.

In this somewhat theoretical section we will take a look at reducing the drag or increasing the horsepower on the same four types of manufacturer's general aviation light airplanes we used in Chapter Four on the wing drag: For each of these four types of manufacturer's light airplanes we will look at three aspects of drag reduction:

1. How the horsepower required goes down with a reduction in drag, at the same maximum speed.
2. How much the maximum speed will increase with the same reduction in drag, with the same engine and horsepower.
3. How much extra horsepower it takes to get the same 26 percent maximum speed increase as in case 2, with the same drag and increased horsepower.

Airplane No. 1. $V_{max.}$ = 123 kts or 141.5 mph @ S/L, HP = 160

For this type airplane we will show in detail how we go about getting the figures we are after. For the other three airplane types we can then keep to the actual calculations. Using the old stand-by formula, we work out the total drag at $V_{max.}$:

Total Drag = (HP x 375) / speed (mph)
= (160 x 375) / 141.5
= 60.000 / 141.5
= 424 lb

To find the GEDA value, we divide the 424 pound drag figure over the air-pressure q at the 141.5 mph maximum speed of our airplane.

424 / 51.21 = 8.3 sf

To find the horsepower required for the decreased amount of drag for each step, we use the formula:

Horsepower = (Drag x V) / 375

Checking this out with our basic data for the maximum speed we get

(424 x 141.5) / 375
= 59,996 / 375
= 160 HP

As shown in Table 24-1 for and Fig. 24-1, for each step we list the following seven items:

1. The percentage of drag.
2. The drag in pounds.
3. The GEDA value.
4. The horsepower required
5. The number of gallons of fuel used per hour based on 0.50 lb/hp/hr.
6. The total cost of the fuel per hour of flight based on $2.00 per U.S. gallon.
7. The number of miles per U.S. gallon obtained at this speed.
8. The cost per mile in U.S. dollars.

Drag Reduction Results at Maximum Speed at Sea Level.

Table No. 1.
Airplane No. 1. Drag Reduction at $V_{max.}$ $V_{max.}$ = 141.5 mph.

D%	Drag lb	GEDA sf	HP	gph	Cost $/h	Savings $/hr /step	Savings total	mpg	Cost c/m	Savings c/m total
100	424	8.27	160	13.33	26.67	----------	-------------	10.61	18.85	----------
95	403	7.85	152	12.67	25.33	1.33	1.33	11.17	17.90	1.22
90	382	7.44	144	12,00	24.00	1.33	2.67	11.79	16.96	1.90
85	360	7.03	136	11.33	22.67	1.33	4.00	12.49	16.02	2.83
80	339	6.61	128	10.67	21.33	1.33	5.33	13.20	15.07	3.78
75	318	6.20	120	10.00	20.00	1.33	6.67	14.15	14.13	4.72
70	297	5.79	112	9.33	18.67	1.33	8.00	15.16	13.19	5.66
65	276	5.37	104	8.67	17.33	1.33	9.33	16.33	12.26	6.59
60	254	5.00	96	8.00	16.00	1.33	10.67	17.09	11,31	7.54
55	233	4.55	88	7.33	14.67	1.33	12.00	19.30	10.37	8.48
50	212	4.14	80	6.67	13.33	1.33	13.33	21.23	9.42	9.43

Drag Reduction Results at Maximum Speed at Sea Level. As Table No. 24-1 shows, for the same airspeed, for every five percent drag reduction there is an equal five percent reduction in horsepower required. Which thus also goes for the fuel-consumption and fuel-dollars. The number of miles per gallon increases in the same ratio. All this clearly shows the potential benefit of aerodynamic drag reduction. For example, a 2400 pound light airplane designed for a maximum speed of 141.5 mph (123 knots), with its drag reduced by 25 percent:

a) needs only a 120 HP engine.
b) will use 25 cents less fuel per hour.
c) can do with a smaller wing.
d) a narrower wing chord takes a shorter tail.

Thus, as with the Questair Venture kitplane, for example, the whole airplane can be smaller and lighter. There is a domino-effect. So instead of 8.3 sf. its GEDA would be only 6.2. sf. or even less. This 6.2 sf. figure, by the way, is still rather high.

Among the newest General Aviation certified composite four-seaters available, (and a good number available and flying as kitplanes) have a GEDA of less than 4.0. This shows that with the present state-of-the-art, low-drag light airplanes are possible. Therefore we worked out this table for drag reductions up to 50%, which gives us a GEDA of 4.15 sf for this airplane.

Now we will work it out for the other three airplanes.

Table No. 2.
Airplane No. 2. Drag Reduction at $V_{max.}$ $V_{max.}$ = 180.0 mph

D%	Drag lb	GEDA sf	HP	gph	Cost	Savings $/hr / step	Savings $/hr total	mpg	Cost c/m	Savings c/m total
100	417.0	5.03	200	16.67	33.33	1.67	------------	10.80	18.52	------------
95	396.2	4.78	190	15.83	31.67	1.67	1.67	11.37	17.59	0.93
90	375.3	4.53	180	15.00	30.00	1.67	3.33	12.00	16.67	1.85
85	354.5	4.28	170	14.17	28.33	1.67	5.00	12.71	15.74	2.78
80	333.6	4.02	160	13.33	26.67	1.67	6.67	13.50	14.82	3.70
75	312.8	3.77	150	12.50	25.00	1.67	8.33	14.40	13.89	4.63
70	291.9	3.47	140	11.67	23.33	1.67	10.00	15.43	12.96	5.56
65	271.1	3.27	130	10.83	21.67	1.67	11.67	16.62	12.04	6.48
60	250.2	3.02	120	10.00	20.00	1.67	13.33	18.00	11.11	7.41
55	229.4	2.77	110	9.17	18.33	1.67	15.00	19.64	10.18	8.34
50	208.5	2.52	100	8.33	16.67	1.67	16.67	21.60	9.26	9.26

Table No. 3.
Airplane No. 3. Drag Reduction at $V_{max.}$ $V_{max.}$ = 210.0 mph.

D%	Drag lb	GEDA sf	HP	gph	Cost $/hr	Savings $/hr / step	Savings $/hr total	mpg	Cost c/m	Savings c/m total
100	511.0	4.53	285.0	23.75	47.50	–––––	–––––	8.84	22.60	–––––
95	485.5	4.30	270.8	22.56	45.13	2.375	2.375	9.31	21.49	1.11
90	459.9	4.08	256.5	21.38	42.75	2.375	4.750	9.82	20.36	2.24
85	434.4	3.85	242.3	20.19	40.38	2.375	7.125	10.40	19.23	3.37
80	498.8	3.62	228.0	19.00	38.00	2.375	9.500	11.05	18.09	4.51
75	383.3	3.40	213.8	17.81	35.63	2.375	11.875	11.79	16.97	5.63
70	357.7	3.17	199.5	16.63	33.25	2.375	14.250	12.63	15.83	6.77
65	332.2	2.94	185.3	15.44	30.88	2.375	16.625	13.60	14.70	7.90
60	306.6	2.72	171.0	14.25	28.50	2.375	19.000	14.74	13.57	9.03
55	281.1	2.49	156.8	13.06	26.13	2.375	21.375	16.08	12.44	10.16
50	255.5	2.27	142.5	11.88	23.75	2.375	23.750	17.68	11,31	11.30

Table No. 4.

Airplane No. 4. Drag Reduction at $V_{max.}$ $V_{max.}$ = 238.0 mph.

D%	Drag lb	GEDA sf	HP	gph	Cost $/hr	Savings $/hr / step	Savings $/hr total	mpg	Cost c/m	Savings c/m total
100	898.0	6.20	570.0	47.50	95.00	-----------	------------	5.01	39.92	------------
95	853.1	5.89	541.5	45.13	90.25	4.75	4.75	5.27	37.92	2.00
90	808.2	5.58	513.0	42.75	85.50	4.75	9.50	5.57	35.92	4.00
85	763.3	5.27	484.5	40.38	80.75	4.75	14.25	5.89	33.93	5.99
80	718.4	4.96	456.0	38.00	76.00	4.75	19.00	6.26	31.93	7.99
75	673.5	4.65	427.5	35.63	71.25	4.75	23.75	6.68	29.94	9.98
70	628.6	4.34	399.0	33.25	66.50	4.75	28.50	7.16	27.94	11.98
65	583.7	4.03	370.5	30.88	61.75	4.75	33.25	7.71	25.95	13.97
60	538.8	3.72	342.0	28.50	57.00	4.75	38.00	8.35	23.95	15.97
55	493.9	3.41	313.5	26.13	52.25	4.75	42.75	9.11	21.95	17.97
50	449.0	3.10	285.0	23.75	47.50	4.75	47.50	10.02	19.96	19.96

The Effect of Drag Reduction

Part **2**

Speed Increase with Drag Decrease.

Keeping the Same Engine. Next we first take a look at how the maximum performance of our 160 HP 2400-pound airplane increases when we reduce the drag in the same way but keep the same engine. Like when the owner decides to have some mod shop do something about reducing the fuel-consuming parasite drag of his airplane. Our calculations show how much the speed will increase with each five percent step of drag decrease. For this purpose we use the formula:

V2 = V1 x (Third root of (High drag / lower drag)

For example, for a 25 percent drag reduction this works out to

V2 = V1 x third root of (higher drag / lower drag)
= third root of (100 / 75)
= third root of 1.33333
= 1.10064

So for 25 percent drag reduction at the same power

V2 = 1.10064 x 141.5 mph = 155.74 mph.

This is practically a ten-percent speed increase.

Table No. 1 shows the results of our calculations. Using the same method, you can apply these factors to any light airplane. That's why we also use the same values for the other three airplanes. Our final figures show that when we reduce the drag by 50%, the speed increases by 26%. Thus for every two percent drag decrease we get about one percent increase in speed. And because we fly more miles per hour on the same fuel-consumption, the maximum range of the airplane also goes up.

Of course, we can splice up this performance gain any way we want. For example, by throttling-down the engine to fly at the "old" speed, fuel-consumption decreases even more. That could give a still higher range in slightly longer flying time. Or we could settle for some more speed, some decrease in fuel-consumption, and a bit more range. There are various scenarios available to you here.

Table No. 1.
Airplane No. 1.
V1 = 141.5 mph. Increase in $V_{max.}$ with Drag Reduction at same Horsepower.

D%	GEDA sf	V1 mph		Third-root value	%+		V2 mph	+V/ step mph	+V total mph
100	8.27	–––––––		–––––––	–––––––		141.5	–––––––	–––––––
95	7.85	141.5	x	1.0172	1.72	=	143.9	2.44	2.44
90	7.44	141.5	x	1.0357	3.57	=	146.6	2.62	5.06
85	7.03	141.5	x	1.0557	5.57	=	149.4	2.82	7.88
80	6.61	141.5	x	1.0772	7.72	=	152.4	3.05	10.93
75	6.20	141.5	x	1.1006	10.06	=	155.7	3.31	14.24
70	5.79	141.5	x	1.1263	12.62	=	159.4	3.62	17.86
65	5.37	141.5	x	1.1544	15.44	=	153.3	3.99	21.85
60	5.00	141.5	x	1.1856	18.56	=	167.8	4.42	26.27
55	4.55	141.5	x	1.2205	22.05	=	172.7	4.93	31.20
50	4.14	141.5	x	1.2600	26.00	=	178.3	5.59	36.79

Note: The percentages speed increase are the same for these four tables. See Table No. 5.

Table No. 2.
Airplane No. 2. V1 = 180 mph. Increase in $V_{max.}$ with Drag Reduction at same Horsepower.

D%	GEDA sf	V1 mph	Third-root value	V2	+V/ step mph	+V total mph

100	5.03	–––––––––––– ––––––––––––––				180.00	––––––––––	––––––––––––––
95	4.78	180.0	x	1.0172	=	183.10	3.10	3.10
90	4.53	180.0	x	1.0357	=	186.43	3.33	6.43
85	4.28	180.0	x	1.0556	=	190.02	3.59	10.02
80	4.02	180.0	x	1.0772	=	193.90	3.88	13.90
75	3.77	180.0	x	1.1006	=	198.12	4.22	18.12
70	3.52	180.0	x	1.1263	=	202.72	4.60	22.72
65	3.27	180.0	x	1.1544	=	207.79	5.07	27.79
60	3.02	180.0	x	1.1856	=	213.41	5.62	33.41
55	2,77	180.0	x	1.2205	=	219.69	6.28	39.69
50	2.52	180.0	x	1.2600	=	226.80	7.11	46.80

Table No. 3.
Airplane No. 3. V1 = 238 mph. Increase in $V_{max.}$ with Drag Reduction at Same HP.

D%	GEDA sf	V1 mph		Third-root value		V2 mph	+V/ step mph	+V total mph
100	4.53	210.0		–––––––––––––––	=	210.0	––––––––––	––––––––––––
95	4.30	210.0	x	1.0172	=	213.6	3.62	3.62
90	4.08	210.0	x	1.0357	=	217.5	3.89	7.51
85	3.85	210.0	x	1.0557	=	221.7	4.18	11.69
80	3.62	210.0	x	1.0772	=	226.2	4.53	16.22
75	3.40	210.0	x	1.1006	=	231.1	4.91	21.13
70	3.17	210.0	x	1.1262	=	236.5	5.38	26.51
65	2.94	210.0	x	1.1544	=	242.4	5.92	32.43
60	2.72	210.0	x	1.1856	=	249.0	6.55	38.98
55	2.49	210.0	x	1.2205	=	256.3	7.33	46.31
50	2.27	210.0	x	1.2600	=	264.6	8.29	54.60

Table No. 4.
Airplane No. 4. V1 =   mph. Increase in $V_{max.}$ with Drag Reduction with Same Horsepower.

D%	GEDA sf	V1 mph		Third-root value		V2 mph	+V/ step mph	+V total mph
100	6.20	238.0		––––––––––––––––		–––––––––––––	–––––––––––	–––––––––––––
95	5.89	238.0	x	1.0172	=	242.1	4.10	4.10

90	5.58	238.0	x	1.0357	=	246.5	4.41	8.51
85	5.27	238.0	x	1.0557	=	251.3	4.74	13.25
80	4.96	238.0	x	1.0772	=	256.4	5.13	18.38
75	4.65	238.0	x	1.1006	=	262.0	5.57	23.95
70	4.34	238.0	x	1.1262	=	268.0	6.10	30.05
65	4.03	238.0	x	1.1544	=	274.8	6.70	36.75
60	3.72	238.0	x	1.1856	=	282.2	7.43	44.18
55	3.41	238.0	x	1.2205	=	290.5	8.30	52.48
50	3.10	238.0	x	1.2600	=	299.9	9.40	61.88

Speed Increase in Percentages - Same for Each Case.

While the actual speed increase-values in mph for each of the four airplanes are of course different, the speed-increase for each step as a percentage of the base maximum speed is the same. This is so because all the calculations are based on five-percent drag- reduction steps. Table No. 5 gives the figures for the individual drag-reduction steps.

The first column shows the drag-percentage for the step, the second column shows the speed-increase for the step as a percentage, and the third column shows the percentage of speed-increase for the step over the five percent of the drag decrease.

Column four shows the total percentage speed increase of each step, while column five shows the total speed-increase over the total percentage of drag decrease for each step.

Table No. 5.

Speed Increase in Percentages.
Increase per Step, and Total Increase.

D%	(% +V) for step	(% +V) / % -D	(% +V) total	(% +V) total %-D
100	----------	----------	-------------	-----------
95	1.72	34.4	1.72	34.4
90	1.82	36.4	3.58	35.8
85	1.92	38.4	5.57	37.1

80	2.04	40.8	7.72	38.6
75	2.17	43.4	10.19	40.8
70	2.32	46.4	12.62	42.1
65	2.50	50.0	15.44	44.1
60	2.71	54.2	18.66	46.7
55	2.94	58.8	22.05	49.0
50	3.24	64.7	26.00	52.0

The Effect of Drag Reduction

Part 3

Increase in Horsepower Required for same increase in $V_{max.}$

Next we look at by how much we will have to increase the engine's horsepower rating to get up to the same 26% speed increase. Here again we use the same formula, with the $V_{max.}$ multiplied by the third root of the relation between the higher HP over the original hp. This time we increase the horsepower in steps of ten hp, up to double (100 % extra) the original hp. The resulting figures in Table 1-3 clearly show that increasing your airplane's speed by putting in more horsepower is the least efficient way.

To get the same 26% speed-increase we get from a 50% drag decrease you would have to put in 100% more horsepower. Short of adding another engine, that is only valuable as a pencil and paper-exercise. Which, of course, is what we are doing here.

Suppose you put double the engine power in your airplane.

a) You increase the total weight.
b) The fuel-consumption per hour doubles, but you are only going at most 26% faster.
c) Therefore you need a lot more fuel aboard for the same range.
d) So you will need a bigger wing.
e) A bigger wing requires a longer tail-arm and control areas.

As we already saw in Chapter One, what you will get is an airplane which is a lot bigger, heavier, and more expensive. Not only to buy, but also to fly, maintain, and hangar. With a lot more aerodynamic drag. This all means that you will not get the 26% higher speed you want. In contrast to this, (for a new design), a decrease in drag can lead to either a smaller airplane or a higher speed at the same operating expense for the same airplane.

Table No. 1.
Airplane No. 1. V1 = 141.5 mph.

HP	%+HP	V2	%+V	%+V /% HP
160	–––––––––––––––	––––––––––––	––––––––––––	–––––––––––––
170	6.25	144.4	2.05	32.80
180	12.50	147.2	4.00	32.00
190	18.75	149.8	5.89	31.41
200	25.00	152.4	7.72	30.88
210	31.25	154.9	9.49	30.37
220	37.50	157.4	11.12	29.65
230	43.75	159.7	12.86	29.39
240	50.00	162.0	14.47	28.94
250	56.25	164.2	16.04	28.52
260	62.50	166.4	17.57	28.11
270	68.75	168.5	19.06	27.72
280	75.00	170.5	20.51	27.35
290	81.25	172.5	21.92	26.98
300	87.50	174.5	23.31	26.64
310	93.75	176.4	24.67	26.42
320	100.00	178.3	26.00	26.00

Table No. 2.
Airplane No. 2. V1=180 mph.

HP	%+HP	V2	%+V	%+V /%+HP
200	––––––––––––	––––––––––––	–––––––––––––	–––––––––––––
210	5.0	183.0	1.64	32.80
220	10.0	185.8	3.23	32.30
230	15.0	188.6	4.77	31.80
240	20.0	191.3	6.27	31.35
250	25.0	193.9	7.72	30.88
260	30.0	196.5	9.14	30.47
270	35.0	198.9	10.52	30.06
280	40.0	201.4	11.87	29.68
290	45.0	203.7	13.19	29.31
300	50.0	206.0	14.47	28.94
310	55.0	208.3	15.73	28.60
320	60.0	210.5	16.96	28.27
330	65.0	212.7	18.17	27.95
340	70.0	214.8	19.35	27.64
350	75.0	216.9	20.51	27.35
360	80.0	219.0	21.64	27.05
370	85.0	221.0	22.76	26.78
380	90.0	222.9	23.86	26.51

390	95.0	224.9	24.93	26.24
400	100.0	226.8	26.00	26.00

Table No. 3.
Airplane No. 3. V1= 210 mph.

HP	%+HP	V2	%+V	%+V /%+HP
285	–––––––––––––––	–––––––––––––––	––––––––––––	–––––––––––––
295	3.51	212.4	1.16	33.05
305	7.02	214.8	2.29	32.62
315	10.53	217.1	3.39	32.19
325	14.04	219.4	4.48	31.91
335	17.54	221.6	5.54	31.58
345	21.05	223.8	6.58	31.26
355	24.56	226.0	7.60	30.94
365	28.07	228.0	8.60	30.64
375	31.58	230.1	9.58	30.34
385	35.09	232.1	10.55	30.07
395	38.60	234.1	11.49	29.77
405	42.11	236.1	12.43	29.52
415	45.61	238.0	13.35	29.27
425	49.12	239.9	14.25	29.01
435	52.63	241.8	15.14	28.77
445	56.14	243.6	16.01	28.52
455	59.65	245.4	16.88	28.30
465	63.16	247.2	17.73	28.07
475	66.67	249.0	18.56	27.84
485	70.18	250.7	19.39	27.63
495	73.68	252.4	20.20	27.42
505	77.19	254.1	21.00	27.21
515	80.70	255.8	21.80	27.01
525	84.21	257.4	22.59	26.83
535	87.72	259.1	23.36	26.63
545	91.23	260.7	24.12	26.44
555	94.74	262.2	24.88	26.26
565	98.25	263.8	25.62	26.08
570	100.00	264.6	26.00	26.00

Table No. 4.
Airplane No. 4. V1= 238 mph.

HP	%+HP	V2	%+V	%+V /%+HP
570	–––––––––––––––	–––––––––––––––	–––––––––––––	–––––––––––––––––
590	3.51	240.8	1.16	33.05
610	7.02	243.4	2.29	32.62
630	10.53	246.1	3.39	32.19
650	14.04	248.7	4.48	31.91
670	17.54	251.2	5.54	31.58
690	21.05	253.7	6.58	31.26
710	24.56	256.1	7.60	30.94
730	28.07	258.4	8.60	30.64
750	31.58	260.8	9.58	30.34
770	35.09	263.1	10.55	30.07
790	38.60	265.4	11.49	29.77
810	42.11	267.6	12.43	29.52
830	45.61	269.8	13.35	29.27
850	49.12	271.9	14.25	29.01
870	52.63	274.0	15.14	28.77
890	56.14	276.1	16.01	28.52
910	59.65	278.2	16.88	28.30
930	63.16	280.2	17.73	28.07
950	66.67	282.2	18.56	27.84
970	70.18	284.2	19.39	27.63
990	73.68	286.1	20.20	27.42
1010	77.19	288.0	21.00	27.21
1030	80.07	289.9	21.80	27.01
1050	84.21	291.8	22.59	26.83
1070	87.72	293.6	23.36	26.63
1090	91.23	295.4	24.12	26.44
1110	94.74	297.2	24.88	26.26
1130	98.25	299.0	25.26	26.08
1140	100.00	299.9	26.00	26.00

SECTION THREE

Drag Reduction

The Safety Factor

Chapter 20

Drag Reduction
Climbing Out Faster

While most information on climb-out mentions the effect of increased horsepower available, decreasing an airplane's drag will also increase its rate of climb. Therefore in this chapter we will look into this interesting subject. Our purpose here is not to work out airplane performance figures. Rather we only want to see how rate-of-climb figures increase as a result of decreasing an airplane's drag.

The Rate of Climb figure is worked out on the basis of Thrust Horsepower or THP available for climb. Therefore we will begin by assuming a number of thrust horsepower available for the two purposes of a) flying straight and level at climb-out speed Vy, and, b) the number of THP then left for the actual climb-out.

For each of our four airplane types we will work out our figures by assuming a number of total THP available that will give us enough THP left to give a for this type of airplane realistic rate-of-climb.

Working It Out For Airplane No. 1.

Climb-out speed Vy = 1.4 x Vs = 1.4 x 56 = 78.4, which we'll make 78.00 exactly.

Total power available at Vy we assume to be 70.0 THP.

Required for flying straight and level at 78 mph: Net drag area EDA = 6.62 sf, air pressure q = 15.56 lb/sf. So drag = 6.62 x 15.56 = 103 lb

Thrust HP required = (203 x 78) / 375 = 803.456 / 375 = 21.4 thp. Subtracting this from the total THP available, we get 70 - 21.4 = 48.6 THP.

RoC = ((33000 / 2400) / 2400) x 48.6 = 13.75 x 48.6 = 668.3 fpm

We will now work out the table for Airplane No. 1 with drag decreasing in steps of 5 percent from 100 percent to 50 percent.

Table No. 1.
Airplane No. 1.
RoC increase with drag decrease.

Drag %	THP req.	From	Leaves	Times 13.75
100	21.4	70	48.6	668
95	20.3	70	49.7	683
90	19.3	70	50.7	698
85	18.2	70	51.8	712
80	17.1	70	52.8	727
75	16.0	70	54.0	742
70	15.0	70	55.0	756
65	13.9	70	56.1	771
60	12.8	70	57.2	786
55	11.8	70	58.2	801
50	10.7	70	59.3	815

Airplane No. 2.

For our airplane No. 2 we have a Vy of 87 mph and a q value of 1936 lb/sf. The EDA = 4.17 sf. Therefore, our drag is 4.17 x 19.36 = 80.73 lb

THP req = (80.32 x 87) / 375) = 7023.5 / 375 = 18.73

Assuming a total 100 THP available for both straight and level flight and climbing out, we get

100 - 18.73 = 81.27 THP for climb-out

RoC = (33000 / 2800) x 81.3) = 11.786 x 81.3 = 958 fpm
Which again looks realistic. So now for the table.

Table No. 2.
Airplane No. 2.
RoC increase with drag decrease.

Drag %	THP req.	From	Leaves	Times 11.786
100	18.7	100	81.3	958
95	17.8	100	82.2	969
90	16.9	100	83.1	980
85	15.9	100	84.1	991
80	15.0	100	85.0	1002
75	14.0	100	86.0	1013
70	13.1	100	86.9	1024
65	12.2	100	87.8	1035
60	11.2	100	88.8	1046
55	10.3	100	89.7	1057
50	9.4	100	90.6	1068

Airplane No. 3. For our airplane No. 3 we have a Vy of 104 mph and a q value of 27.66 lb/sf. The EDA = 4.51 sf. Therefore, our drag is 4.51 x 27.66 = 103.45 lb
Thrust horsepower required is .8 / 375 = 28.69 THP
Assuming a total 150 THP available for both straight and level flight and climb-out, we get

150 - 28.69 = 121.3 THP for climb-out

We'll work with resp. 29 and 121.0 THP. RoC = (33000 / 3400) x 121) = 9.706 x 121 = 1174 fpm. Which again looks realistic. So now for the table.

Table No. 3.
Airplane No. 3.
RoC increase with drag decrease.

Drag %	THP req.	From	Leaves	Times 13.75
100	29.0	150	121.0	1174
95	27.6	150	122.4	1188
90	26.1	150	123.9	1203
85	24.7	150	125.3	1216
80	23.2	150	126.8	1231
75	21.8	150	128.2	1245
70	20.3	150	129.7	1259
65	18.9	150	131.1	1272
60	17.4	150	132.6	1287
55	16.0	150	134.0	1301
50	14.5	150	135.5	1315

For our airplane No. 4 we have a Vy of 87 mph and a q value of 1936 lb/sf.
The EDA = 4.17 sf. Therefore, our drag is 4.17 x 19.36 = 80.73 lb
and THP req = (80.32 x 87) / 375) = 7023.5 / 375 = 18.73 THP.
Assuming a total 100 THP available for both straight and level flight and climb-out, we get

100 - 18.73 = 81.27 THP for climb-out.

RoC = (33000 / 2800) x 81.3) = 11.786 x 81.3 = 958 fpm. Which again looks realistic. So now for the table.

Table No. 4.
Airplane No. 4.
RoC increase with drag decrease.

Drag %	THP req.	From	Leaves	Times 13.75
100	49.0	326	277.0	1662
95	46.6	326	279.4	1676
90	44.1	326	281.9	1691
85	41.7	326	284.3	1706
80	39.2	326	286.8	1721
75	36.8	326	289.2	1735
70	34.3	326	291.7	1750
65	31.9	326	294.1	1765
60	29.4	326	296.6	1780
55	27.0	326	299.0	1794
50	24.5	326	301.5	1809

Table No. 5.
Rate of Climb Comparison for the Four Airplanes

Airplane No.	R.0.C. 1 fpm	R.o.C. 2 fpm	Improvement percent
1	668	815	22.00
2	958	1068	11.50
3	1174	1315	12.00
4	1662	1809	8.85

Chapter Twenty-one

Drag Reduction - Gliding Farther

Parasite Drag: Your Enemy

Note No. 1. Countless articles and books are available on what to do when the prop stops and you find yourself flying an overweight glider. Therefore, there is no need for me to go into that here. My purpose here is strictly to show the effect of drag decrease on a number of hypothetical airplanes, with the also hypothetical propellers are all stopped.

Note No. 2. The tables in this Chapter are based on computer calculations, and include induced drag. For preliminary calculations, flying speeds in 1.0 mph speed increments were used from stall speed to maximum speed. Final calculations for Rate of Sink and L/D-ratios are based on speed increments of 0.10 mph.

Your gliding airplane descends through the air because energy is being consumed by the drag forces acting on it. This energy can only be provided by your airplane gliding downward relative to the air. Not to mention relative to the hard ground! Therefore parasite drag is your great enemy especially in power-off gliding flight.

Power-Off Glide Speeds. When making a power-off landing, how far you can glide is very important to you. You like to have the maximum time and distance available. For your airplane's power-off gliding flight there are two specific but rather different flying speeds to choose from.

1) The speed for maximum lift-to-drag ratio (L/D-ratio), or optimum gliding ratio. Flying at this speed gives you the maximum gliding distance.

2) The minimum sinking speed, in feet per minute (fpm). This flying speed gives you the maximum time to landing.

The L/D Ratio. The gliding angle of your airplane depends upon its aerodynamic cleanliness. If your airplane's drag is high, the glide ratio is steeper. It will come down quicker and you have to land sooner. To keep the glide-ratio as high as possible, your airplane should be as aerodynamically clean as possible, with its total drag at a minimum.

The Minimum Rate of Sink. Sometimes a low sinking speed is desirable because you then can stay in the air that much longer. Flying at the minimum rate of sink, you will gain a minute or more extra endurance. Flying at the minimum Rate of Sink speed, your airplane comes down at a slightly steeper glide angle. However, it is losing altitude at a slower rate than when flying at the best glide speed. Although your airplane will cover fewer miles over the ground, the landing is delayed. The speed giving the minimum rate of sink is lower, and much closer to your airplane's stalling speed, than the speed for maximum gliding distance.

Drag-reduction Effects. Any worthwhile improvement in reducing your airplane's parasite drag will increase its glide-ratio in direct proportion. It also will increase your gliding range. The lower the drag and thus the higher this ratio, the flatter the gliding angle. The minimum rate of sink also is lower. Because the attitude is flatter, duration also goes up. The airplane will be in the air longer. Making a forced landing, either way you have more of a chance to find a good field. Those vital extra minutes or seconds may save your life and perhaps those of your passengers. There is, thus, an important safety angle to your power-off glide ratio or minimum rate of sink.

Total Landing Area Available. Your airplane's glide ratio or L/D equals horizontal speed divided by vertical speed. Thus altitude multiplied by the L/D ratio equals the potential total gliding distance over the ground. Let's say your airplane has a maximum glide ratio of 10:1 with the prop stopped. While flying at 5,280 feet - or one mile high - AGL, its engine quits. Then, with no wind, you can expect to glide roughly 52,800 feet or ten miles in any direction. This gives you a potential area of 314 square miles. In a 20-miles diameter circle, actually. The potential land area you can reach in a glide is proportional to the square of your altitude. The larger the value of L/D-total, the larger the circle available for landing. There should be an airport down there somewhere!

What the Tables Show You. Let's take a good look at this subject, and work out some numbers. We use as our example an airplane with a Gross Weight of 2400 pounds, a span of 35.6 feet, and a wing area (S) of 170 square feet (sf.). We assume that the airplane normally has a Gross Equivalent Drag Area of 8.0 square feet. In the case of a power-off landing, there's no propeller-efficiency factor to consider. Therefore the Equivalent (or net) Drag Area = .75 x 8.0 = 6.0 square feet.

We will take a look at a decrease in drag area of from 6.00 sf. to 3.00 sf. in steps of 0.50 sf. Note the different drag percentages in the tables. First we will look at the difference in glide-ratio.

Table No. 1.
The L/D or Glide Ratio.

Drag %	EDA Area	V-L/D max.	L/D max.	Imprvnt %
100.0	6.00	77.9	12.88	–––––––––––––
91.7	5.50	79.6	13.45	4.43
83.3	5.00	81.6	14.11	9.55
75.0	4.50	83.7	14.87	15.45
66.7	4.00	86.2	15.77	22.44
58.3	3.50	89.2	16.86	30.90
50.0	3.00	92.7	18.21	41.38

Table No. 2.
Improvement in minimum rate of sink.

Drag %	EDA sf.	Glide Speed	RoSm. fpm	Improvement %
100.0	6.00	59.2	467.2	–––––––––––
91.7	5.50	60.5	457.2	2.15
83.3	5.00	62.0	446.4	4.45
75.0	4.50	63.6	434.8	6.94
66.7	4.00	65.5	422.2	9.63
58.3	3.50	67.5	408.3	12.61
50.0	3.00	70.4	392.8	15.92

Now we'll see what difference the increased streamlining makes to the gliding time and distance. We start our power-off glide at 8,500 feet above ground level somewhere over the flattest area in the USA Mid-West. We leave 500 feet for the final maneuvering at the selected landing site.

Table No. 3. Gliding time and distance for maximum glide ratio.

DRAG %	EDA sf	Glide Speed MPH	Min. RoS fpm	Time left minutes seconds	Dist. st. m.	Imp't. %
100.0	6.00	77.9	532.5	15.02	19.5	–––––––––––––
91.7	5.50	79.6	521.0	15.35	20.4	4.62
83.3	5.00	81.6	508.8	15.75	21.4	9.74
75.0	4.50	83.7	495.5	16.14	22.5	15.38
66.7	4.00	86.2	481.2	16.62	23.9	22.56
58.3	3.50	89.2	465.4	17.19	25.5	30.77
50.0	3.00	92.7	447.8	17.86	27.6	41.54

Table No. 4
Gliding Time and Distance at minimum R.o.S.

Drag %	EDA Area sf	Glide Speed mph	Max. L/D	Min. RoS fpm	Time left min'ts	Impt. %	Gliding Distance St.m.	Imp't %
100.0	6.00	59.2	11.15	467.2	17.12	––––––––––––	16.9	–––––––––––––
91.7	5.50	60.5	11.65	457.2	17.50	2.22	17.6	4.14
83.3	5.00	62.0	12.22	446.4	17.92	4.67	18.5	9.47
75.0	4.50	63.6	12.90	434.8	18.40	7.48	19.5	15.38
66.7	4.00	65.5	13.70	422.2	18.95	10.69	20.7	23.08
58.3	3.50	67.5	14.60	408.3	19.60	14.49	22.1	30.77
50.0	3.00	70.4	15.80	392.8	20.36	18.93	23.9	41.42

The tables in this Chapter show some interesting points. We shall take a closer look at each case we work with here.

Table No. 5
Varying Gliding Time and Distance with varying gliding speed. EDA = 6.0 sf

Gliding	RoS.	L/D	Time
Dist.			
Speed	fpm	min.	min.
st.m.			
73.0	503.11	12.77	15.90
19.3			
74.0	508.38	12.81	15.74
19.4			
75.0	514.02	12.84	15.56
19.5			
76.0	520.00	12.86	15.38
19.5			
77.0	532.50	12.87	15.20
19.5			
77.93	532.50	12.88	15.02
19.5			
78.0	533.02	12.88	15.01
19.5			
79.0	540.05	12.87	14.81
19.5			
80.0	547.44	12.86	14.61
19.5			
81.0	555.18	12.84	14.41
19.5			
82.0	563.26	12.81	14.20
19.4			
83.0	571.71	12,78	13.99
19.4			

Table No 6.
Varying Gliding Time and Distance with varying gliding speed. EDA = 5.5 sf

Gliding	RoS.	L/D	Time
Dist.			
Speed	fpm		
min.	st.m.		
74.0	489.38	13.31	16.35
20.2			
75.0	494.23	13.35	16.19
20.2			
76.0	499.41	13.39	16.02
20.3			
77.0	504.92	13.42	15.84
20.3			
78.0	510.76	13.44	15.66
20.4			
79.0	516.93	13.45	15.48
20.4			
79.64	521.00	13.45	15.35
20.4			
80.0	523.43	13.45	15.28
20.4			
81.0	530.26	13.44	15.09
20.4			
82.0	537.41	13.43	14.89
20.3			
83.0	544.89	13.40	14.68
20.3			
84.0	552.71	13.37	14.47
20.3			
85.0	560.85	13.34	14.26
20.2			

Table No. 7
Varying Gliding Time and Distance with varying gliding speed. EDA = 5.0 sf

Gliding	RoS.	L/D	Time
Dist.			
Speed	fpm		
min.	st.m.		
76.0	478.83	13.97	16.71
21.2			
77.0	483.52	14.01	16.55
21.2			
78.0	488.51	14.05	16.38
21.3			
79.0	493.81	14.08	16.20
21.3			
80.0	499.42	14.10	16.02
21.4			
81.0	505.34	14.11	15.83
21.4			
81.56	508.78	14.11	15.75
21.4			
82.0	511.56	14.11	15.64
21.4			
83.0	518.08	14.10	15.44
21.4			

84.0	524.92	14.08	15.24	21.3
85.0	532.05	14.06	15.04	21.3
86.0	539.50	14.03	14.83	21.3
87.0	547.25	14.00	14.62	21.2

Table No. 8.
Varying Gliding Time and Distance with varying gliding speed. EDA = 4.5 sf

Gliding Speed	RoS. fpm	L/D	Time min.	Dist. st.m.
78.0	466.26	14.72	17.16	22.3
79.0	470.70	14.77	17.00	22.4
80.0	475.41	14.81	16.83	22.4
81.0	480.42	14.84	16.65	22.5
82.0	485.70	14.86	16.47	22.5
83.0	491.27	14.87	16.28	22.5
83.74	495.55	14.87	16.14	22.5
84.0	497.12	14.87	16.09	22.5
85.0	503.26	14.86	15.90	22.5
86.0	509.67	14.85	15.70	22.5
87.0	516.37	14.83	15.49	22.5
88.0	523.36	14.80	15.29	22.4
89.0	530.62	14.76	15.08	22.4

Table No. 9.
Varying Gliding Time and Distance with varying gliding speed. EDA = 4.0 sf

Gliding Speed	RoS. fpm	L/D	Time min.	Dist. st.m.
78.0	444.61	15.46	18.02	23.4
79.0	447.58	15.53	17.87	23.5
80.0	451.41	15.60	17.72	23.6
81.0	455.50	15.65	17.56	23.7
82.0	459.85	15.69	17.40	23.8
83.0	464.46	15.73	17.22	23.8
84.0	469.33	15.75	17.05	23.9
85.0	474.46	15.77	16.86	23.9
86.0	479.85	15.77	16.67	23.9
86.24	481.18	15.77	16.62	23.9
87.0	485.50	15.77	16.48	23.9
88.0	491.40	15.76	16.28	23.9
89.0	497.57	15.74	16.08	23.9
90.0	503.99	15.71	15.87	23.8
91.0	510.81	15.68	15.46	23.5
92.0	517.62	15.64	15.24	23.4

Table No. 10.
Varying Gliding Time and Distance with varying gliding speed. EDA = 3.5 sf

Gliding Speed	RoS. fpm	L/D	Time min.	Dist. st.m.
84.0	441.54	16.74	18.12	25.4
85.0	445.66	16.78	17.95	25.4
86.0	450.02	16.82	17.78	25.5
87.0	554.62	16.84	17.60	25.5
88.0	459.45	16.86	17.41	25.5
89.0	464.51	16.86	17.22	25.5
89.17	465.37	16.86	17.19	25.5
90.0	469.81	16.86	17.03	25.5
91.0	475.34	16.85	16.83	25.5
92.0	481.11	16.83	16.63	25.5
93.0	487.11	16.80	16.42	25.5
94.0	493.34	16.77	16.22	25.2
95.0	499.81	16.73	16.01	25.3

Table No. 11 .
Varying Gliding Time and Distance with varying gliding speed. EDA = 3.0 sf

Gliding Speed	RoS. fpm	L/D	Time min.	Dist. st.m.
87.0	423.74	18.07	18.88	27.4
88.0	427.49	18.11	18.71	27.4

89.0	431.46	18.15	18.54	27.5
90.0	435.63	18.18	18.36	27.5
91.0	440.00	18.20	18.18	27.6
92.0	444.59	18.21	17.99	27.6
92.67	447.79	18.21	17.86	27.6
93.0	449.39	18.21	17.80	27.6
94.0	454.40	18.20	17.61	27.6
95.0	459.61	18.19	17.41	27.6
96.0	465.03	18.17	17.20	27.5
97.0	470.67	18.14	17.00	27.5
98.0	476.51	18.10	16.79	27.4

It is interesting to note the little changes in gliding time and distance from about five or six miles below to about five or six miles above your airplane's best gliding speed. Tables 5 to 11 show that you can vary your gliding speed by at least five or six miles up or down and still have about the same gliding distance. Of course, when you glide faster than best gliding speed, you go down faster. However, because your gliding speed is higher, your gliding distance is still about the same. Nice to know.

Appendix No. 1.

Table of Dollar-Cost Per Pound of Drag at Speeds from 100 to 300 mph.

This table shows the cost for one pound of aerodynamic drag at flying speeds from 100 mph to 300 mph. Propeller efficiency factor "n" = 0.80. Fuel cost = $US2.00 per US gallon. The purpose of the table is strictly for cost comparison. Although we know that fast airplanes have higher "n" factors, as the table is meant only to show the increasing cost of drag with higher speeds, the "n" factor is kept at 0.80.

V	HPr	Cost cts.	V	HPr	Cost cts.	V	HPr	Cost cts.	V	HPr	Cost cts.
100	0.333	5.55									
101	0.343	5.72	131	0.749	12.49	161	1.391	23.18	191	2.323	38.71
102	0.354	5.90	132	0.767	12.78	162	1.417	23.62	192	2.359	39.32
103	0.364	6.07	133	0.784	13.07	163	1.444	24.06	193	2.396	39.94
104	0.375	6.25	134	0.802	13.37	164	1.470	24.51	194	2.434	40.56
105	0386	6.43	135	0.820	13.67	165	1.497	24.96	195	2.472	41.19
106	0.397	6.62	136	0.839	13.97	166	1.525	25.41	196	2.510	41.83
107	0.408	6.81	137	0.857	14.29	167	1.552	25.87	197	2.549	42.47
108	0.420	7.00	138	0.876	14.66	168	1.581	26.34	198	2.588	43.12
109	0.432	7.20	139	0.895	14.92	169	1.609	26.82	199	2.627	43.78
110	0.444	7.39	140	0.915	15.24	170	1.638	27.29	200	2.667	44.44
111	0.456	7.60	141	0.934	15.57	171	1.667	27.78	201	2.707	45.11
112	0.468	7.81	142	0.954	15.91	172	1.696	28.27	202	2.748	45.79
113	0.481	8.02	143	0.975	16.25	173	1.726	28.77	203	2.789	46.48
114	0.494	8.23	144	0.995	16.59	174	1.756	29.27	204	2.830	47.16
115	0.507	8.45	145	1.016	16.94.	175	1.786	29.77	205	2.872	47.86
116	0.520	8.67	146	1.037	17.29	176	1.817	30.29	206	2.914	48.57

117	0.534	8.90	147	1.059	17.65	177	1.848	30.81	207	2.957	49.28
118	0.548	9.13	148	1.081	18.01	178	1.880	31.33	208	3.000	50.00
119	0.562	9.36	149	1.103	18.38	179	1.912	31.86	209	3.043	50.72
120	0.576	9.60	150	1.125	18.75	180	1.944	32.40	210	3.087	51.45
121	0.591	9.84	151	1.148	19.13	181	1.977	32.94	211	3.131	52.19
122	0.605	10.09	152	1.171	19.51	182	2.010	33.49	212	3.176	52.93
123	0.620	10.34	153	1.194	19.80	183	2.043	34.05	213	3.221	53.69
124	0.636	10.59	154	1.217	20.29	184	2.077	34.61	214	3.267	54.45
125	0.651	10.85	155	1.241	20.69	185	2.111	35.18	215	3.313	55.21
126	0.667	11.11	156	1.265	21.09	186	2.145	35.75	216	3.359	55.99
127	0.683	11.38	157	1.290	21.50	187	2.180	36.33	217	3.406	56.77
128	0.699	11.65	158	1.325	21.91	188	2.215	36.92	218	3.453	57.56
129	0.716	11.93	159	1.340	22.33	189	2.250	37.51	219	3.501	58.35
130	0.732	12.21	160	1.365	22.76	190	2.286	38.11	220	3.549	59.16

V	HPr	Cost cts.	V	HPr	Cost cts.	V	HPr	Cost cts.	V	HPr	Cost cts.
221	3.598	59.97	241	4.666	77.76	261	5.927	98.78	281	7.396	123.27
222	3.647	60.78	242	4.724	78.74	262	5.995	99.92	282	7.475	124.59
223	3.697	61.61	243	4.783	79.72	263	6.064	101.10	283	7.555	125.92
224	3.747	62.44	244	4.842	80.70	264	6.133	102.20	284	7.635	127.26
225	3.797	63.28	245	4.902	81.70	265	6.203	103.40	285	7.716	128.61
226	3.848	64.13	246	4.962	82.71	266	6.274	104.60	286	7.798	129.96
227	3.899	64.98	247	5.023	83.72	267	6.345	105.80	287	7.880	131.33
228	3.951	65.85	248	5.084	84.74	268	6.416	106.90	288	7.963	132.71
229	4.003	66.72	249	5.146	85.57	269	6.488	108.14	289	8.048	134.10
230	4.056	67.59	250	5.208	86.81	270	6.561	109. 35	290	8.130	135.49
231	4.109	68.48	251	5.271	87.05	271	6.634	110. 57	291	8.214	136.90
232	4.162	69.37	252	5.334	88.91	272	6.708	111. 80	292	8.299	138.32
233	4.216	70.27	253	5.398	89.97	273	6.782	113. 04	293	8.385	139.74
234	4.271	71.18	254	5.462	91.04	274	6.857	114. 28	294	8.471	141.18
235	4.326	72.10	255	5.527	92.12	275	6.932	115. 54	295	8.558	142.62
236	4.381	73.02	256	5.592	93.21	276	7.008	116. 80	296	8.645	144.08
237	4.437	73.96	257	5.658	94.30	277	7.085	118. 08	297	8.733	145.54
238	4.494	74.90	258	5.725	95.41	278	7.162	119. 36	298	8.821	147.02
239	4.551	75.84	259	5.791	96.52	279	7.239	120. 65	299	8.910	148.50
240	4.608	76.80	260	5.859	97.64	280	7.317	122. 96	300	9.000	150.00

Appendix No. 2.

Air-pressure Values from 100 to 310 mph..

This Table shows the values for the air-pressure q is pounds per square foot.

V	q	V	q	V	q	V	q	V	q	V	q
100	25.577										
101	26.091	136	47.307	171	74.789	206	108.537	241	148.552	276	194.833
102	26.610	137	48.005	172	75.666	207	109.594	242	149.787	277	196.248
103	27.134	138	48.708	173	76.549	208	110.655	243	151.028	278	197.667
104	27.664	139	49.417	174	77.436	209	111.722	244	152.274	279	199.092
105	28.198	140	50.130	175	78.329	210	112.793	245	153.524	280	200.521
106	28.738	141	50.849	176	79.226	211	113.870	246	154.780	281	201.956
107	29.283	142	51.573	177	80.129	212	114.952	247	156.041	282	203.396
108	29.833	143	52.302	178	81.037	213	116.039	248	157.307	283	204.841
109	30.388	144	53.036	179	81.950	214	117.131	249	158.578	284	206.292
110	30.948	145	53.775	180	82.869	215	118.228	250	159.854	285	207.747
111	31.513	146	54.519	181	83.792	216	119.331	251	161.136	286	209.207
112	32.083	147	55.269	182	84.720	217	120.438	252	162.422	287	210.673
113	32.659	148	56.023	183	85.654	218	121.551	253	163.714	288	212.143
114	33.239	149	56.783	184	86.593	219	122.668	254	165.011	289	213.619
115	33.825	150	57.548	185	87.536	220	123.791	255	166.313	290	215.100
116	34.416	151	58.317	186	88.485	221	124.919	256	167.620	291	216.586

117	35.012	152	59.092	187	89.439	222	126.052	257	168.932	292	218.077
118	35.613	153	59.873	188	90.398	223	127.190	258	170.249	293	219.574
119	36.219	154	60.658	189	91.363	224	128.334	259	171.571	294	221.075
120	36.830	155	61.448	190	92.332	225	129.482	260	172.899	295	222.581
121	37.447	156	62.243	191	93.306	226	130.636	261	174.231	296	224.093
122	38.068	157	63.044	192	94.286	227	131.794	262	175.569	297	225.610
123	38.695	158	63.850	193	95.271	228	132.958	263	176.912	298	227.131
124	39.327	159	64.660	194	96.261	229	134.127	264	178.259	299	228.658
125	39.964	160	65.476	195	97.255	230	135.301	265	179.612	300	230.190
126	40.606	161	66.297	196	98.256	231	136.480	266	180.971	301	231.728
127	41.253	162	67.124	197	99.261	232	137.664	267	182.334	302	233.270
128	41.905	163	67.955	198	100.271	233	138.853	268	183.702	303	234.817
129	42.562	164	68.791	199	101.286	234	140.048	269	185.076	304	236.370
130	43.225	165	69.633	200	102.307	235	141.247	270	186.454	305	237.927
131	43.892	166	70.479	201	103.333	236	142.452	271	187.838	306	239.490
132	44.565	167	71.331	202	104.363	237	143.662	272	189.227	307	241.058
133	45.243	168	72.188	203	105.399	238	144.877	273	190.621	308	242.631
134	45.926	169	73.050	204	106.440	239	146.097	274	192.020	309	244.209
135	46.614	170	73.917	205	107.486	240	147.322	275	193.424	310	245.792

Appendix No. 3. - List of Tables

SECTION ONE - Your Airplane's Parasite Drag

Chapter 3. Wing Drag - Causes.

Chapter 4. Wing Drag Calculations.

Chapter 5. Fuselage Drag - Some Causes.

Chapter 6. Fuselage Drag - the Cost.

Chapter 7. Landing Gear Drag - Some Causes.

Chapter 8. Landing Gear Drag - the Cost.

Chapter 9. Engine Drag - Some Causes.

Chapter 10. Engine Drag - the Cost.

Chapter 12. Tail Drag - the Cost.

Chapter 13. Maneuvering Drag.

Chapter 14. Trim Drag. Causes and Costs.

SECTION TWO - Drag Reduction.

Chapter 17. Flying-time Savings from Drag Reduction.

Chapter 18. Savings in Fuel Costs.

Section 1. Drag Reduction Results at Maximum Speed at Sea Level.

Section 2. Speed Increase with Drag Decrease.

Section 3. Increase in Horsepower Required for same increase in Vmax.

SECTION THREE - The Safety Factor

Chapter 20. Climbing Out Faster.

Chapter Twenty-one. Gliding Farther.

Appendix No. 4.

Gross Equivalent Drag Area Calculation Sheet

Airplane Make and Model: ....

Airplane Specification: Vmax. @ S.L. = ... mph

HPmax. @ S.L. = ... Propeller "n" factor = ... %

Air pressure "q" at Vmax. = ...

Calculation: Gross Drag = (HPmax. x 375) / Vmax. @ S.L.

= (............ x 375) / ....

GEDA Value = (Gross Drag / q) = ... / .... = ... sf.

EDA = GEDA / n = ... / .... = ... sf

Notes: ....

....

……

Airplane Make and Model: ....

Airplane Specification: Vmax. @ S.L. = ... mph

HPmax. @ S.L. = ... Propeller "n" factor = ...%

Air pressure "q" at Vmax. = ...

Calculation: Gross Drag = (HPmax. x 375) / Vmax. @ S.L.

= (............ x 375) / ....

GEDA Value = (Gross Drag / q) = ... / .... = ... sf.

EDA = GEDA / n = ... / .... = ...sf

Notes: ....

....

Author's Note: All these Drag Calculation Forms may be freely copied for your own use.

Wing Drag Calculation Sheet

Required airplane available on GEDA calculation sheet.

Airplane Data: ....

Maximum horsepower rating @ S.L.: ....hp

Horsepower rating at 75% power @ S.L. = 0.75 x .... = ... hp

Speed @ 75% cruise-power = ... mph Air pressure q = ... lb/sf

Total airplane drag = (HP x 375) / speed = (........... x 375) / .... = ... lb

Nominal Wing Area S = ... sf

Estimated Effective Area Se = ... sf

Wing Profile: ....

Estimated profile minimum drag-coefficient (Cd) = 0. ....

Estimated minimum wing profile drag-coefficient (Cdmin) = 0. ....

Wing Profile Drag = Cd x (q x Se) = 0. .... x (.............. x ....)

= 0. .... x .... = ... lb

Percent wing drag / total airplane drag

= .... / .... = ... %

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375) = ... / 375 = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ...x 0.50 = ...lb / hr

Fuel Consumption in Gallon / hour = .../ 6.0 = ... gallon

Fuel cost = gph x price/gallon = ... x $ .... = ...$ / hour

Fuselage Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data: ....

Maximum horsepower rating @ S.L.: ....hp

Horsepower rating at 75% power @ S.L. = 0.75 x .... = ... hp

Speed @ 75% cruise-power = ... mph Air pressure q = ... lb/sf

Total airplane drag = (hp x 375) / speed = (........... x 375) / .... = ... lb

Speed Multiplication Factor (M.F.) from pg. = ...

Fuselage type: (see Table No. 1, page) ....

Estimated drag per square foot (lb/sf): ....lb

Fuselage cross-sectional area (est): ....sf

Single-engine factor, if applicable, = ...%

Fuselage drag = (b/sf x c.s. area) x M.F.

= .... x .... x .... - ....lb

Percentage of fuselage drag / total airplane drag = ... / .... = ...%

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375) = ... / 375 = ... hp

Fuel consumption / hour @ SFC of 0.50 lb/hp/hr = hp x 0.50

= .... x 0.50 = ...lb / hr

Fuel consumption in gallon / hour = lb/hr / 6.0

= ..../ 0.50 = ... gallon / hour

Fuel cost = gph x (price/gallon) = ... x $ .... = ...$ / hour

Landing Gear Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data: ....

Maximum horsepower rating @ S.L.: ....hp

Horsepower rating at 75% power @ S.L. = 0.75 x .... = ... hp

Speed @ 75% cruise-power = ... mph Air pressure q = ... lb/sf

Total airplane drag = (hp x 375) / speed = (........... x 375) / .... = ... lb

Speed Multiplication Factor (M.F.) from pg. = ...

Estimated percentage of landing gear drag of total airplane drag

= .... x .... = ... lb

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375) = ... / 375 = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ... x 0.50 = ...lb / hr

Fuel Consumption in gallon / hr = .../ 6.0 = ...gallon / hour

Fuel cost = gph x price/gallon = ... x $ .... = ...$ / hour

Engine Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data: ....

Maximum horsepower rating @ S.L.: ....hp

Horsepower rating at 75% power = 0.75 x .... = ... hp

Flying Speed @ 75% cruise-speed: .... mph

Total airplane drag = ... lb

Total Airplane drag = GEDA x q = ...lb

Speed Multiplication Factor (M.F.) from pg. ....= ....

Estimated drag of cowling in lb/sf = ... lb/sf

Estimated frontal area of cowling = ... sf

Estimated total drag of cowling = (lb/sf) x area = ... x .... = ...lb

Percentage of engine drag / total airplane drag = ... / .... = ...%

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375) = ... / 375 = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ...x 0.50 = ...lb / hr

Fuel Consumption in gallon/hour = .../ 6.0 = ...gallon

Fuel cost = gph x price/gallon = ... x $ .... = ...$ / hour

Fuel cost = gallon/hour x gallon price = ... x .... = $ ....

Tail Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data: ....

Maximum horsepower rating @ S.L.: ....hp

Horsepower rating at 75% power = 0.75 x .... = ... hp

Flying Speed @ 75% cruise-speed: ....mph

Total airplane drag = ...lb = GEDA x q

Speed Multiplication Factor (M.F.) = ...

Estimated total tail surface area = ...sf

Estimated tail drag in lb/sf =

Total estimated tail drag = (area x lb/sf) = ... x .... = ...lb

Percentage of tail drag / total airplane drag = ... / .... = ...%

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375)

= .... / 375 = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ...x 0.50 = ...lb / hr

Fuel Consumption in gallon / hour = .../ 6.0 = ... gallon

Fuel cost = gph x price/gallon = ... x $ .... = ...$ / hour

Maneuvering Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data: ....

Maximum horsepower rating @ S.L.: ....hp

Horsepower rating at 75% power = 0.75 x .... = ... hp

Flying Speed @ 75% cruise-speed: ....mph

Total airplane drag (from pg. = ...lb

Speed Multiplication Factor (M.F.) = ...

Estimated maneuvering drag as percentage of total airplane drag = ... %

Maneuvering drag = ... x .... = ... lb

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375)

= .... / 375 = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ...x 0.50 = ...lb / hr

Fuel Consumption in Gallon / hour = .../ 6.0 = ...gallon

Fuel cost = gph x price / gallon = ... x $ .... = ...$ / hour

Trim Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data from pg.   : ....

Maximum horsepower rating @ S.L.: .... hp

Horsepower rating at 75% power = 0.75 x .... = ... hp

Flying Speed @ 75% cruise-speed: .... mph

Total airplane drag from pg.   = ... lb

Speed Multiplication Factor (M.F.)   ....

Estimated percentage of trim drag of total airplane drag

= .... / .... = ...%

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375) = ... / 375 = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ...x 0.50 = ...lb / hr

Fuel Consumption in gallon / hour = .../ 6.0 = ... gallon

Fuel cost = gph x price/gallon = ... x $ .... = ...$ / hour

Slipstream Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data from pg. ....

Maximum horsepower rating @ S.L.: .... hp

Horsepower rating at 75% power = 0.75 x .... = ... hp

Flying Speed @ 75% cruise-speed: .... mph

Total airplane drag from pg. = ... lb

Estimated percentage of slipstream drag total airplane drag = ...%

Slipstream drag = ... x .... = ... lb

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375)

= .... / 375 = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ...x 0.50 = ...lb / hr

Fuel Consumption in gallon / hour = .../ 6.0 = ...gallon

Fuel cost = gph x price / gallon = ... x $ .... = ...$ / hour

Interference Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data: ....

Maximum horsepower rating @ S.L.: ....hp

Horsepower rating at 75% power = 0.75 x .... = ... hp

Flying Speed @ 75% cruise-speed: ....mph

Total airplane drag = ... lb

Estimated percentage of interference drag of total airplane drag: = ... %

Interference drag = ... / .... = ...lb

Horsepower required (hp req) = (drag x speed) / (375)

= (............... x ....) / (375)

= .... / 375 = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ...x 0.50 = ...lb / hr

Fuel Consumption in gallon / hour = .../ 6.0 = ...gallon

Fuel cost = gph x price / gallon = ... x $ .... = ...$ / hour

Airplane Drag Calculation Sheet

Required airplane data from GEDA calculation sheet.

Airplane Data from pg. ....

Maximum horsepower rating @ S.L.: ....hp

Horsepower rating at 75% power = 0.75 x .... = ... hp

Flying Speed @ 75% cruise-speed: .... mph

Total airplane drag = ... lb = GEDA x q

Percentage of fuselage drag / total airplane drag = ... / .... = ...%

Horsepower required = (drag x speed) / 375)

= (............... x ....) / (375)

= .... / .... = ... hp

Fuel Consumption / hour @ SFC of 0.50 lb/hp/hr = ...x 0.50 = ...lb / hr

Fuel Consumption in gallon / hour = .../ 6.0 = ...gallon

Fuel cost = gph x price / gallon = ... x $ .... = ...$ / hour

Appendix No. 5.

ALPHABETICAL SUBJECT INDEX

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