There are essentially two approaches to wing design. In the direct approach, one finds the planform and twist that minimize some combination of structural weight, drag, and \( C_{L_{\text{max}}} \) constraints. The other approach involves selecting a desirable lift distribution and then computing the twist, taper, and thickness distributions that are required to achieve this distribution. The latter approach is generally used to obtain analytic solutions and insight into the important aspects of the design problem, but is difficult to incorporate certain constraints and off-design considerations in this approach. The direct method, often combined with numerical optimization is often used in the latter stages of wing design, with the starting point established from simple (even analytic) results.

This chapter deals with some of the considerations involved in wing design, including the selection of basic sizing parameters and more detailed design. The chapter begins with a general discussion of the goals and trade-offs associated with wing design and the initial sizing problem, illustrating the complexities associated with the selection of several basic parameters. Each parameter affects drag and structural weight as well as stalling characteristics, fuel volume, off-design performance, and many other important characteristics.

Wing lift distributions play a key role in wing design. The lift distribution is directly related to the wing geometry and determines such wing performance characteristics as induced drag, structural weight, and stalling characteristics. The determination of a reasonable lift and \( C_1 \) distribution, combined with a way of relating the wing twist to this distribution provides a good starting point for a wing design. Subsequent analysis of this baseline design will quickly show what might be changed in the original design to avoid problems such as high induced drag or large variations in \( C_1 \) at off-design conditions.

A description of more detailed methods for modern wing design with examples is followed by a brief discussion of nonplanar wings and winglets.

**Wing Geometry Definitions**
The wing geometry may be specified in several ways. This section defines a few commonly used terms and how to compute them.

**Wing Areas**

The definition of wing area is not obvious and different companies define the areas differently. Here, we always take the reference wing area to be that of the trapezoidal portion of the wing projected into the centerline. The leading and trailing edge chord extensions are not included in this definition and for some airplanes, such as Boeing’s Blended Wing Body, the difference can be almost a factor of two between the "real" wing area and the "trap area". Some companies use reference wing areas that include portions of the chord extensions, and in some studies, even tail area is included as part of the reference area. For simplicity, we use the trapezoidal area in this text.

In addition to the reference area, we use the exposed planform area depicted above in the calculation of skin friction drag and the wetted area which is a bit more than twice the exposed planform area.

**Wing Span and Aspect Ratio**

Of all the parameters that might be defined without a footnote, span seems to be the most unambiguous; however, even this is not so clear. The small effect of wing bending on the geometric span can become very measurable when the wing includes winglets. We ignore the differences here, but suggest that a reference span should be measured on the ground with a prescribed fuel load since this is the only condition in which it may be conveniently verified.

Aspect ratio is often used in place of the dimensional span in many of the aerodynamic equations of interest. Aspect ratio, or AR, is roughly the ratio of span to average wing chord. It may be computed by: \( \text{AR} = \frac{b^2}{S_{\text{ref}}} \). It is important that the same definition of reference area be used in the definition of aspect ratio as is used in the definition of coefficients such as \( C_L \) and \( C_D \).

**Reference Lengths**
Various wing reference lengths are used in aerodynamic computations. One of the most important of these is the mean aerodynamic chord, or M.A.C. The M.A.C. is the chord-weighted average chord length of the wing, defined as:

$$M.A.C. = (2/S) \int_0^{b/2} c^2 dy$$

For a linearly tapered (trapezoidal) wing, this integral is equal to:

$$M.A.C. = 2/3 \left( C_{root} + C_{tip} - C_{root} C_{tip} / (C_{root}+C_{tip}) \right)$$

For wings with chord extensions, the MAC may be computed by evaluating the MAC of each linearly-tapered portion then taking an average, weighted by the area of each portion. In many cases, however, the MAC of the reference trapezoidal wing is used.

The M.A.C. is often used in the nondimensionalization of pitching moments. The M.A.C. of just the exposed area is also used to compute the reference length for calculation of Reynolds number as part of the wing drag estimation. The M.A.C. is chosen instead of the simpler mean geometric chord for quantities whose values are weighted more strongly by local chord that is reflected by their contribution to the area.

### Wing Design Parameters

- **S** = wing area
- **AR** = aspect ratio = \( \frac{b^2}{S} = \frac{b}{c} \)
- **A** = taper ratio = \( \frac{c_{tip}}{c_{root}} \)
- **Δ** = sweep of c/4 line
- **θ** = wing twist angle

**Span**

Selecting the wing span is one of the most basic decisions to made in the design of a wing. The span is sometimes constrained by contest rules, hangar size, or ground facilities but when it is not we might decide to use the largest span consistent with structural dynamic constraints (flutter). This would reduce the induced drag directly.
However, as the span is increased, the wing structural weight also increases and at some point the weight increase offsets the induced drag savings. This point is rarely reached, though, for several reasons.

1. The optimum is quite flat and one must stretch the span a great deal to reach the actual optimum.

2. Concerns about wing bending as it affects stability and flutter mount as span is increased.

3. The cost of the wing itself increases as the structural weight increases. This must be included so that we do not spend 10% more on the wing in order to save .001% in fuel consumption.

4. The volume of the wing in which fuel can be stored is reduced.

5. It is more difficult to locate the main landing gear at the root of the wing.

6. The Reynolds number of wing sections is reduced, increasing parasite drag and reducing maximum lift capability.

On the other hand, span sometimes has a much greater benefit than one might predict based on an analysis of cruise drag. When an aircraft is constrained by a second segment climb requirement, extra span may help a great deal as the induced drag can be 70-80% of the total drag.

The selection of optimum wing span thus requires an analysis of much more than just cruise drag and structural weight. Once a reasonable choice has been made on the basis of all of these considerations, however, the sensitivities to changes in span can be assessed.

Area

The wing area, like the span, is chosen based on a wide variety of considerations including:

1. Cruise drag
2. Stalling speed / field length requirements

3. Wing structural weight

4. Fuel volume

These considerations often lead to a wing with the smallest area allowed by the constraints. But this is not always true; sometimes the wing area must be increased to obtain a reasonable $C_L$ at the selected cruise conditions.

Selecting cruise conditions is also an integral part of the wing design process. It should not be dictated a priori because the wing design parameters will be strongly affected by the selection, and an appropriate selection cannot be made without knowing some of these parameters. But the wing designer does not have complete freedom to choose these, either. Cruise altitude affects the fuselage structural design and the engine performance as well as the aircraft aerodynamics. The best $C_L$ for the wing is not the best for the aircraft as a whole. An example of this is seen by considering a fixed $C_L$, fixed Mach design. If we fly higher, the wing area must be increased by the wing drag is nearly constant. The fuselage drag decreases, though; so we can minimize drag by flying very high with very large wings. This is not feasible because of considerations such as engine performance.

Sweep

Wing sweep is chosen almost exclusively for its desirable effect on transonic wave drag. (Sometimes for other reasons such as a c.g. problem or to move winglets back for greater directional stability.)

1. It permits higher cruise Mach number, or greater thickness or $C_L$ at a given Mach number without drag divergence.

2. It increases the additional loading at the tip and causes spanwise boundary layer flow, exacerbating the problem of tip stall and either reducing $C_{L_{max}}$ or increasing the required taper ratio for good stall.

3. It increases the structural weight - both because of the increased tip loading, and because of the increased structural span.
4. It stabilizes the wing aerodynamically but is destabilizing to the airplane.

5. Too much sweep makes it difficult to accommodate the main gear in the wing.

Much of the effect of sweep varies as the cosine of the sweep angle, making forward and aft-swept wings similar. There are important differences, though in other characteristics.

**Thickness**

The distribution of thickness from wing root to tip is selected as follows:

1. We would like to make the t/c as large as possible to reduce wing weight (thereby permitting larger span, for example).

2. Greater t/c tends to increase $C_{L_{\text{max}}}$ up to a point, depending on the high lift system, but gains above about 12% are small if they’re at all.

3. Greater t/c increases fuel volume and wing stiffness.

4. Increasing t/c increases drag slightly by increasing the velocities and the adversity of the pressure gradients.

5. The main trouble with thick airfoils at high speeds is the transonic drag rise which limits the speed and $C_L$ at which the airplane may fly efficiently.

**Taper**

The wing taper ratio (or in general, the planform shape) is determined from the following considerations:

1. The planform shape should not give rise to an additional lift distribution that is so far from elliptical that the required twist for low cruise drag results in large off-design penalties.

2. The chord distribution should be such that with the cruise lift distribution, the distribution of lift coefficient is compatible with the section performance. Avoid high $C_l$'s which may lead to buffet or drag rise or separation.

3. The chord distribution should produce an additional load distribution which is compatible
with the high lift system and desired stalling characteristics.

4. Lower taper ratios lead to lower wing weight.

5. Lower taper ratios result in increased fuel volume.

6. The tip chord should not be too small as Reynolds number effects cause reduced $C_l$ capability.

7. Larger root chords more easily accommodate landing gear.

Here, again, a diverse set of considerations are important.

The major design goal is to keep the taper ratio as small as possible (to keep the wing weight down) without excessive $C_l$ variation or unacceptable stalling characteristics.

Since the lift distribution is nearly elliptical, the chord distribution should be nearly elliptical for uniform $C_l$'s. Reduced lift or t/c outboard would permit lower taper ratios.

Evaluating the stalling characteristics is not so easy. In the low speed configuration we must know something about the high lift system: the flap type, span, and deflections. The flaps-retracted stalling characteristics are also important, however (DC-10).

**Twist**

The wing twist distribution is perhaps the least controversial design parameter to be selected. The twist must be chosen so that the cruise drag is not excessive. Extra washout helps the stalling characteristics and improves the induced drag at higher $C_L$'s for wings with additional load distributions too highly weighted at the tips.

Twist also changes the structural weight by modifying the moment distribution over the wing.

Twist on swept-back wings also produces a positive pitching moment which has a small effect on trimmed drag. The selection of wing twist is therefore accomplished by examining the trades between cruise drag, drag in second segment climb, and the wing structural weight. The selected washout is then just a bit higher to improve stall.

**Wing Lift Distributions**
As in the design of airfoil sections, it is easier to relate the wing geometry to its performance through the intermediary of the lift distribution. Wing design often proceeds by selecting a desirable wing lift distribution and then finding the geometry that achieves this distribution.

In this section, we describe the lift and lift coefficient distributions, and relate these to the wing geometry and performance.

About Lift and $C_l$ Distributions

The distribution of lift on the wing affects the wing performance in many ways. The lift per unit length $l(y)$ may be plotted from the wing root to the tip as shown below.

In this case the distribution is roughly elliptical. In general, the lift goes to zero at the wing tip. The area under the curve is the total lift.

The section lift coefficient is related to the section lift by: $C_l(y) = l(y)/q c(y)$

So that if we know the lift distribution and the planform shape, we can find the $C_l$ distribution.

The lift and lift coefficient distributions are directly related by the chord distribution. Here are some examples:

The lift and $C_l$ distributions can be divided into so-called basic and additional lift distributions. This division allows one to examine the lift distributions at a couple of angles of attack and to infer the lift distribution at all other angles. This is especially useful in the process of wing design.
The distribution of lift can be written:

\[ \{l\} = C_L \{I_a\} + \theta \{I_b\} \]

Here, the distributions \( \{I_a\} \) and \( \{I_b\} \) are the wing lift distributions with no twist at \( C_L = 1 \) and with unit twist at zero lift respectively. The first term, \( C_L \{I_a\} \), is called the additional lift. It is the lift distribution that is added by increasing the total wing lift. Theta \( \{I_b\} \) is called the basic lift distribution and is the lift distribution at zero lift.

Why is this useful? Consider the following example.

![Graph showing lift distribution](graph.png)

We can use the data at these two angles of attack to learn a great deal about the wing.

From the expression above:

\[ \{I_a\} = (\{l\}_{C_L = 1} - \{l\}_{C_L = 2}) / 0.8 \]

or:

\[ \{C_l\} = C_L \{C_{I_a}\} + \theta \{C_{I_b}\} \]

The additional lift distribution, \( C_L \{I_a\} \) may be interpreted graphically as shown below.

![Graph showing additional lift distribution](graph2.png)

The additional lift coefficient distribution at \( C_L = 1.0 \) is plotted below. Note that it rises upward toward the tip -- this is indicative of a wing with a very low taper ratio or a wing with sweepback.

![Graph showing additional lift coefficient distribution](graph3.png)

The basic lift distribution is negative near the tip implying that the wing has washout.
Wing Geometry and Lift Distributions

The wing geometry affects the wing lift and $C_l$ distributions in mostly intuitive ways. Increasing the taper ratio (making the tip chords larger) produces more lift at the tips, just as one might expect:

![Diagram showing lift distribution with different taper ratios]

But because the section $C_l$ is the lift divided by the local chord, taper has a very different effect on the $C_l$ distribution.

![Diagram showing lift distribution with different taper ratios and $C_l$ values]

Changing the wing twist changes the lift and $C_l$ distributions as well. Increasing the tip incidence with respect to the root is called wash-in. Wings often have less incidence at the tip than the root (wash-out) to reduce structural weight and improve stalling characteristics.

![Diagram showing lift distribution with different twist angles]

Since changing the wing twist does not affect the chord distribution, the effect on lift and $C_l$ is similar.

Wing sweep produces a less intuitive change in the lift distribution of a wing. Because the downwash velocity induced by the wing wake depends on the sweep, the lift distribution is affected. The result is an increase in the lift near the tip of a swept-back wing and a decrease near the root (as compared with an unswept wing.)
This effect can be quite large and causes problems for swept-back wings. The greater tip lift increases structural loads and can lead to stalling problems.

The effect of increasing wing aspect ratio is to increase the lift at a given angle of attack as we saw from the discussion of lifting line theory. But it also changes the shape of the wing lift distribution by magnifying the effects of all other parameters.

Low aspect ratio wings have nearly elliptic distributions of lift for a wide range of taper ratios and sweep angles. It takes a great deal of twist to change the distribution. Very high aspect ratio wings are quite sensitive, however and it is quite easy to depart from elliptic loading by picking a twist or taper ratio that is not quite right.

Note that many of these effects are similar and by combining the right twist and taper and sweep, we can achieve desirable distributions of lift and lift coefficient.

For example: Although a swept back wing tends to have extra lift at the wing tips, wash-out tends to lower the tip lift. Thus, a swept back wing with washout can have the same lift distribution as an unswept wing without twist.

Lowering the taper ratio can also cancel the influence of sweep on the lift distribution. However, then the $C_l$ distribution is different.

Today, we can relate the wing geometry to the lift and $C_l$ distributions very quickly by means of rapid computational methods. Yet, this more intuitive understanding of the impact of wing parameters on the distributions remains an important skill.

**Lift Distributions and Performance**
Wing design has several goals related to the wing performance and lift distribution. One would like to have a distribution of $C_l(y)$ that is relatively flat so that the airfoil sections in one area are not "working too hard" while others are at low $C_l$. In such a case, the airfoils with $C_l$ much higher than the average will likely develop shocks sooner or will start stalling prematurely.

The induced drag depends solely on the lift distribution, so one would like to achieve a nearly elliptical distribution of section lift. On the other hand structural weight is affected by the lift distribution also so that the ideal shape depends on the relative importance of induced drag and wing weight.

With taper, sweep, and twist to "play with", these goals can be easily achieved at a given design point. The difficulty appears when the wing must perform well over a range of conditions.

One of the more interesting tradeoffs that is often required in the design of a wing is that between drag and structural weight. This may be done in several ways. Some problems that have been solved include:

- Minimum induced drag with given span -- Prandtl
- Minimum induced drag with given root bending moment -- Jones, Lamar, and others
- Minimum induced drag with fixed wing weight and constant thickness -- Prandtl, Jones
- Minimum induced drag with given wing weight and specified thickness-to-chord ratio -- Ward, McGeer, Kroo
- Minimum total drag with given wing span and planform -- Kuhlman

... there are many problems of this sort left to solve and many approaches to the solution of such problems. These include some closed-form analytic results, analytic results together with iteration, and finally numerical optimization.

The best wing design will depend on the construction materials, the arrangement of the high-lift devices, the flight conditions ($C_L$, Re, M) and the relative importance of drag and weight. All of this is just to say that it is difficult to design just a wing without designing the entire airplane. If we were just given the job of minimizing cruise drag the wing would have a very high aspect ratio. If we add a constraint on the wing's structural weight based on a trade-off between cost and fuel savings then the problem is somewhat better posed but we would still select a wing with very small taper ratio. High $t/c$ and high sweep are often suggested by studies that include only weight and drag.

The high lift characteristics of the design force the taper ratio and sweep to more usual values and therefore must be a fundamental consideration at the early stages of wing design. Unfortunately the estimation of $C_{L_{\text{max}}}$ is one of the more difficult parts of the preliminary design process. An example of this sensitivity is shown in the figure below.
The determination of a reasonable lift and $C_l$ distribution, combined with a way of relating the wing twist to this distribution provides a good starting point for a wing design. Subsequent analysis of this baseline design will quickly show what might be changed in the original design to avoid problems such as high induced drag or large variations in $C_l$ at off-design conditions.

Once the basic wing design parameters have been selected, more detailed design is undertaken. This may involve some of the following:

- Computation or selection of a desired span load distribution, then inverse computation of required twist.
- Selection of desired section Cp distribution at several stations along the span and inverse design of camber and/or thickness distribution.
- All-at-once multivariable optimization of the wing for desired performance.

Some examples of these approaches are illustrated below.
This figure illustrates inverse wing design using the DISC (direct iterative surface curvature) method. The starting pressures are shown (top), followed by the target (middle), and design (bottom); light yellow = low pressure and green = high pressure. This is an inverse technique that has been used very successfully with Navier-Stokes computations to design wings in transonic, viscous flows.

Below is an example of wing design based on "fixing" a span load distribution. When the 737 was re-engined with high bypass ratio turbofans, a drag penalty was avoided by changing the effective wing twist distribution.

The details of the pressure distribution can then be used to modify the camber shape or wing thickness for best performance. This sounds straightforward, but it is often very difficult to accomplish this, especially when it takes hours or days to examine the effect of the proposed change.
This is why simple methods with fast turnaround times are still used in the wing design process.

As computers become faster, it becomes more feasible to do full 3-D optimization. One of the early efforts in applying optimization and nonlinear CFD to wing design is described by Cosentino and Holst, *J. of Aircraft*, 1986.

In this problem, a few spline points at several stations on the wing were allowed to move and the optimizer tried to maximize L/D.

Although this was an inviscid code, the design variables were limited, and the objective function simplistic, current research has included more realistic objectives, more design degrees of freedom, and better analysis codes.
--but we are still a long way from having "wings designed by computer."

Nonplanar Wings and Winglets

One often begins the wing design problem by specifying a target $C_p$ distribution and/or span loading and then modifying the wing geometry (either manually, by direct inverse, or by nonlinear optimization). In the case of planar wings, the elliptic loading results provide a useful benchmark in the creation of target loadings. (For high aspect ratio wings, 2D airfoil results may provide a useful reference for the chordwise loading.)

More complex methods for creating target $C_p$’s are beyond the scope of this discussion, but we have little guidance at all when the wing is nonplanar.

This section deals with the problem of optimal loading for nonplanar lifting surfaces. It is easily generalized to multiple surfaces.

When the wing is not planar, many of the previous simple results are no longer valid. Elliptic loading does not lead to minimum drag and the span efficiency can be greater than 1.0.

Here we will describe a method for computing the minimum induced drag for planar and nonplanar wings. First, consider the distribution of downwash for minimum drag. This can be obtained by using the method of restricted variations as follows.
We consider an arbitrary variation in the circulation distribution represented by \( \delta G_1 \) and \( \delta G_2 \) which do not change the lift:

\[
\delta L = \rho U_\infty \delta \Gamma_1 + \rho U_\infty \delta \Gamma_2 = 0
\]

This implies: \( \delta \Gamma_1 = -\delta \Gamma_2 \)

If the drag was minimized by the initial distribution:

\[
\delta D = \rho / 2 \ w_1 \delta \Gamma_1 + \rho / 2 \ w_2 \delta \Gamma_2 = 0
\]

So, \( w_1 = w_2 \)

That is, the downwash is constant behind a planar wing with minimum drag.

In the general case, with multiple surfaces or nonplanar wings, the same approach may be used. In this case, the condition for constant lift is:

\[
\delta L = \rho U_\infty \delta \Gamma_1 \cos \theta_1 + \rho U_\infty \delta \Gamma_2 \cos \theta_2 = 0
\]

where \( \theta \) is the local dihedral angle of the lifting surface.

For minimum drag:

\[
\delta D = \rho / 2 \ \nu_{n1} \delta \Gamma_1 + \rho / 2 \ \nu_{n2} \delta \Gamma_2 = 0
\]

where \( \nu_n \) is the induced velocity in the Trefftz plane in a direction normal to the wake sheet (the normalwash).
In this case, \( \delta \Gamma_1 \cos \theta_1 = -\delta \Gamma_2 \cos \theta_2 \)

so, \( V_n = k \cos \theta \).

The normal-wash is proportional to the local dihedral angle. Thus, the side-wash on optimally-loaded winglets is 0, for example.

We may then solve for the distribution of circulation that produces this distribution of normal-wash.

Alternatively, one may use a more direct optimization approach. With the circulation distribution represented as the row vector, \( \Gamma \) and the wake modeled as a collection of line vortices of strength \( \Gamma_w \), we may write the wake vorticity in terms of the surface circulation, based on a discrete vortex model as shown below.

The drag is then given by: \( D = \frac{\rho}{2} \{ V_n \} \cdot \Gamma \)

where \( V_n \) is the normal wash in the Trefftz plane computed using the Biot Savart law.

\( \{ V_n \} \) is related to the circulation strengths by:

\( \{ V_n \} = [VIC] \Gamma \)

where \([VIC]\) is a function of the geometry.

So, \( D = \frac{\rho}{2} [VIC] \Gamma \cdot \Gamma \)

The lift is also a function of the circulations:

\( L = \rho U \Gamma \cdot \{ \cos \theta \} \)

with theta the local dihedral angle.

Finally, the optimal values of \( \Gamma \) are given by setting

\( (D + \lambda (L - L_{ref})) \Gamma_i = 0 \) where \( \lambda \) is a Lagrange multiplier.

This problem is sometimes done as homework, but some results are summarized below:

· When the wing/winglet combination is optimized for minimum drag at fixed span, it achieves about the same drag as a planar wing with a span increased by about 45% of the winglet height.
The wing lift distribution is as shown below with increased lift outboard compared with the no winglet case.

This increased tip loading along with the extra bending moment of the winglet leads to increased structural weight. When a bending moment constraint replaces the span constraint, wings with winglets are seen to have about the same minimum drag as the stretched-span planar wings. This is shown below.

Induced drag of wings with winglets and planar wings all with the same integrated bending moment (related to structural weight). Note that solutions to the left of the span ratio = 1.0 line are not meaningful.

The same approach may be taken for general nonplanar wake shapes. The figure below summarizes some of these results, showing the maximum span efficiency for nonplanar wings of various shapes with a height to span ratio of 0.2.
Several points should be made about the preceding results.

1. The result that the sidewash on the winglet (in the Trefftz plane) is zero for minimum induced drag means that the self-induced drag of the winglet just cancels the winglet thrust associated with wing sidewash. Optimally-loaded winglets thus reduce induced drag by lowering the average downwash on the wing, not by providing a thrust component.

2. The results shown here deal with the inviscid flow over nonplanar wings. There is a slight difference in optimal loading in the viscous case due to lift-dependent viscous drag. Moreover, for planar wings, the ideal chord distribution is achieved with each section at its maximum $C_l/C_d$ and the inviscid optimal lift distribution. For nonplanar wings this is no longer the case and the optimal chord and load distribution for minimum drag is a bit more complex.

3. Other considerations of primary importance include:
   Stability and control
   Structures
   Other pragmatic issues

More details on the design of nonplanar wings may be found in a recent paper, "Highly Nonplanar Lifting Systems," accessible here.

Wing Layout
Having decided on initial estimates for wing area, sweep, aspect ratio, and taper, an initial specification of the wing planform is possible. Three additional considerations are important:

*High and Low Wings*

High wing aircraft have the following advantages: The gear may be quite short without engine clearance problems. This lowers the floor and simplifies loading, especially important for small aircraft or cargo aircraft that must operate without jet-ways. High wing designs may also be appropriate for STOL aircraft that make use of favorable engine-flap interactions and for aircraft with struts. Low wing aircraft are usually favored for passenger aircraft based on considerations of ditching (water landing) safety, reduced interference of the wing carry-through structure with the cabin, and convenient landing gear attachment.

*Wing Location on the Fuselage*

The wing position on the fuselage is set by stability and control considerations and requires a detailed weight breakdown and c.g. estimation. At the early stages of the design process one may locate the aerodynamic of the wing at the center of constant section or, for aircraft with aft-fuselage-mounted engines, at 60% of constant section. (As a first estimate, one may take the aerodynamic center to be at the quarter chord of the wing at the location for which the local chord is equal to the mean aerodynamic chord.)

For low-wing aircraft, the main landing gear is generally attached to the wing structure. This is done to provide a sufficiently large wheel track. The lateral position of the landing gear is determined based on roll-over requirements: one must be able to withstand certain lateral accelerations without falling over.

The detailed computation requires knowledge of landing gear length, fuselage mass distribution, and ground maneuver requirements. For our purposes, it is sufficient to assume that the main gear wheel track is about 1.6 fuselage diameters. For general aviation aircraft or commuters with gear attached to turbo-prop nacelles, the value is usually much larger.

<table>
<thead>
<tr>
<th>Airplane</th>
<th>ytrack / fuse dia. (approx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>737-200</td>
<td>1.39</td>
</tr>
<tr>
<td>747-200</td>
<td>1.67</td>
</tr>
<tr>
<td>757-200</td>
<td>1.85</td>
</tr>
<tr>
<td>767-300</td>
<td>1.67</td>
</tr>
<tr>
<td>E-3 Sentry</td>
<td>1.62</td>
</tr>
<tr>
<td>Citation III</td>
<td>1.49</td>
</tr>
<tr>
<td>Lear 55</td>
<td>1.25</td>
</tr>
<tr>
<td>Gulfstream III</td>
<td>1.70</td>
</tr>
</tbody>
</table>
It is desirable to mount the main landing gear struts on the wing spar (usually an aft spar) where the structure is substantial. However, the gear must be mounted so that at aft c.g. there is sufficient weight on the nose wheel for good steering. This generally means gear near the 50% point of the M.A.C. For wings with high sweep, high aspect ratio, or high taper ratio, the aft spar may occur forward of this point. In this case a chord extension must be added. The drawing here shows the gear mounted on a secondary spar attached to the rear spar and the addition of a chord extension to accommodate it.