Basic Criteria for Powerboat Stability

By Dave Gerr, © 2007 Dave Gerr

In the two articles on sailboat stabiltiy, we took a look at the fundamental considerations regarding sailboat stability. The heeling moment from a sailboat's rig is so large that ensuring adequate sail-carrying power tends to be an overriding consideration. Powerboats stability is equally important, though governed by factors other than the need to stand up to an adequate rig. We'll look at some of the basic criteria for proper powerboat stability here.

Roll Time

One useful indicator of powerboat stability is roll time (the natural roll period of a boat). This is the time in seconds it takes a boat to complete a roll: all the way to starboard, all the way to port, and then back all the way to starboard again. The critical thing here is that long roll times indicate a boat with a center of gravity (CG) located too high, which is both uncomfortable and potentially dangerous.

Optimum Roll-Time

The optimum roll time in seconds for any powerboat is between 1.0 and 1.1 times the boat's beam overall in meters. If the boat's beam is in feet, divide feet by 3.28 to get beam in meters.

Long Roll Times are Dangerous

A roll time greater than 1.1 times beam in meters is a clear danger signal. A vessel with such a roll time should be considered to have suspect stability characteristics, and—unless exhaustive further stability analysis proves otherwise—such a boat should not be used in anything but protected waters inshore and with minimum passenger or other weights high up.

A further drawback to such long roll times is that the deep slow roll is quite uncomfortable, leading to seasickness and reduced crew performance.

Short Roll Times are Uncomfortable but Common and Often Unavoidable

While long roll times are dangerous, short roll times are uncomfortable. A vessel with a roll time well under one times the beam in meters will have a quick snappy motion that will be jarring to the crew. Nevertheless, a quick roll time is an indicator of a low center of gravity and a large metacentric height or GM (see *Stability Part 1* for a definition of metacentric height) and is not a cause for concern in terms of the boat safety with regard to stability. Indeed, most planing powerboats can't avoid having quite short roll times because of their heavy engines, and usually fairly wide, hard-chine hulls (high waterplane moment of inertia relative to their weight).

Where a boat with a roll time greater than 1.1 times the beam in meters is a safety problem, shorter roll times indicate less comfort in rough conditions but are acceptable. On displacement boats, the snap in the roll can be damped out effectively with a quite small steadying sail. In fact, on my voyaging motorcruiser designs, I tend to design for roll times just under 1 (between 0.9 and 1), and install a steadying sail. In this way, I can be sure of a stiff, safe boat—even after weight and gear are added over the boat's operational life—and still keep the motion comfortable.

Planing boats will often have roll times less than 0.8 times beam in meters. This is unavoidable and acceptable. The nature of the dynamic lift under a planing hull changes the apparent roll period in any case, and makes them more comfortable in this regard when on plane.

Calculating or Measuring Roll Time

The roll time for an existing boat can be measured simply by slacking the lines at a dock well off and allowing the boat to roll freely. Get one or two people to rhythmically press down on the sheer from the dock until the boat is rolling deeply enough to be timed. Let go and—using a stopwatch—time the complete roll. That's it.

For a new design or new construction, you can calculate the roll time exactly from:

$$\text{Roll, sec.} = 2\pi\sqrt{\frac{\sum \text{Ir}}{\text{GM x Disp., lb.}}}$$

Vertical Center of Gravity (VCG) estimate for powerboats:

Typical motorcruisers = 4.5% of WL length above the WL
Voyaging motorcruisers = 5% of WL length above the WL
Planing powerboats = 5.5% of WL length above the WL

Another way to estimate the VCG for powerboats is to measure the height from the bottom of the keel to the top of the highest structural deckhouse or cabin roof. Take 40% of that distance and measure up from the lowest point of the keel. Mark how high this is above the waterline and that is the VCG estimate above the DWL. If you use both methods, use the highest CG location result.

(Note: Heavy, steel voyaging motorcruisers, with steel superstructures can have high VCGs, as high as 8% or 10% of WL length above the WL, possibly higher.)

As described in the article Stability Part 1, these are just estimates of VCG and—for final accurate results—a comprehensive and detailed weight calculation must be done or an inclining experiment conducted. You will also find that keeping weight low (to lower the center of gravity) is important to getting adequate stability.

Powerboat Stability Criteria For Pleasure Craft
In addition to checking that roll-time is in the correct range for powerboat stability, you need to ensure two primary things:

1) **Wind Heel:**
   That the boat will not heel more than between one-quarter to one-half of freeboard (see below), but never more than 14 degrees in the strongest average beam wind it is likely to experience. This is based on CFR (Code of Federal Regulations) 170.170, often termed *GM Weather*.

2) **Passenger Heel:**
   That the boat will not heel more than between one-quarter to one-half of freeboard (see below), but never more than 14 degrees with two thirds of the normal passengers and crew usually aboard standing on one side deck or along the rail on one side of the boat. This is based on, CFR 171.050, often called *passenger heel*.

Wind Heel
Wind heel is checked exactly as you check Dellenbaugh angle as discussed in Stability Part 1; however, the sailboat-Dellenbaugh-angle formula is set to find the heel angle in 14 knots of wind. For powerboats—since you can't reef the boat's structure itself—you use a multiplier in pounds per square foot of wind pressure for the appropriate maximum average wind speed the boat is likely to experience. Also, instead of sail area, you take the complete area of the profile of the boat. Draw this in outline including all: stanchions, rails, lee cloths, davits, radar masts, and so on. Find the area and the center of the area (CE) above the waterline.

Again—just as with a sailboat—find the center of the lateral plane (CLP) of the hull underbody. Measure the distance it is down from the waterline. This can be estimated as 50% of draft on powerboats.

Add the distance WL to CLP to the distance WL to CE to find the total heeling arm HA.

You now enter this in the powerboat wind-heel formula just as with a sailboat Dellenbaugh-angle formula. The answer should be one quarter to one half freeboard or 14 degrees or less (see below regarding cockpit size) depending on whether it's an open boat, or a boat with a cockpit, or a flush-deck boat with no cockpit at all. If the resulting heel angle is greater, you must either reduce the "sail" area of the boat's profile, increase beam, or lower the center of gravity, or some combination of these.

We can work though the wind heel for an actual design, a 27-foot, sterndrive cruiser designed by Westlawn graduate Joe Speight. Dimensions are:

LOA: 27.5 ft.
DWL: 23.25 ft.
BOA: 8.5 ft.
BWL: 7.75 ft.

Where:
Roll, sec. = natural roll period, sec.
GM = metacentric height, ft.
Disp. = displacement, lb.
$\pi \approx 3.14$
$\Sigma Ir = m \times k^2$
m = the mass of each individual component or part of the boat
k = the distance of the component from the roll axis of the boat
(The roll axis is considered to be a straight fore-n-aft line longitudinally through the center of gravity of the boat.)

Imagine - 57-Foot Aluminum Motorcruiser

Though the above is accurate, the extensive calculations required are laborious and seldom undertaken. Happily, there is greatly simplified method which will provide a close estimate of roll time for any vessel of normal form. It is:

$$\text{Roll, sec.} \approx \frac{0.44 \times \text{Beam, ft.}}{\sqrt{\text{GM, ft.}}}$$

Where:
Roll, sec. = natural roll period, sec.
Beam = beam overall, ft.
GM = metacentric height, ft.

Let's take a 57-foot voyaging motorcruiser from my drawing board, *Imagine,* 14.17-foot beam, with a GM of 2.16 ft., we'd find:

$$\frac{0.44 \times 14.17 \text{ ft. Beam}}{\sqrt{2.16 \text{ ft. GM}}} \approx 4.24 \text{ sec. roll time}$$

14.17 ft. beam ÷ 3.28 = 4.3 m beam
4.24 sec. roll time ÷ 4.3 m beam = 0.98

This is very close to the ideal of 1, just a tad under, and so indicates good stability characteristics for a voyaging motorcruiser of this type. Any roll-time-to-beam between 1 and 1.1 would be excellent, but not over 1.1.

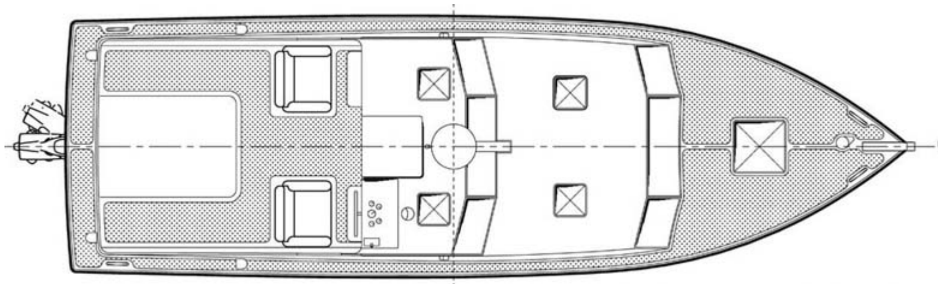
Finding GM
Back in Stability Part 1, we described how to estimate GM closely using the waterplane area and the coefficient of the waterplane to find the moment of inertia of the waterplane. We then used this to find BM from the moment of inertia of the waterplane and displacement. Finally—estimating (or calculating) the location of the vertical center of gravity (VCG)—we determined GM. Refer back to this article to see how this is done. Though this procedure was explained in regard to sailboats, exactly the same procedure and principles apply to powerboats.

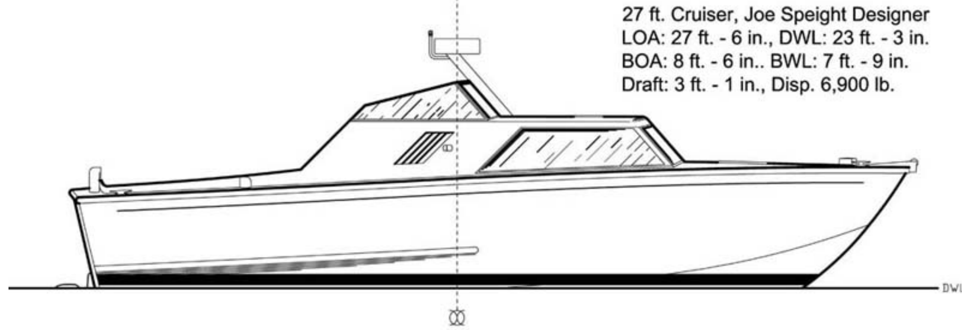
A few estimates are somewhat different for powerboats, however:

For powerboats the waterplane coefficient can be estimated as:

Displacement powerboats = 0.68
Semi-displacement powerboats = 0.74
Planing powerboats = 0.80

Draft to propeller: 3.08 ft.
Draft, hull: 1.41 ft.
Disp.: 6,900 lb.





27 ft. Cruiser, Joe Speight Designer
LOA: 27 ft. - 6 in., DWL: 23 ft. - 3 in.
BOA: 8 ft. - 6 in.. BWL: 7 ft. - 9 in.
Draft: 3 ft. - 1 in., Disp. 6,900 lb.

Maximum Allowable Heel Angle
For a flush-deck boat with no cockpit or well deck, the maximum heel is 1/2 the freeboard or 14 degrees, whichever is less.

For a completely open boat with a "cockpit" the full length, the maximum heel is 1/4 the freeboard or 14 degrees, whichever is less.

Most contemporary boats are largely flush decked but have a cockpit (or a well deck) of some form. For such craft, the maximum heel is somewhere between 1/2 and 1/4 freeboard, or 14 degrees, whichever is less. The amount of heeled freeboard allowed is determined by the following formula (from CFR 178.330):

For exposed waters:

$$\text{immersion} = \frac{f \times \left((2 \times LOD) - (1.5 \times cl)\right)}{4 \times LOD}$$

For protected waters:

$$\text{immersion} = \frac{f \times \left((2 \times LOD) - cl\right)}{4 \times LOD}$$

Where:
immersion = maximum allowable immersion due to heel, ft.
f = lowest or minimum freeboard, ft.
LOD = length on deck, ft.
cl = cockpit length, ft.

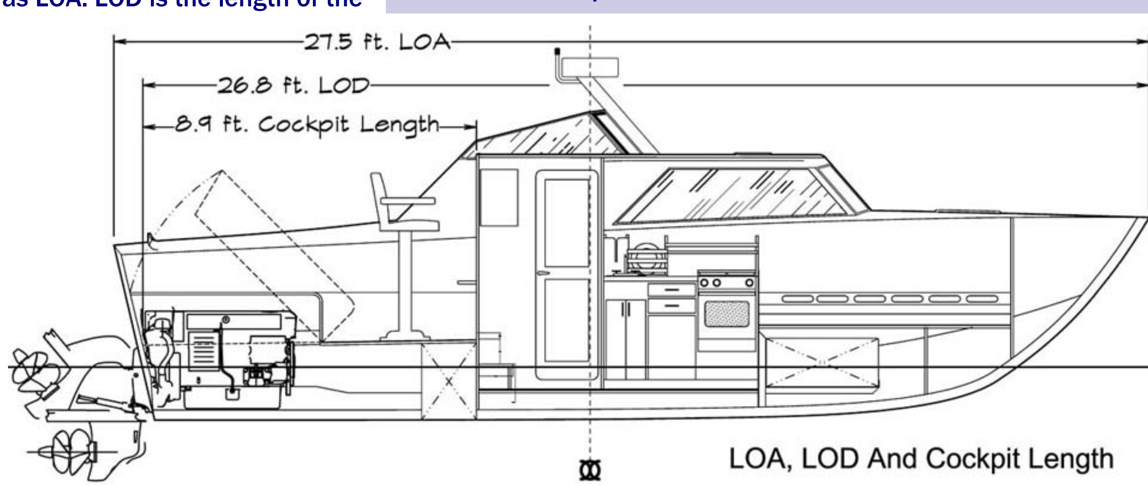
LOD is not the same as LOA. LOD is the length of the deck itself and is almost always less than LOA. For our 27-foot cruiser it is 26.8 feet, not the LOA of 27.5 feet, see drawing.

Using the formula for maximum allowable immersion, for our 27-foot motorcruiser, which will operate on exposed waters:

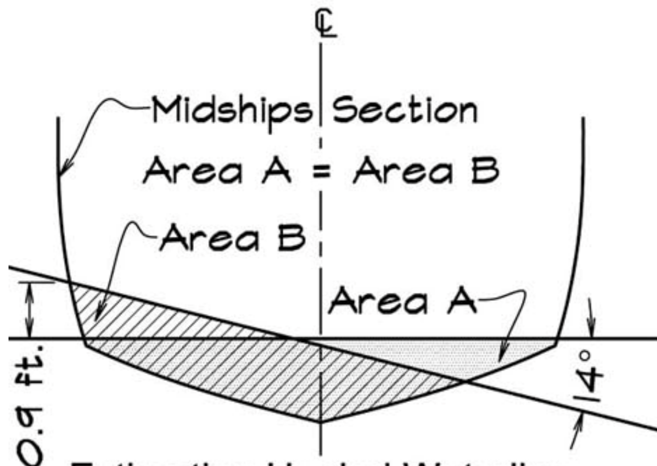
Finding the Heeled Waterline

You need to find the 14-degree heeled waterline to determine **both** if it is at less than half or one quarter the freeboard (as appropriate) and that the allowable immersion isn't exceeded. Note that the boat will "roll out" as it heels. If you are using a hull-fairing program, it should allow you to heel the boat and exactly determine the heeled waterline. If you don't have the lines in such a program, you can estimate the heeled waterline quite well by drawing the a full midships section of the boat, and then drawing a first-trail heeled waterline at 14 degrees through the centerline at the waterline (see illustration next page). Measure the area under the upright waterline and then measure the area under this first-trial heeled waterline. You'll find the area under the first-trial heeled waterline will be greater than under the upright waterline. By trial and error, lower the 14-degree waterline until the area under the heeled waterline is the same as under the upright waterline. This will be very close to the actual heeled waterline. Now, you can check to see if the 14-degree heeled waterline meets the requirements.

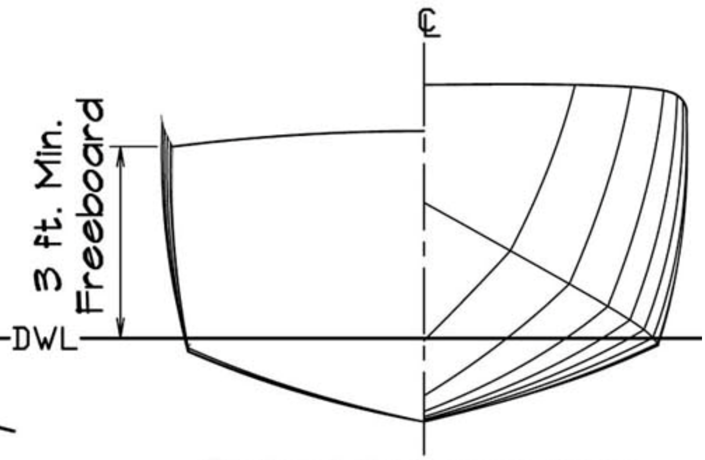
Note: On boats with bulwarks, the deck edge is the edge of the watertight deck extended out to the hullside, not the edge or top of the bulwark caprail.



LOA, LOD And Cockpit Length



Estimating Heeled Waterline



27-Foot Cruiser Sections

$$\frac{3\text{ ft. freeboard x}\left((2 \text{ x } 26.8\text{ ft.}) - (1.5\text{ x }8.9\text{ ft.})\right)}{4\text{ x }26.8\text{ ft.}} = 1.1\text{ ft. allowable immersion}$$

We see from the sections that the lowest freeboard happens to be at the transom on this boat. This is 3 feet minimum freeboard. The immersion to the 14-degree heeled waterline is 0.9 feet, which is well under half the lowest freeboard and also is under the maximum allowable immersion for this boat of 1.1 feet allowing for the cockpit. Accordingly, we can use the 14-degree heel angle as maximum allowable. If we'd found the heeled waterline at 14 degrees was higher than half the freeboard or if the immersion depth had been greater than 1.1 feet for this boat, we would have had to find a lower heel angle (using the same method) until we had a heel angle that met all criteria.

Calculating the Heel Angle from Wind Pressure

The heel angle from the wind pressure can be found from:

Heel angle, degrees = P x 57.3 x Profile Area x Heeling Arm ÷ GM x Disp.

Where:
Heel angle = degrees of heel
P = wind pressure for the selected wind speed, lb./sq.ft.
Profile Area = area of the profile of the boat above the waterline, sq.ft.
Heeling Arm = distance from center of lateral plane of the underbody to the center of effort of the profile area, ft.
GM = metacentric height, ft.
Disp. = displacement, lb.

Use wind pressures (P) as follow for the intended boat use:

- Ocean crossing (50 knots wind) = 13.2 lb./sq.ft.
- Coastwise ocean (45 knots wind) = 10.7 lb./sq.ft.
- Partially protected waters such as lakes, bays, and harbors (40 knots wind) = 8.5 lb./sq.ft.
- Protected waters such as rivers, inland lakes, and sheltered harbors (35 knots wind) = 6.5 lb./sq.ft.
- Note: For the U.S. Great Lakes, use coastwise ocean for summer service and ocean crossing for winter service.

To find the GM of our 27-foot cruiser, first we need to find the moment of inertia of the waterplane. Estimating the waterplane coefficient at 0.80 for a planing hull, and using the formula from Stability Part 1, we find:

$$ItWP = \left(\frac{0.80^2}{11.7}\right) \text{x } 23.25\text{ ft. WL x }(7.75\text{ ft. BWL})^3 = 592\text{ ft.}^4$$

We can estimate the location of VCG for this planing hull as about 5% (or 0.05) of DWL above the DWL, or:

0.05 x 23.25 ft. DWL = 1.16 ft. above DWL

Referring to *Stability Part 1*, we find BM:

6,900 lb. disp. ÷ 64 lb./cu.ft. salt water = 107.8 cu.ft.
BM, ft. = ItWP ÷ Disp., cu.ft.
592 ft.^{4} ÷ 107.8 ft.^{3} = 5.49 ft. BM

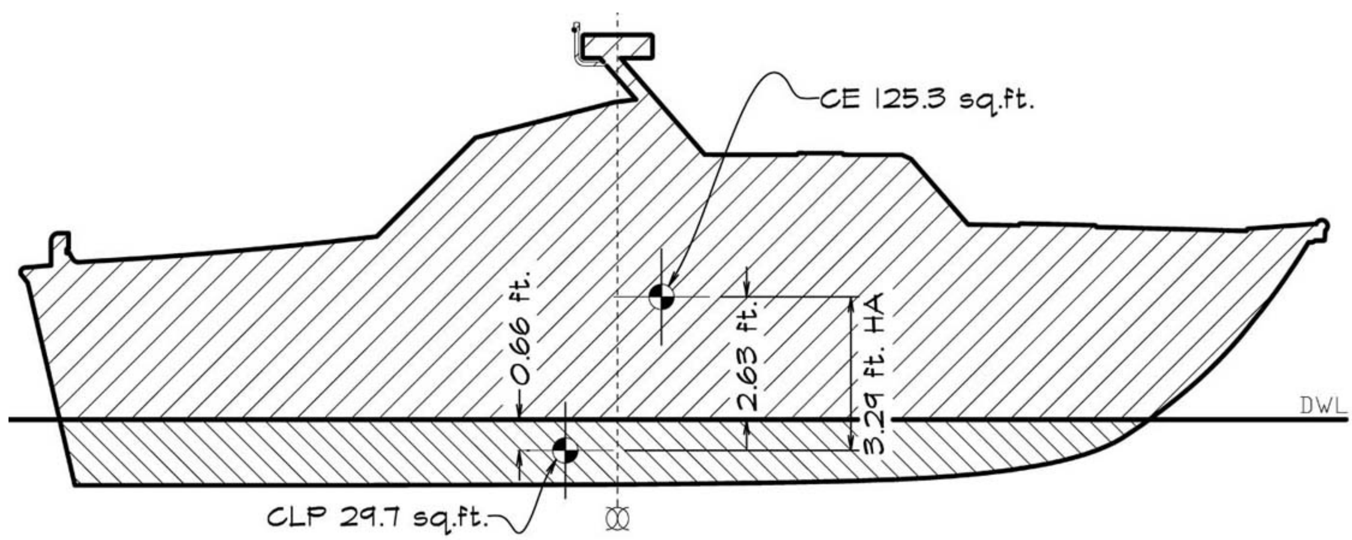
Using the Morrish formula to find VCB (see Stability Part I):

Waterplane area = 23.25 ft. DWL x 7.75 ft. BWL x 0.80 waterplane coefficient = 144.1 sq.ft. WPA

$$\frac{1}{3}\left(\frac{1.41\text{ ft. Hull Draft}}{2} + \frac{107.8\text{ cu.ft. Disp.}}{144.1\text{ sq.ft. WPA}}\right) = 0.48\text{ ft. VCB, below DWL}$$

Then, referring again to Stability Part 1, we can find an estimated GM:

GM = BM - (VCG + VCB)
5.49 ft. BM - (1.16 ft. VCG + 0.48 ft. VCB) = 3.85 ft. GM



From the drawings of our 27-foot sterndrive cruiser, we find the CLP is 0.66 ft. below the DWL and the CE of the profile area (of 125.3 sq.ft.) of the boat above the DWL, is 2.63 ft. above the DWL. The heeling arm is then:

2.63 ft. + 0.66 ft. = 3.29 ft. HA (heeling arm)

This is rugged little cruiser intended for venturing anywhere along the coast and possibly some offshore fishing, so the wind pressure (P) should be based on 45 knots wind, or 10.7 lb./sq.ft. Accordingly:

Heel angle = 10.7 lb./sq.ft. x 57.3 x 125.3 sq.ft. Profile Area x 3.29 ft. HA ÷ 3.85 ft. GM x 6,900 Disp.
Heel angle = 9.5 degrees.

This is well under the 14 degrees we found earlier was allowable and indicates that this boat is well suited to its intended use with regard to wind-heel stability.

Comparing Wind-Heel Criteria With Roll Time

Using the roll-time formula from page 9, we can find the roll time for our 27-foot motorcruiser as:

Martin's Wind-Pressure Formula

Wind pressure for a given wind speed is found from Martin's formula which is:
P = 0.004 x mph^2
or
P = 0.0053 x kts^2
Where:
P = wind pressure, lb./sq.ft.
mph = wind speed in miles per hour
kts = wind speed in knots

$$\frac{0.44 \text{ x } 8.5 \text{ ft. Beam}}{\sqrt{3.85 \text{ ft. GM}}} \approx 1.9 \text{ sec. roll time}$$

8.5 ft. beam ÷ 3.28 = 2.59 m beam
1.9 sec. roll time ÷ 2.59 m beam = 0.73

Since this is well under a roll-time-to beam of 1, this boat will have a rather quick snappy roll. As noted earlier, this is nearly unavoidable in most planing hulls of normal form. Luckily, the dynamic lift under a planing hull damps out some of the snap from this quick roll at speed. This is not the case at low speed, drifting, or at anchor, however.

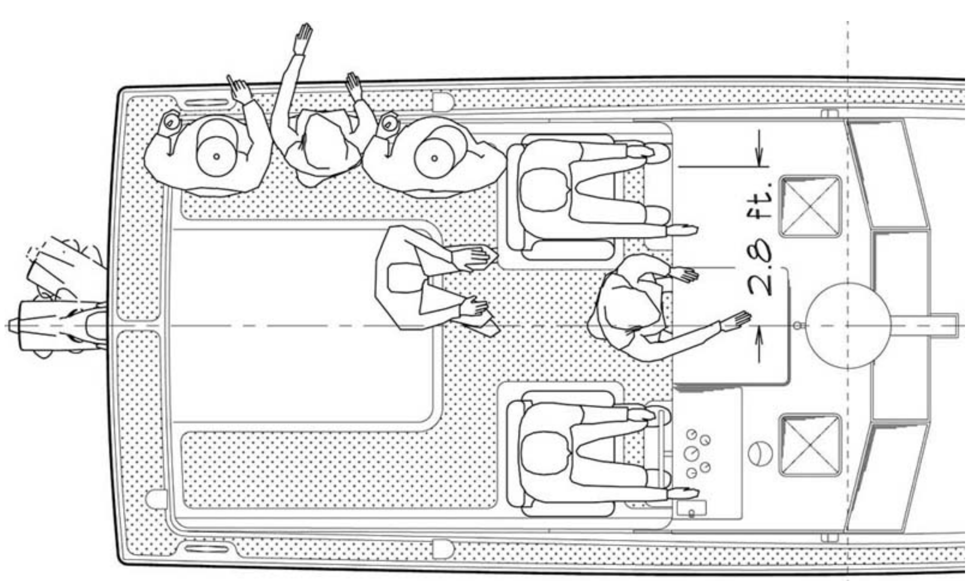
For displacement, voyaging motorcruisers, getting the roll time in the ideal range (between 1 and 1.1 time beam in meters) is more critical. These boats should offer crew comfort over long passages. It pays in early design to work out the relationship of beam and CG to optimize roll time for comfort. Keep in mind, though, that meeting the wind-heel criteria is even more important. In some instances—particularly for voyaging cruisers with high topsides and superstructures—you may have no choice to settle for a quicker roll time than ideal for crew comfort to obtain sufficient wild-heel stability. In these cases, a steadying sail can help take the snap out.

Pleasure-Craft Passenger Heel
The angle of heel resulting from moving weights already aboard a boat a given distance is found from:

$$\text{Heel angle, degrees} = \arctan\left(\frac{\text{W lb. x d ft.}}{\text{Disp. lb. x GM ft.}}\right)$$

Where:
W = weight moved, lb.
d = distance moved, ft.
Disp. = boat displacement, lb.
GM = metacentric height, ft.
arctan = The arctan of X is an angle whose tangent is X, often notated as $\tan^{-1}$. It is not the same as 1/tan. The arctan or arc tangent can be found quickly on any inexpensive scientific calculator or in any standard spreadsheet program.

Our weights, in this case, are people and the U.S. Coast Guard formula for passenger heel uses 140 pounds per person, assuming a mix of men, women, and children. (Other rules from the CFR use as much as 165 pounds.) These weights were settled on decades ago when the U.S. population was smaller. Over the last few years, there have been a few capsizing incidents where it became apparent that the average weight of the passengers aboard was well over 140 pound (though, interestingly, passenger-heel itself was not the cause of these capsizes). As I write this, the Coast Guard is evaluating whether to increase the assumed weight per person. In fact—with all adult male passengers—it wouldn't unlikely for the average weight to be close to 200 pounds. We do know of one yacht that capsized, with an all male crew on the flybridge, with an average weight approaching 250 pounds each! For Westlawn work, we recommend using a passenger weight of 175 pounds, which is also what the FAA uses for average passenger weight, including clothes and a few personal items.



2/3rds Passengers To Port

We can see how this works out for our 27-foot cruiser.

Say we have total crew of 8. Two thirds of this is 5.28, say, 6. Six times

175 pounds equals 1,050 pounds shifted to the rail. Then, for our 27-ft. cruiser passenger heel would be:

$$\arctan\left(\frac{1,050 \text{ lb. x } 2.8 \text{ ft.}}{6,900 \text{ lb. Disp. x } 3.85 \text{ ft. GM}}\right) = 6.3 \text{ degrees passenger heel}$$

Referring back to our earlier calculations for wind heel, we already found that the maximum 14-degree heel was acceptable and so this vessel easily meets passenger-heel criteria.

Commercial-Boat Wind-Heel Criteria

The pleasure-craft heel criteria we've discussed so far are based on U.S. Coast Guard requirements for commercial passenger vessels, but don't follow these rules exactly. Still, they will generally be very close to the USCG rules or even—in the case of passenger heel—slightly exceed them. Nevertheless, the USCG rules must be followed precisely for commercial vessels. They set the minimum metacentric height a boat must have for various operating services. This is CFR 170.170, often termed *GM Weather*. The formula for this rule (really a regulation with the force of law) for commercial vessels is:

$$GM \geq \frac{P \text{ x } A \text{ x } h}{W \text{ x } \tan T}$$

Where:
GM = metacentric height, ft.
P = wind pressure in long tons per square foot, tons/ft.^{2}

$P = 0.005 + (L \div 14{,}200)^2$, tons/ft.^{2}
for ocean and coastwise service.

$P = 0.0033 + (L \div 14{,}200)^2$, tons/ft.^{2}
for partially protected waters such as lakes, bays, and harbors

$P = 0.0025 + (L \div 14{,}200)^2$, tons/ft.^{2}
for protected waters such as rivers and harbors

L = length between perpendiculars (waterline length for most ordinary boats), ft.
A = projected lateral area of boat profile above the waterline, sq.ft.
h = vertical distance from center of "A" down to center of underwater area (center of lateral plane), ft.
W = weight of vessel (displacement), long tons (tons of 2,240 lb.)
T = heel angle = Heel not greater than between one-quarter to one-half of freeboard (as explained earlier regarding cockpit size), but never more than 14 degrees. The amount of heeled freeboard allowed is determined by the formula from CFR 178.330, exactly as described earlier.

The wind velocities in P for the factors 0.005, 0.0033, and 0.0025 are (using Martin's formula):
46 knots for ocean and coastwise
37 knots for partially protected waters
33 knots for protected waters

The "$(L \div 14{,}200)^2$" factor in the wind-pressure calculation (P) is to increase the wind speed by 0.0458 knots for each foot of boat length.

Commercial-Boat Passenger-Heel Criteria

The U.S. Coast Guard requires that commercial passenger vessels comply with CFR 171.050, *Intact Stability Requirements for a Mechanically Propelled or a Non Self-Propelled Vessel*, often called *Passenger Heel*. Again, this is a legal requirement for commercial passenger vessels and is governed by the formula:

$$GM \geq \frac{N \text{ x } b}{24 \text{ passengers/long ton x } W \text{ x } \tan T}$$

Where:
GM = metacentric height, ft.
N = number of passengers
b = distance from the boat's centerline to the geometric center of the passenger deck, ft.
W = weight of vessel (displacement), long tons—tons of 2,240 lb.
The "24 passengers/long ton" makes the following assumptions:
That the average weight of all passengers (a mix of men, women, and children) is 140 pounds each, and that 2/3rds of them move to the side of the vessel, so – 2/3 x 140 lb. = 93.34 lb., and 2,240 lb./long ton ÷ 93.34 lb. = 24 passenger/

long ton.
T = heel angle = Heel not greater than between one-quarter to one-half of freeboard (as explained earlier regarding cockpit size), but never more than 14 degrees. The amount of heeled freeboard allowed is determined by the formula from CFR 178.330, exactly as describe earlier.

Note on Stabilizers and Steadying Sails

It is vital to keep in mind that stabilizers (such as active fin stabilizers) ***never*** do anything to improve the actual stability of a boat. Stabilizers reduce roll motion and so enhance crew comfort, but if the boat's CG is too high, the boat will be in just as much danger from capsize as it is without stabilizers. In fact, it may be ***more*** dangerous as the improved comfort from the stabilizers will conceal from the crew the seriously uncomfortable roll—a warning sign of too little stability (center of gravity to high)—until a particularly large wave rolls the boat too far and it keeps on going all the way over. You cannot correct or compensate for insufficient stability with stabilizers. Their sole function is to increase crew comfort.

Active fin stabilizers are the most effective means of stabilization available but they only work when a boat is underway. They will not function at anchor or at a mooring. Active fin stabilizers are also not ideal for damping out quick snap roll. For this reason, I often use a combination of a small steadying sail and active fins on displacement motorcruisers. This is highly effective and further provides some redundant stabilization should one of the two systems go offline.

***Gerr 34 Sportfish*, designed by Dave Gerr**