# Racing at Bonneville:
# Determining the "center of pressure" and center of gravity of your vehicle

By **Eva Håkansson** and **Bill Dube'**, June 2014 (rev 1.1)
Owners of the Record Holding **KillaJoule** Electric Streamliner Sidecar Motorcycle

*Eva and Bill with their electric streamliner sidecar motorcycle "KillaJoule". KillaJoule is piloted by Eva and her current record (as of August 2013) is 212.040 mph, making KillaJoule the official world record holder for all types of sidecar motorcycles. Photo: Bonnevillestories.com.*

<u>A "Pig on Ice"</u>

At 200 mph, everything wants to fly. Track cars like Le Mans cars have a lot of traction and lots of downforce, but the situation at Bonneville is very different. The coefficient of friction on the salt is only a fraction of that of pavement. It is perhaps as high as 0.6 on a really good year, but typically more like 0.3 or 0.4 (this should be compared to about 1.0 for pavement, and up to 3.0 for the dragstrip). Most of the traction is used up for forward motion and the faster you go the more time your tires may spend in the air due to surface roughness. To make matters worse, many Bonneville vehicles are built for minimum drag and not downforce. The consequence of this is that a vehicle at 200 mph at Bonneville behaves like a "pig on ice."

In order to avoid the worst consequences of becoming a "pig on ice", you need to design your vehicle to be "aerodynamically stable." That is, absent ideal wheel traction, your vehicle needs to inherently *want* to point down track in a forward orientation.

<u>Aerodynamic Stability, CG and CP</u>

To accomplish this, during the design phase and after your vehicle is built, you need to determine both the center of gravity (CG) and the aerodynamic "center of pressure" (CP) of your vehicle. We care about the relative positions of the CG and CP because this determines the overall aerodynamic stability of your vehicle when making a land speed record. The CG <u>must</u> be in front of the CP for the vehicle to be stable at high speeds. A good comparison is a dart or a rocket. A dart has a heavy nose and feathers in the back. This ensures that the CG is ahead of the CP. If you throw a dart with the feathers forward, the dart will turn in the air and hit the board nose first.

You want your Bonneville vehicle to display the same behavior as the dart – no matter what happens, you want your vehicle to *want* to go nose first. Rockets have the same requirements to fly stable. At the end of this document is a link to *NASA's Beginner's Guide to Rockets* which has an in-depth discussion about stability (and of course also rocket propulsion and other exciting topics).


*Two land speed vehicles going tail first. Photo courtesy of Tom Burkland.*

Most folks know (or at least have some idea) what the center of gravity is. Basically, if you suspended your vehicle from the CG point - wherever it may lie within your vehicle - it would balance perfectly. Once your vehicle was suspended by the CG point, you could reposition it with a light touch of your hand and it would simply hang in that new position.

The center of aerodynamic pressure (CP) is similar to the CG, but with the CP we are not worried about how gravity will act on your vehicle, but instead we are concerned about the aerodynamic forces exerted on the outer skin of your vehicle by the wind. With the center of gravity (CG), we find the balance point with respect to the force of gravity, but with the center of pressure (CP) we will find the balance point with respect to the wind.

<u>Finding Your Vehicle's CG</u>

*This tutorial will use a four-wheeled vehicle with a relatively simple, symmetric body as an example. The method will also apply directly to a two-wheeled vehicle. The methods of finding CG and CP can also be applied to other vehicles such as our three-wheeled KillaJoule sidecar streamliner, but the asymmetric body will make the CP estimation a bit more complicated. To keep the tutorial more simple, and because there are indeed significantly more cars than sidecar streamliners, we are using a car as example.*

*Your vehicle must be 100 % "race ready" in order to get an accurate estimate of the CG. That means that the driver is position and wearing all the safety equipment. Picture shows Eva in the KillaJoule electric sidecar streamliner.*

Let's begin by calculating the position of the CG in the horizontal plane. There are countless ways to find the CG, but we are going to show the standard method that is used on aircraft. It is important that when you are performing these CG measurements, the vehicle is in 100% "race ready" condition. That is, the driver is in position (wearing all the safety equipment), the tanks are all full, and all equipment and covers are in place. It is also useful to think about (and perhaps measure) how the CG will change at the end of a race, when the tanks are empty, perhaps the fire bottle is empty, etc.

We begin by choosing some standard fixed “zero” point. A typical fixed point to choose is the nose of the vehicle. Put your vehicle in a position where it won’t roll and mark the point straight down from the nose with tape on your garage floor. Use a “plumb bob” or a level to get your zero point transferred accurately on the floor. Next, make a line that goes straight out to the left and right of that point, so that it is perfectly parallel with the axles and aligned with the front of your car. This is your zero line (or formally your “datum reference”).

Now, measure from your zero line (that you marked on the floor right at the nose of the car) to the center of the contact patch on each of your tires. Write down the distance for each of your tires, keeping track of left-front, right-front, right-rear, left-rear.

Now we determine the weight on each tire. If you have four identical platform scales, then this is easy. Most folks (like us) have just one scale. If you have just one scale, then you must make three small platforms that are the same height as your scale. (Typically, you simply use thick wood planks the same thickness as your scale.) You then, somehow, get your vehicle up on the three planks and the scale. Read the scale. Then swap the scale to another tire. Again, write down the weights and keep track of how much each wheel weighed.

We know it would be easier not to bother with the platforms and just move the scale from wheel to wheel, but unless the other wheels remain at the same height as the wheel on the scale, the scale will read incorrectly.

We are now going to calculate the “moments” for each wheel with respect to our zero line (*moment = distance to the zero line x weigh*t).

We make a table like this (values are for a fictitious vehicle):

| **Tire position** | **Distance to zero line** [Inches] | **Weight** [lbs] | **Moment** [Inch-lbs] |
|---|---|---|---|
| Front right | 11.5 | 1,221 | 14,041.5 |
| Front left | 11.75 | 1,196 | 14,053 |
| Rear right | 117 | 1,127 | 131,859 |
| Rear left | 117.25 | 1,130 | 132,492.5 |
| **Total** | | **4,674** | **292,446** |

Now we take the total moment and divide by the total weight:

292,446 [inch-lbs] / 4,674 [lbs] = 62.57 [inches]

This is the location of the CG, measured from our chosen zero line (which happens to be the nose of the vehicle). Carefully measure this spot using your tape measure and transfer it to the side of the vehicle using a little masking tape.


*Weighing the KillaJoule streamliner for the FIM record certification (electric motorcycles are currently classified based on their weight, KillaJoule is in the class above 300 kg).*

*Notice the platforms that bring all the wheels to the scale height. If your vehicle is being weighed for record certification, keep in mind that those numbers do not include the driver and perhaps also not fuel and other fluids. You could use those numbers, but you will have to calculate the moments for the driver, fuel etc. and add to the table above.*

Estimating Your Vehicle's CP

While it is *possible* to determine the center of pressure exactly in a wind tunnel or by 3D scanning and use of simulation software, we are going to use a clever (and easy) way of estimating it. While not perfect, it works pretty well for most purposes. It is an old trick used by the model airplane crowd.

First, you must have as accurate a side-view profile of your vehicle as possible. The easiest way to get this is to take a side picture of your vehicle. It is best if you position the camera dead-on perpendicular to center of the side. Use a telephoto lens setting and take the photo from as far away as the vehicle will fill most of the frame. Alternatively, you can make careful measurements and sketch the profile on graph paper. (This is what the old model aircraft folks would do. Probably only useful if you have a *lot* of spare time or you are in the design stage and have nothing to take a picture of.)

Print the profile photo about 11 x 17 and on as heavy a paper as your printer can manage. Smaller and/or lighter tends to be less accurate. Mounting on cardboard or foam board can help, but only if you *evenly* spray on the adhesive. You can go really big, but it doesn't improve the accuracy of the overall estimate, however. (If you don't have access to a printer, Walmart offers a 1-hour digital photo 10x20 mounted on foam board for $20. This can be a simpler, easier option. Get a spare to hang on your wall. ☺ )

CAREFULLY cut out the profile of your vehicle with an Exacto knife or scissors. You can then balance the cutout on the edge of a ruler to get close to the balance point, next you will do the final balancing with a push pin, moving the pin slightly forward and backwards until you are able to get the exact balance point of your vehicle shape.

You are now pretty darn close to locating the center of pressure for your vehicle. It is technically the "area center of moment", but for our purposes it is a good enough estimate of the CP. Go back out to your garage, and find this same point on your vehicle and mark it with a piece of masking tape.

Now compare the relative positions of the CG to your new estimate of the CP. The rule of thumb is that the CG should be in front of the CP by at least 6 inches for the vehicle to be aerodynamically stable at high speed. (More is better.) If it is not at least six inches, or if it is behind the CP, you have some work to do.

How to Fix a Badly Placed CP or CG

If you have discovered a problem with your CG or CP, how do you fix it? The answer is; you can move either the CG forward or the CP rearward. The choice is dictated by practicality. You may end up moving them both a bit.

Moving the CG

The simplest (and probably most common) fix used is to move the CG forward by adding ballast to the front of the vehicle. The farther forward the ballast is added, the more effective it will be. This is why you often see a heavy 12 volt battery or a water cooling tank relocated up in the nose of vehicles at Bonneville. By moving a heavy component from behind the CG to way up in front of the CG, this often doubles the effect of simply adding the weight in ballast. It also does not change the total weight, which is also a good practice.

Removing weight from the rearmost of a vehicle is also very effective. The further back you can remove weight, the better. A thinner rear bumper might be used, for example. Can the rear seats be removed? Spare tire? Jack? Mother-in-law?

Moving the CP

Moving the CP rearward can be harder (or darn near impossible) to do in many classes of vehicles. In other classes, like a streamliner, it can perhaps be the easiest solution.

If you look at historical photos of streamliners, you will notice that the majority of them "grow" a bigger and bigger fin in the rear over time. This is invariably an effort to add area in the rear of the vehicle (without adding much weight in the rear) to move the CP rearward. You can also make the rear section longer, or dip a bit closer to the ground, all adding area while not adding much weight or drag.

When you are thinking about adding area to the rear of your vehicle, you can test out your ideas by adding a fin or whatever, out of the scraps you cut away, to your photo, and rebalancing the result. You will need to move the CP a bit more than you think, however, because that new fin will add a bit of weight, which will move the CG just a touch.

Conclusion

In land speed racing, especially at Bonneville, vehicles that are not aerodynamically stable *invariably* have serious handling problems at speed. The vehicles get "squirrely" and/or just suddenly spin out. It is like throwing an arrow or dart backwards. It wants to travel with the CG in front of the CP, and when the aerodynamic forces get a grip on the body at speed, (the traction forces no longer dominate,) it *will* travel CG in front. This can ruin your whole day.

The fastest vehicles at Bonneville are the best prepared. Finding and fixing a CP or CG problem before it actually puts the "rubber side up" on you vehicle can often make your vehicle the very fastest of them all. Regardless, it will give you one less problem to conquer out on the track.

**More resources:**

NASA's Beginner's Guide to Rockets: http://exploration.grc.nasa.gov/education/rocket/

Rocket stability: http://exploration.grc.nasa.gov/education/rocket/rktstabc.html

There are plenty of videos of spins and crashes on YouTube, however, we have chosen to not list any of them here. Although sometimes educational, we see no value in watching other people's misfortunes. We also don't want to spread videos of events that the drivers and crews probably just want to forget.

**Contact us:**

The latest news can be found on our Facebook page: www.facebook.com/killacycle

Info about the KillaJoule and our dragbike the KillaCycle, records, sponsors etc.: www.killacycleracing.com

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