RACE CAR ENGINEERING: 400+ MPH: HOW TO STAY STRAIGHT AND ON TRACK?

by EVA HAKANSSON & BILL DUBE', APRIL 5, 2015

The fastest cars in the world go well over 400 mph (640 km/h). How do you stay on track and stay straight at this extreme speed? This article covers one of the most important characteristics of the world's fastest cars: aerodynamic stability. We dig deep into the science of extreme speed and explain how this is accomplished by the location of the centre of gravity in relation to the aerodynamic centre of pressure.

Track cars like NASCAR and Formula 1 cars have a lot of traction and lots of downforce. Some of these cars have so much downforce that they could theoretically run upside down on the ceiling. These cars don't have to be inherently aerodynamically stable because the sticky tires and huge downforce make sure they go wherever the drivers want them to. The situation for the extreme land speed racing cars racing on salt or dry lakes is very different. Here we describe the science of aerodynamic stability, how you locate the centre of gravity and centre of pressure, and what you can do if you have a racing vehicle that isn't aerodynamically stable.

Nascar track race cars with a top speed of about 200 mph (left) are quite different from the extreme streamliner cars (right) built for outright speed records having top speed of over 400 mph. Sources: NASCAR– CC0 Public Domain, SpeedDemon – www.speeddemon.us.

A “Pig on Ice”

There is no paved track in the world that is long enough to accelerate to over 400 mph (and even more importantly – to slow down again). Instead, these ultra-fast cars must be run on dry lake beds. The most famous is the Bonneville Salt Flats in Utah, USA. The surface at Bonneville Salt Flats consists of salt, just as the name implies: it looks like a snow covered lake, it’s huge, and perfectly flat.

It is also often called the fastest place on Earth.

The problem with salt is that the surface is similar to a dirt road or packed snow, with the coefficient of friction only a fraction of that of pavement. It can perhaps be as high as 0.6 on a really good year, but is typically closer to 0.3 or 0.4 (this should be compared to about 1.0 for ordinary pavement, and up to 3.0 for the dragstrip with a prepped surface sprayed with a form of adhesive, called TrackBite).

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 a bit 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.

The easiest way to understand this concept is to think of a dart or an arrow. If you throw a dart with its feathers first, it will turn in the air and hit the board with the steel tip first. A dart wants to go tip first and is aerodynamically stable in that direction.

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

Aerodynamic Stability, CG and CP

To determine if your vehicle is aerodynamically stable, during the design phase and after your vehicle is built, you need to determine both the centre of gravity (CG) and the aerodynamic “centre 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 attempt. The CG must be in front of the CP for the vehicle to be stable at high speeds. Again, think of that 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.

You want your Bonneville vehicle to display the same behaviour as the dart – no matter what happens, you want your vehicle to want to go nose first. Even if the track conditions are good, a bit too much throttle can result in wheel spin that will make you lose traction, giving your car the opportunity to turn around. Rockets have the same requirements to fly stable. At the end of this post 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).

Most folks know (or at least have some idea) what the centre 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. (If you are uncertain about the CG or how to locate it, a short tutorial is included at the bottom of the page. When you have estimated your CG, mark it on your car with a piece of masking tape.)

The centre 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 centre of gravity (CG), we find the balance point with respect to the force of gravity, but with the centre of pressure (CP) we will find the balance point with respect to the wind.

At almost 300 mph, the aerodynamic forces on the vehicle are huge. Photo by BonnevilleStories.com

Estimating Your Vehicle's CP

While it is possible to determine the centre 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 centre 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 inches 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, many of the 1-hour print shops offer affordable prints mounted on foam board for. This can be a simpler, easier option. Get a spare to hang on your wall. ;-))

Carefully cut out the profile of your vehicle with a precision knife or scissors. You can then balance the cut-out on the edge of a ruler to get close to the balance point (or if you have long fingernails, you can pinch it and see if you find 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.

For a symmetric vehicle with a fairly simple shape, the Centre of Pressure (CP) is close to the area centroid of its side profile. An old trick to find the centroid is to cut out the profile of heavy paper and find its balance point. The balance point is the centroid, and it is a pretty good estimate of the CP.

You are now pretty darn close to locating the centre of pressure for your vehicle. It is technically the "centroid of the area", 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 (150 mm) 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.

The two small pieces of blue tape right above the University of Denver logo mark the Centre of Gravity (CG) and the Centre of Pressure (CP) of the KillaJoule. The CG is in front of the CP, just as it should be. Marking them with tape made the technical inspectors quite happy.

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 streamliner cars at Bonneville, 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 high speed. The vehicles get "squirrely" and/or just suddenly spin out. It is much 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 and is something all racers fear.

The fastest vehicles at Bonneville are the best prepared. Finding and fixing a CP or CG problem before it actually puts the "shiny side down" 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.

A car that has also grown "tail heavy" over the years is the Royal Purple streamliner. It is also one of the world's fastest cars with records of close to 400 mph. It had a close call in 2014 at 320 mph, but stayed on the wheels.

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

About the authors:

Eva Håkansson is a mechanical engineer and land speed racer. She has built her "KillaJoule" electric streamliner motorcycle together with her husband Bill Dube', also a mechanical engineer. Although the KillaJoule is officially a sidecar motorcycle, Eva typically describes it as "a three-wheeled asymmetric car that according to international competition rules happen to be a sidecar motorcycle". It runs like on rails and has so far – knock on wood – shown no aerodynamic instability as it is approaching 300 mph.

The latest news about Eva, Bill and KillaJoule can be found on her Facebook page: www.facebook.com/killacycle
Info about the KillaJoule and its "sister" the KillaCycle: www.killacycleracing.com
Eva Håkansson and Bill Dube's personal blog: www.TwiztedPair.com

Disclaimer:

Every form of racing is dangerous. The text above reflects opinions of the authors based upon engineering principles. Hopefully, these opinions could lead to a lower probability of an accident, or, a lower severity of an accident. However, racing is inherently dangerous and no responsibility can be taken by the authors for injury or death sustained as a result of, or in spite of, following the ideas presented in this document. The authors make no warranties, express or implied, that the information is free of errors.

Cover photo:

The cockpit view of the SpeedDemon's spectacular crash in 2014. Thanks to state-of-the-art vehicle safety equipment, the driver George Poteet walked away with just a bruise after this 370 mph (600 km/h) crash. Photo courtesy for Mike Cook's Shootout.

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Thanks to Tom Burkland and Rex Svoboda for initiating this article. Thanks to the Nish family for sharing their experience and videos, so the rest of us can race more safely.

TUTORIAL: Finding Your Vehicle's Centre of Gravity (CG)

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 (instructions in the article above) 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.

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 etc.

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. Perhaps the GoPro cameras don't need to be in place, but you will get a more accurate measurement if they are. Picture shows the author Eva Hakansson in her KillaJoule electric sidecar streamliner.

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 straight back from your zero line (that you marked on the floor right at the nose of the car) to the centre 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 “moment” for each wheel with respect to our zero line (moment = distance to the zero line x weight).

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

Tire position	**Distance to zero line** [inches]	**Weight** [lb]	**Moment** [inch-lb]
Front right	11.50	1,221	14,041.5
Front left	11.75	1,196	14,053
Rear right	117.00	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-lb] / 4,674 [lb] = 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. The CG should be in front of the CP, or your vehicle is not inherently aerodynamically stable.

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. Electric cars are also classified by weight.) 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.

Source: http://scienceenvy.com/race-car-engineering-400-mph-how-to-stay-straight-and-on-track/