Countersteering

By James R. Davis

Everyone who has driven a motorcycle has experienced it, the MSF classes mention (but don't explain) it, and motorcyclists discuss it all the time. But what is it, really? How does it work? Why does it work? All questions I will try to deal with in this discussion.

At very slow speeds we steer a motorcycle by turning the handlebar in the direction we wish to go. We can only do that at speeds of less than about 5 MPH. At any higher speed we do the exact opposite, whether we realize it or not. For example, assuming we want to turn to the right, we actually TRY to turn the handlebar left. This results in the front wheel leaning to the right and, as a result of the lean of the wheel, a turn to the right. This is counter-steering.

Why is it that we don't get confused regardless of our speed? Because we have learned that steering a motorcycle is an effortless chore. That attempt to turn the handlebar to the left FEELS like we are pushing the right grip rather than pulling on the left one. It feels like that because the harder we push it, the more the motorcycle turns to the right and, thus, it feels like the right grip is pushing back at you that much harder. In other words, we quickly learn to associate counter-steering feedback with the hand closest to the direction in which we wish to turn. Further, even a little bit of experience shows that counter-steering is essentially effortless while trying to turn the handlebar in the direction you want to go is virtually impossible. Humans are relatively fast studies, after all.

It takes only a modest familiarity with a gyroscope to understand counter-steering - at least to understand how most people believe it starts to work. The phenomenon is called Gyroscopic Precession. This is what happens when a lateral force is applied to the axis of a spinning gyroscope.

The spinning gyroscope translates the force vector ninety degrees off the direction of spin. Thus, if we try to turn our front wheel to the left, the force we use appears as a lateral force forward against the axle on the right side and this is translated into a force that tries to lean the wheel to the right. Similarly, trying to turn the wheel to the right results in the wheel trying to lean to the left.

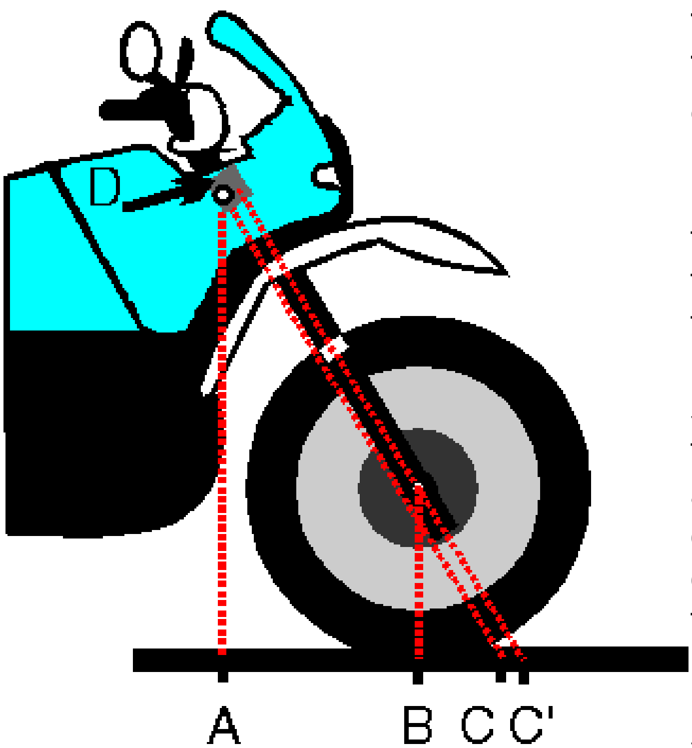
But gyroscopic precession is not a necessary component of counter-steering. No matter how slight, if your front wheel deviates from a straight path your motorcycle will begin to lean in the opposite direction. It is entirely accurate to assume that even without gyroscopic precession, the act of steering the front wheel out from under the bike would start counter-steering in the opposite direction. This is a result of steering geometry - rake. You can observe it at a complete stop. Just turn your handlebars in one direction and you will see that your bike leans in the opposite direction as a result.

In the case of a motorcycle, your handlebar input is immediately translated by gyroscopic precession into a lean in the opposite direction. Since your front wheel is attached to the bike's frame, the body of the bike also attempts to lean. It is the lean of the BIKE that overwhelms the handlebar effort and drags the front wheel over with it - gyroscopic precession merely starts the process and soon becomes inconsequential in the outcome.

If, for example, you had a ski rather than a front wheel, the front would actually begin to turn in the direction of handlebar input (just like it does with a wheel instead of a ski) and body lean in the opposite direction would then overwhelm that ski making counter-steering still effective.

The ONLY WAY to turn a motorcycle that is moving faster than you can walk is by leaning it (if it only has two wheels). We have talked only about what starts that lean to take place. Indeed, all we have talked about is the directional change of the front wheel along with the simultaneous lean of the bike, both in the opposite direction signaled by handlebar input. So then what happens?

Before getting into what is actually somewhat complicated let me say that if you were to let go of your handlebars and provide no steering information whatever (or you were to get knocked off your motorcycle), after some wildly exciting swings from side to side your motorcycle would 'find' a straight course to travel in and would stabilize itself on that course, straight up! That's right, your motorcycle has a self-correcting design built into it -known as its Steering Geometry - that causes it to automatically compensate for all forms of leaning and speed changes and end up standing straight up, going in a straight line, whether you are on the bike or not - until it is traveling so slowly that it will fall down.



RAKE GEOMETRY

This diagram shows a typical motorcycle front-end. The handlebars are connected to the steering column, which is connected to the knee bone, which is... Oops, wrong discussion. The steering column (actually called the 'steering stem') does not connect to the knee bone, nor does it connect directly to your forks! Instead, it connects to what is known as the triple-tree (shown as D in the diagram.) This is merely where both forks are tied, along with the steering stem, to the bike's frame. You will notice that the triple-tree extends towards the front and that as a result the forks are offset forward some distance from the steering stem. (Notice the red diagonal lines marked C and C'.) This is known as the offset.

Now please notice that the forks are not pointing straight down from the triple-tree, but are instead at an angle. This angle is known as the rake. Were it not for that rake (and modest offset) the front tire would touch the ground at point A. (Most rake angles are approximately 30 degrees.)

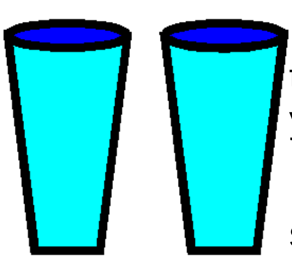
What the rake does for you is profoundly important. For one thing, it causes any lean of the wheel to be translated into a turn of the wheel towards that lean. For another, it slows down your steering. That is, if you turn your handlebar 20 degrees at slow speed your course will change something less than 20 degrees. [At higher speeds you NEVER would turn your handlebars 20 degrees - the front wheel is always pointing virtually straight ahead.] Rake, in the case of higher speed turning then really does SLOW DOWN the realization of the turn. (We will see why soon.)

Looking at the diagram, imagine that instead of pointing to the right the wheel is pointing straight at you. (The body of the motorcycle remains pointing to the right.) You will now recognize that the contact patch which was B before the wheel turned has now got to be near where C' is at. In other words, the fact that your wheel is on a rake results in the consumption of part of your steering input into a displacement of the contact patch of the wheel. (This is why steering is 'slower' - and the greater the rake, the slower it is. Note that 'slow steering' is NOT the same as 'under-steer'.)

Notice also that where the red diagonal line marked C' touches the tire is higher than where B touches the tire. This demonstrates that a consequence of turning is that the front-end of your motorcycle actually lowers based on rake geometry. The distance between where B and C (not C') touch the ground is called trail. The more extreme the rake angle, and the shorter the offset, the longer the trail is. Some motorcycles will have the hub of the front wheel either above or below the forks rather than directly in the middle of them. In effect, these placements are designed to reduce or increase the effect of the offset in order to increase or reduce trail.

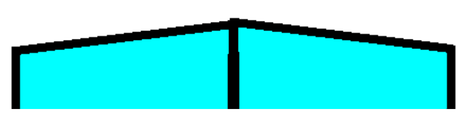
The stability of your motorcycle at speed is a function of how long its trail is. However, have you ever noticed that the front wheel on bikes that have excessive rakes (and therefore long trail) have a tendency to flop over (at low speeds) when they are not aligned perfectly straight ahead? This is the phenomena that explains just one of the reasons why your wheel actually turns in the direction you want to go after it begins to lean in that direction. Any lean whatever of the wheel, because gravity tries to lower the front-end, receives an assist from gravity in its efforts to move the contact patch forward along the trail. Further, notice that the pivot axis of your forks is along C, not C' and that this is behind the bulk of the front-end. Thus, gravity plays an even bigger role in causing the wheel to turn than at first glance it would appear. (And now you see why you have steering dampers - so that a little lean doesn't result in a FAST tank-slapping fall of the wheel in the direction of the lean.)

But there is another, more powerful, reason that the lean is translated into a turn - Camber Thrust. Unlike automobile tires, your motorcycle rides on tires that are rounded instead of flat from side to side. When you are riding vertically your contact patch is right in the middle of the tire, at its farthest point from the hub of the wheel. When you are leaning you are riding on a part of the tire that is closer to the hub of the wheel. The farthest parts of the tire from the hub of the wheel are TURNING FASTER than any part closer to that hub. Thus, when you are leaning the outside edge of the contact patch is moving faster than is the inside edge.

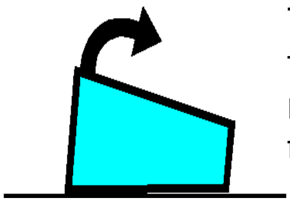


Imagine taking two tapered drinking glasses and putting them together as in the next diagram. Does this not bear a striking resemblance to the profile of your tires when looking at them head on?

Now imagine placing one of those glasses on its side on the table and giving it a push. Note that



the glass MUST move in a circle because the lip of the glass is moving faster than any other part of it. The same is true of your tires. This camber thrust forces your wheel to turn in response to a lean.



Thus, both the rake geometry and camber thrust conspire to cause a leaning front wheel to become a turn in the direction of the lean. Then, of course, the motorcycle body follows the wheel and it, too, leans in the direction of the turn.

So, now you know what counter-steering is, how it works, and why. What might just now be occurring to you is with all of these forces conspiring to cause the wheel to lean and then turn in the direction you want to go, what stops that wheel from going all the way to a stop every time a little counter-steer is used? And, as I earlier mentioned, how does a pilotless motorcycle automatically right itself?

The answer to both of those questions is centrifugal force and, again, rake geometry. For any given speed and lean combination there is only one diameter of a circle that can be maintained. This is a natural balance point at which gravity is trying to pull the bike down and centrifugal force is trying to stand it up, both with equal results.

If the speed is increased without a corresponding decrease in the diameter of the turn being made, centrifugal force will try to stand the bike more vertically - i.e., decreases the lean angle. This, in turn, decreases the camber thrust and the bike will, of its own accord, increase the diameter of the turn being made.

If the speed had been held constant but the bike attempts to shorten the diameter of the turn beyond that natural balance point then centrifugal forces are greater than gravity and it stands taller, again lengthening the diameter of the turn as described earlier.

Once your bike is stable in a curve (constant speed and constant lean) then it will stay that way until it receives some steering input. i.e., you again use some counter-steering or the road surface changes or the wind changes or you shift your weight in some way or you change speed.

As soon as any form of steering input occurs the stability of the bike is diminished. Momentum, camber forces and rake geometry will then engage in mortal combat with each other which will, eventually, cause the motorcycle to find a way to straighten itself out. That momentum will try to keep the motorcycle going in a straight line is obvious, but it also works with traction in an interesting way. That is, because the front tire's contact patch has traction the momentum of the entire motorcycle is applied to the task of trying to 'scrub' the rubber off that tire. If the body of the motorcycle is aligned with the front tire (only possible if traveling in a straight line) then there is essentially no 'scrubbing' going on. But if the bike is not in perfect alignment with the front tire, then momentum will try to straighten the wheel by pushing against the edge of that contact patch which is on the outside of the curve. As the contact patch touches the ground somewhere near point B, and because that is significantly behind the pivot axis of the front-end (red-dashed line C), the wheel is forced to pivot away from the curve.

I believe you now see why if the bike were to become pilotless it would wildly gyrate for a few moments as all of these conflicting forces battled each other and the bike became stable by seeking a straight path and being vertical. Clever, these motorcycle front-end designers. No?

Understeering

Not The Same As 'Slow Steering'
By James R. Davis

In a previous Tip entitled Counter-steering I spent a lot of time talking about the design of the front-end of your motorcycle in an effort to explain how counter-steering works. One of the concepts I put forward was that of steering 'slowness' caused by having trail. Apparently some of the readers concluded that 'slow' steering was the same as 'under-steer'. Not at all.

Whether the vehicle has two wheels or more, under-steer means that the vehicle's front tire(s) will break away (slide) before the rear tire(s) do during a turn. Over-steer, then, is just the opposite and is a design that tends to result in the vehicle's rear tire(s) breaking away first.

[Despite what I just said above, there is a more formal definition of over-and under-steer that describes how a vehicle behaves in a curve as determined by the slip angles of the front and rear tires. That is, if the slip angle of the rear tire(s) of a vehicle is different than that of the front, the vehicle will rotate from this phenomenon alone. If the rear slip angle is greater than the front, the vehicle is said to over-steer. If less, it under-steers.]

'Under' and 'Over' refers to how the vehicle will track the desired turn when either the front or rear wheel(s) begin to slide. For example, in an OVER-steer situation the rear breaks away first. The vehicle then OVER rotates in the direction of the turn.

You might think that it would be better to have a motorcycle designed and setup so that there is neither over-steer nor under-steer so that you could take a turn as hard as possible without worrying about which tire broke free first. I don't think so. I'm sure you would agree that given a choice you would want your rear tire to slide before the front one. In other words, you WANT a certain 'over-steer' built into the design of your motorcycle. [Over-steering from slip angle differences results in the feeling of a modest drift into a turn. This, to most motorcyclists, is mildly reassuring and preferred to the same modest drift out of a curve that under-steering provides.]

But then you notice that your rear tire has a greater contact patch than does the front (at least when riding vertically.) You might assume that because of this it has a higher Coefficient of Friction with the road than does the front and that this should automatically result in under-steering. Again, not true.

Indeed, the front tire MUST develop more forces than the rear one in order to destabilize the motorcycle and cause it to change direction. (In another article you will find that the rear tire actually STEERS the bike when it is stable. Honest!) Thus, something more is at work than merely the size of the contact patch, the rubber compounds used, tread patterns, and flex of our tires that determine whether a vehicle over- or under-steers. Your front fork system (rake, trail, offset), weight transfer, rear-wheel drive and tire camber also play a part. (There should no longer be a question of why your rear tire has a flatter surface than does the front one - tire camber thrust is not as great.)

In summary:

- Your bike is designed such that it has over-steer (the rear wheel tends to break away before the front one does in a turn, and the slip angle is greater on the rear tire than on the front tire.)
- The rear tire contact patch is wider because the surface is flatter than your front tire and this results in reduced tire camber thrust. Further, part of the rear tire's traction is consumed with acceleration. The result, a tendency to over-steer -particularly when accelerating. (Interestingly, unlike with motorcycles, over-throttle in a curve with most cars tends to cause under-steer.)
- Slow steering is a result of steering geometry and is NOT the same thing as 'under-steer'.