BLOCK 40

Frame Geometry and Bike Stability

I find that when trying to master bike handling, it really helps to understand how frame geometry affects bike stability. As I am a framebuilder with a background in physics, this is a favorite subject of mine, but I think you will be able to understand it, take advantage of it when riding, and impress your friends with some demonstrations.

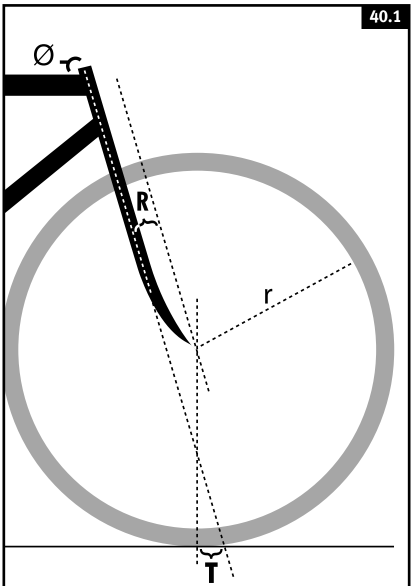
Unlike many other vehicles with stability challenges, a bicycle is not complex. Armed with this brief discussion of the subject, you should be able to corner and descend with more control, as well as choose equipment better and see through the hyperbole of misleading advertising claims. It can also assist you in understanding some of the bike problems encountered by odd-sized riders, particularly short ones.

Defining Terms

In order that we share a common language to describe and understand frame geometry and bike stability, we must define a few terms. You may find it helpful to refer to the Glossary for definition of bike-part terms. Referring to Figure 40.1, note that fork rake, R, is the perpendicular distance (offset) of the center of the front hub from the steering axis. Fork trail, T, is the horizontal distance between the center of the tire contact patch (with the ground) and the intersection of the steering axis with the ground. Head angle, Ø, is the acute angle between the steering axis and the horizontal. The wheel radius is r.

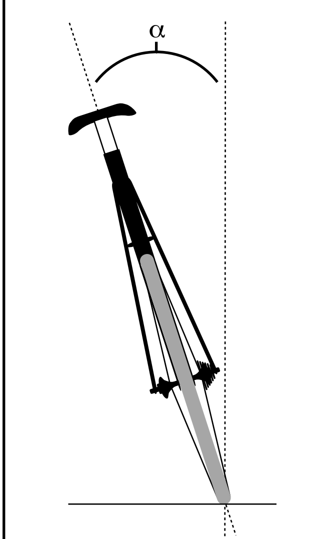
I will begin simply by telling you that the way to increase the stability of a bicycle is to increase T (fork trail). "Wait a second," you say, "there must be more to it than that! What

40.1



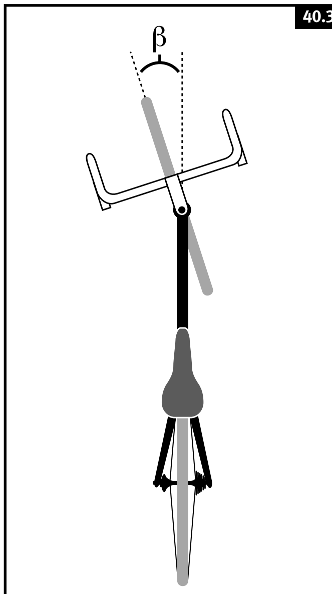
Front end diagram showing geometric dimensions

40.2



Lean angle (α) of the bike out of the vertical plane

40.3



Steering angle (β) of the front wheel out of the plane of the bike about tire width, rider skill, and gyroscopic effect?" While all three of these variables do affect handling, they cannot account for all of the handling characteristics observed when riding a bike, which the fork trail theory can. These other three criteria can work in conjunction with fork trail to increase stability, but they are not indispensable like fork trail is.

Tire Width

If we think that a bike is stable merely because it is a skinny steamroller, we might be in for a shock. I would say that if you made the tires as wide and flat as those on a steamroller, clearly it would be very stable. But in the real world, if you use a wide mountain bike tire with a very square tread profile, you will find that it will still easily tip over onto those knobs' sharp corners, and some other force is required to stabilize the bike. Conversely, you can certainly reduce tire grip by using extremely skinny tires, but you cannot destroy the bicycle's stability that way.

Rider Skill

In their 1948 book, *Advanced Dynamics*, Stephen Timoshenko and D.H. Young theorize that a bike is balanced strictly by the rider, who constantly steers in the direction the bike is falling by a turning radius small enough to generate enough centrifugal force to counteract the fall. Certainly this can explain some of the story, such as how greater speed increases the bicycle's stability and requires less steering correction, since at higher speeds it takes smaller steering corrections to generate enough centrifugal force. It does not, however, explain how a bicycle can stay upright without a rider. We know that a stopped bicycle will fall right over; many of us have marks on our walls and piano to prove it. We also know that if we give a bike a push, it will roll for a while before crashing, and rolling it down a smooth hill will increase the distance it rolls even farther. We also have the sensation that our bicycle is incredibly stable when we're riding fast–a far cry from the feeling we experience when we steer out of a fall.

Gyroscopic Wheels

The gyroscopic effect of the spinning wheels certainly adds to a bike's stability. Hold a wheel in your hand by the axle ends. Tip it from side to side when it is not spinning. Easy, eh? Now try tipping the wheel while it is spinning fast. It is a lot harder to do.

The gyroscopic effect also contributes to what we observe when countersteering (see Block 24). If you push forward on the left end of a spinning wheel's axle, the wheel will tip to the left, as the "right hand rule" of rotational mechanics predicts. Try it!

David E.H. Jones, Ph.D., in his efforts to produce an unrideable bicycle (*Physics Today*, April 1970), mounted on a bicycle a second front wheel parallel to the normal one, but the second wheel did not touch the ground. He could spin it the opposite direction of the normal wheel to cancel the gyroscopic force, or spin it in the same direction to double it. He found that he was able to ride the bike hands-free either way. Rolling along without a rider, the bike remained upright much longer after being pushed with both wheels spinning in the same direction than it did when they were spinning in opposite directions, as one would predict.

Fork Trail

Jones was never able to build a completely unrideable bicycle, which, he said, "by canceling the forces of stability would baffle the most experienced rider." He did, however, produce some bikes that crashed immediately without a rider as well as some that went on and on alone before finally tipping over. We can learn a lot from his experiments.

If you look at the casters of a shopping cart, you will notice that they are held by little forks that have a rake (offset of the hub from the steering axis). The forks flip around backward when you push the cart, and the wheels "trail" the cart. This would seem to be the opposite situation of what you see in a bicycle, where the fork points forward and stays that way when you push the bike forward. Closer inspection reveals something else, though.

The steering-axis angle of the shopping cart casters is vertical (90 degrees), and for the tire contact patch to be behind (to "trail") the steering-axis intersection with the floor, the fork must turn around backward. On a bike, though, you can see from Figure 40.1 that the wheel contact patch trails the steering-axis/ground intercept with the fork pointed forward by virtue of a steering angle quite a bit less than 90 degrees—generally less than 75 degrees.

Thus, the front wheel indeed trails the bicycle, as does the rear wheel. Have any doubts? Try wheeling a bicycle backward by pulling back on the seat. It doesn't work; the front wheel immediately flops to a wide angle. That's because the front wheel is not trailing the bike when the bike is going backward, even though it is behind the bike!

When Jones increased fork trail by turning the fork around backward (by looking at Figure 40.1, notice how a negative fork rake would increase fork trail), the bike became much more stable. Piling weights on the bike's saddle and giving it a push demonstrated this. Even after the bike had slowed down, it wove back and forth, always seeking a position of stability, until it finally ran out of speed and tipped over.

The least-rideable bike that Jones constructed had an enormous amount of fork rake, and it was only a success as "unrideable" in the weighted, riderless configuration, since a rider was always able to counteract its instability and keep it upright. But clearly, the negative fork trail produced by increasing the rake so dramatically (again, refer to Figure 40.1 and envision R as very long to see how trail became negative) eliminated the bicycle's self-righting capabilities with only weights aboard. It crashed immediately when pushed.

Try It Yourself

Any time you have a head angle less than 90 degrees and a finite fork rake, you create an unstable situation where the front wheel and handlebar turn out of the plane of the bike whenever it is leans (Figures 40.2 and 40.3). The handlebar and wheel turn because this allows the frame's height to fall, and the bicycle and rider weight always seek a minimum potential-energy position (see F. R. Whitt and D. G. Wilson's *Bicycling Science*). Notice that the wheel turns into the lean, to get the wheel to roll back under the center of gravity of the bike and rider.

Using simple trigonometry on Figure 40.1, you can see that:

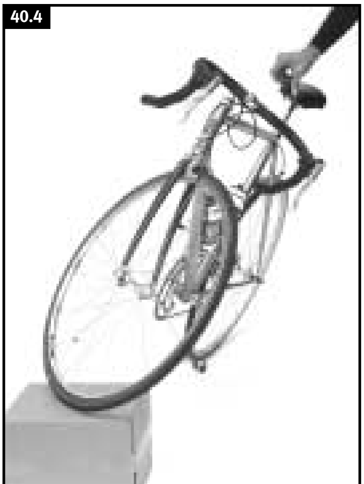
$$R = r\cos\varnothing - T\sin\varnothing \qquad \text{or,} \qquad T = (r\cos\varnothing - R)/\sin\varnothing$$

This second relationship clearly shows what you can see from Figure 40.1, namely that you can increase the trail (and hence the bicycle's stability) by increasing the wheel radius, decreasing the rake, and/or decreasing the head angle.

Using this relationship for the purposes of demonstration, you can increase trail and stability simply by decreasing head angle. You can simulate this with your own bike by stacking cinder blocks and phone books up under the front wheel (see Photo 40.4). Now if you lean the bike, you will see that the front wheel flops over into the turn to a much sharper angle than before, thus enabling the wheel contact patch to get back under the rider's center of gravity more quickly.

Conversely, you can decrease trail and stability simply by increasing head angle. This time, stack cinder blocks and phone books under the rear wheel (see Photo 40.5). Raise the rear of the bike a little at a time, constantly leaning the bike, and see what happens. You will know when your head angle is steep enough (relative to the ground) to make the fork trail negative, because when you lean the bike, the wheel will turn the opposite direction (as in Photo 40.5)—away from the lean! That means whenever you lean over on a bike with negative trail, the front wheel will turn the other way to try to get farther out from under your center of gravity—so you will crash sooner!

40.4



Simulating a very shallow head angle and consequent large fork trail, which imparts great stability: The wheel flops out of the plane of the bike at low lean angles to rapidly get back under the rider's weight and stabilize the rider.

GALEN NATHANSON

40.5

Simulating a very steep head angle to the point of creating negative fork trail and consequent very low stability: When the bike is leaned, the front wheel turns away from the direction of lean to get farther out from under the rider and cause him or her to crash sooner.

GALEN NATHANSON

Analyzing Bikes for Handling

Today's bike market demands that all road bikes come with carbon forks and all mountain bikes come with suspension forks that all have about the same amount of rake. This does not allow the framebuilder to change the head angle and fork rake together. However, the above equation clearly shows that the framebuilder must change both together in order to achieve sufficient fork trail with a small bike for a short rider to get stability and agility without toe overlap of the front wheel (that is, the rider's foot hitting the front tire in a tight turn). Thus, the small rider will generally have to suffer with one of the following:

1. **long top tube**—in order to avoid toe overlap while using a stock fork and a standard head angle.
2. **super stable bike**—due to a very shallow head angle coupled with short fork rake. This is done to avoid toe overlap with a stock fork while offering the rider a short top tube. The bike becomes so stable that it is hard to get it to turn, and the front wheel snakes out ahead of the rider when standing out of the saddle.
3. **toe overlap**—in order to offer a short top tube, stock fork, and standard head angle.

Any of these situations can be uncomfortable or dangerous. To fit small riders with a stable bike and no toe overlap, either use a custom fork with more rake, or smaller wheels and geometry adjusted to offer large enough fork trail for stability.

It is also clear, once you understand fork trail, why it is so hard for little kids to learn how to ride without training wheels. It should be obvious by now that the stability would be very low (that is, the fork trail—the lever that rights the bike—is very small) of a bike with little wheels and a very curved fork (small wheel r, large R). I am mostly talking about little pink bikes made for girls; the straight forks with low offset on mini-BMX bikes are a big improvement.

On the other hand, it is interesting to see that many of these concepts of trail were also well understood at some level for most of last century. For instance, bikes used on the track in derny (motorcycle)-paced events have a small front wheel (to get closer to the motorcycle) coupled with a bent-back fork (negative rake) to increase trail and stability. This is not done on road bikes, because they become too stable to be steered—you want to push the bike toward instability for it to be maneuverable. But on a track at 60mph behind a motorcycle, the banking does the cornering for you and you want the stability!