Weight Transfer

What is it, why does it happen, and why should you care?
By James R. Davis

When you change speed (accelerate or decelerate) the weight of your motorcycle (including you) shifts in such a way as to put more or less load on your tires. You do not have to weigh the load on your tires to know this with certainty because you can see it happen by observing your front-end 'dive' when you brake.

Traction is proportional to the weight carried by your tires. Thus, when you brake your front tire gains traction while the rear one loses it. Clearly losing too much traction is dangerous since the result is that your tire will slide.

Despite what you may think, weight transfer can be controlled beyond simply adjusting your acceleration and braking rates. That is, how fast you change speeds is not the only thing that determines weight transfer. Surely you would be interested in minimizing the odds of losing traction during a panic stop? Read on...

Braking Transfers

Ignoring wind resistance, essentially all the forces that try to slow you down when you apply your brakes are at ground level. That is, at the contact patches of your tires. On the other hand, the inertia of your bike works not at ground level, but directly thru its center of gravity (CG.) Since the CG is higher than ground level the resulting net force translates into a torque. In other words, braking does not simply shift weight forward, it tries to shift it down in the front and up in the rear.

The higher the CG is, the greater the torque. (If the CG was at ground level the torque would be zero.) On the other hand, the longer your wheelbase is, the lesser the torque. This is just another way of saying that the amount of weight transfer resulting from a change in speed is a function of the ratio of the height of the CG to the length of the wheelbase.

Gravity is a force. At ground level gravity tries to make you fall with acceleration at the rate of about 32.1 feet per second per second (henceforth shown as fps/sec.) This acceleration is called '1 g.'

'Weight' is just another word for gravity. Like inertia, gravity works directly thru the CG of an object.

When we brake we apply force which we will simply call a braking force. Braking is nothing more than a negative acceleration. Thus, when the total braking force is such that your bike's forward speed is being reduced at the rate of approximately 32.1 fps/sec, you are decelerating at the rate of 1 g. That is, your braking force then equals the weight of the motorcycle (including the rider.) If your motorcycle weights 1,000 pounds, then braking at 1 g means you are applying 1,000 pounds of braking force.

You can calculate the amount of weight transfer involved in any stop knowing only the braking force being used and the ratio of CG height to wheelbase length. For example, if the total braking force is 1,000 pounds, your CG is 20 inches off the ground, and your wheelbase is 63.4 inches long:

> Wt.Transfer = Braking Force times CG ratio
> Wt.Transfer = 1000 lbs. * 20/63.4
> Wt.Transfer = 1000 lbs. * .3155
> Wt.Transfer = 315.5 lbs.

[We are here discounting entirely the effects caused by tire distortion and suspension compression. Not because these are not important, but because they are of secondary importance to an understanding of these principals.]

Now, just because the bike weighs 1,000 pounds and is sitting on two wheels does not mean that at rest there are 500 pounds on each wheel. Here again we need to know something about the bike's CG. Only if the CG is exactly in the middle of the bike (between contact patches) will the weight be evenly distributed. If the CG is closer to the front wheel than the rear one, for example, then there will be more weight on the front tire than on the rear when the bike is at rest (not moving.) Further, unless there is an upward or downward movement of the bike, the sum of the weight carried by the front and rear tires must equal the total weight of the motorcycle and rider.

Let us assume that at rest the weight is evenly distributed. Then we now know that while braking at 1 g, because of weight transfer, there will be 815.5 lbs. (500 + 315.5) on the front tire and only 184.5 lbs. (500 - 315.5) on the rear tire. Because traction is a function of weight carried by a tire it is clear that there is not a lot of traction left on the rear tire at this time.

Let us look very carefully at what this weight transfer example is showing us. You have heard that you have about 70% of your stopping power in the front brake. This example shows that we have applied 1,000 lbs. of braking power to the tires of the bike. If it was ALL the result of using only the front brake, then we have wasted what traction is still available to us from the rear tire and, worse, we have locked our front tire and started a skid! This, because virtually all standard tires lose their 'sticktion' (stick/friction) when confronted with more than about 1.1 g of braking force. With 815.5 lbs. on the front tire it could with reasonable confidence handle a braking force of 897 lbs. (1.1 * 815.5), yet we applied 1,000 lbs. to it. At least in this case our front brakes could deliver nearly 90% of our stopping power, not just 70% - but not 100%, either.

Now let us look at what would happen if the CG happened to be 30 inches high rather than 20:

> Wt.Transfer = Braking Force times CG ratio
> Wt.Transfer = 1000 lbs. * 30/63.4
> Wt.Transfer = 1000 lbs. * .4732
> Wt.Transfer = 473.2 lbs.

The front tire would have 973.2 lbs. of weight on it and the rear would have only 26.8 lbs. This is close to doing a 'stoppie'!!!

What we are beginning to see is that if the CG gets to a height of 1/2 of the length of the wheelbase we can expect to do a 'stoppie' if we use 1 g of braking force. Further, if we use even the slightest amount of rear brake in such a configuration when we are slowing at the rate of 1 g, we can expect to lock the rear wheel.

One more example - we will attempt a 1.1 g stop with this 'higher' bike:

> Wt.Transfer = Braking Force times CG ratio
> Wt.Transfer = 1100 lbs. * 30/63.4
> Wt.Transfer = 1100 lbs. * .4732
> Wt.Transfer = 520.5 lbs.

At this point we have transferred MORE than the entire weight which had been on the rear wheel - we have left the rear wheel with NEGATIVE 20.5 lbs. on it. i.e., our rear wheel has been lifted off the ground!!!!

Notice, please, that the CG does NOT remain at a constant height during aggressive braking. If we use exclusively front brake, then the front-end will dive and the rear-end will lift. This could result in the CG remaining at the same height, but more likely it will get higher. We have already seen that a higher CG means more weight transfer. Further, as the front-end dives the result of the compression of the front shocks is a shortening of the wheelbase of the bike. This, like raising the CG, results in a higher CG to wheelbase ratio, and therefore more weight transfer. [As an aside, if your bike has an anti-dive feature (TRAC, for example) then MORE weight transfer occurs to the front wheel than without it. This, because the CG is held higher. In other words, anti-dive INCREASES the odds of sliding your rear tire!]

If only the rear brake is used there will be a weight transfer to the front tire which will tend to compress the shocks. Additionally, however, use of the rear brake tends to LOWER the rear-end of your motorcycle and lengthens its wheelbase, (the swing arm become more level). The net effect is to lower the CG of the bike. This offsets neatly the fact that the compressing front-end shortens the wheelbase at the same time. However, since there is a weight transfer, the rear-end gets lighter while braking which quickly limits how much braking power you can apply before you skid that tire. In other words, you must use the front brake for maximum stopping power.

From the above discussion I think you can now see that the use of your rear brake along with the front brake leads to less weight transfer than if you use only the front brake, and why the use of both at the same time always results in maximum stopping power.

When a rider mounts his motorcycle he both raises the CG and moves it towards the rear. The heavier the rider, the more significant these changes to the CG are. We already know that as the CG rises it causes more weight transfer during speed changes. This raising of the CG is far more significant than is its shift towards the rear. (This, because the height of the CG is small compared to the length of the wheelbase.)

What this adds up to is that the heavier the driver of the motorcycle, the easier it is for braking to cause a breakaway of the rear-end. Is there anything that can be done to mitigate this potentially deadly problem? You bet! In a panic stop the driver should bend from the hip and elbows and lean forward! This will cause the CG to lower and move forward. A lower CG is more significant than its slight movement forward. In summary, there will be less weight transfer with him leaning forward than if he was sitting straight up in the saddle, there will be less compression of the front shocks, and less shortening of the wheelbase. i.e., less likelihood of losing rear-end traction.

Anything else? Yep. Always pack your saddlebags with heavy items towards the bottom. Every pound below the CG lowers it, every pound above it raises it.

Accelerating Transfers - Straight Line

This article has so far focused only on weight transfer associated with braking. It should be obvious that exactly the same phenomenon happens when you accelerate - the amount of weight transferred is determined by your rate of acceleration and the CG ratio (height of CG divided by length of wheelbase.) Though you may not believe that you have an 'anti-dive' component for your rear wheel like you may in the front, you do. The rear wheel does not push the frame forward directly. It pushes its 'swing arm' forward. Since the swing arm pivots on the frame aft of your CG, and since that pivot is almost invariably higher than where the swing arm attaches to the rear wheel, any accelerating force applied thru the rear wheel tries to lift the frame of the motorcycle. i.e., rather than calling this an 'anti-dive', think of it as an 'anti-squat'. This keeps the CG higher than it would be otherwise and the result is that there is greater weight transfer to the rear tire (and correspondingly higher traction results.)

Accelerating Transfers - In A Curve Constant Speed

And what about weight transfers when you are in a curve? You have heard the terms 'over-steer' and 'under-steer' before, I'm sure. Over-steer means that when you are in a curve your rear wheel is more likely than the front one to lose traction (ie, your sliding bike will end up pointing towards the inside of the curve.) while under-steer is the opposite. Weight transfer to the rear tire from acceleration leads to over-steer (greater slip angle on rear tire) while braking in a curve, because of weight transfer to the front, leads to under-steer (greater slip angle on front tire.) Both are deadly concerns if you push tire loads to their limits!! (On the other hand, if you have a choice you would almost certainly want a little over-steer rather than under-steer because a brief slide of the rear tire is easier to correct than a similarly brief slide of the front tire.)

It would be a deadly mistake to try to use the kind of weight transfer analysis we have discussed so far in an effort to learn how much acceleration to use while in a curve to equalize tire loads! (I now assume that you have read and understand the article entitled 'Delta V'.) The weight transfer calculations we have been looking at so far deal with consequences of longitudinal acceleration. In a curve you are also subject, even if maintaining constant speed, to centripetal acceleration.

Unlike longitudinal acceleration (changing your speed), which changes your tire loading in a simple proportion to the CG ratio, centripetal acceleration increases tire load in proportion to the SQUARE of your change in speed. The formula to determine these forces is:

Force = Mass times Velocity squared divided by Radius F = M*V^2/R

You can assume that most street tires will lose traction when they are subjected to about 1.1 g of force. So how do you tell whether you are close to 1.1 g when in a turn? Simple. If your effective lean angle is 45 degrees, you are experiencing 1 g of centripetal force. And, from the formula above you see that the force is extremely sensitive to velocity. This means that a very minor increase in speed could easily push you past the 1.1 g limit.

What you should understand from this is that using acceleration (speed change) to balance tire loads while in a curve is foolish. (In general, however, you will want some (minor!!!) acceleration in a curve as this tends to increase the slip angle of the rear tire which increases traction, and because you want your rear-end suspension modestly loaded to enhance control.)

Now you know why you want to be sure the load distribution on your bike is set properly BEFORE you hit the road.

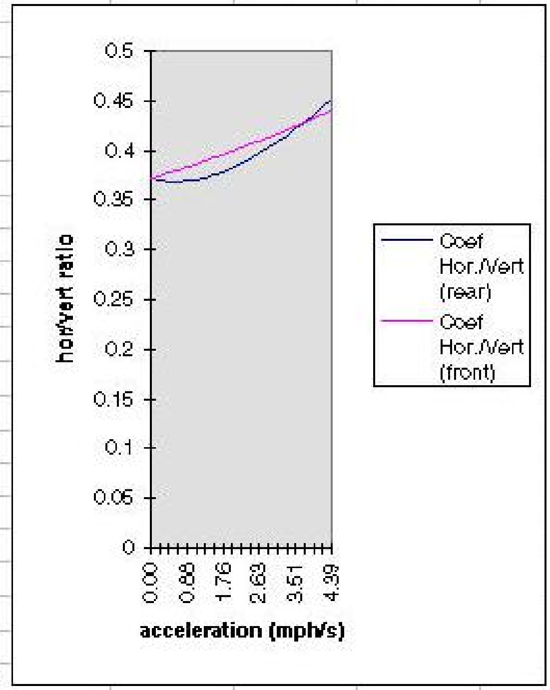
Accelerating Transfers - In A Curve Exiting The Curve

While a modestly increasing speed makes great sense while you are riding thru most of a curve, it is understood that some people find great pleasure in rolling-on their throttle as they exit those curves.

Just a little thought, based on all that we have talked about so far, should now convince you that you must be conservative in this practice while you are leaned over hard, and that you need to be BOTH widening the curve and standing the bike taller as you do it.

Rather see the effects of weight transfer instead of doing the calculations? If you have Excel on your system then just take a look at this spreadsheet/model. With it you can modify any of the inputs shown and observe the effect of the changes. Below is a sample screen displayed while using the model.

	US units		Metric			
All-up weight	1050	lbs	475.7	kg		
			4666	Newton		
Wheelbase	67	in	1702	mm		
CG % (rear weight bias)	60%		60%			
CG height	21	in	533.4	mm		
Static vertical loads						
Rear	630	lbs	2800	Newton		
Front	420	lbs	1866	Newton		
Turn conditions						
Speed	50	mph	22	m/s	80	km/h
Curve radius	450	ft	137.2	m		
Lateral acceleration	12	ft/s^2	3.64	m/s^2	0.37	g
Lean angle	20	degrees	0.36	radian		
Lateral force on rear wheel	234	lbs	1039	Newton		
Lateral force on front wheel	156	lbs	693	Newton		
					lean angle	
Cells with a border outline are the input data						
See sheet 2 for calcs of horizontal/vertical force ratios as a function of acceleration						



example shows a heavily loaded motorcycle weighing 1,050 pounds having a Center of Gravity closer to the rear wheel of the bike than the front which is traveling in a curve with a radius of 450 feet with a speed of 50 MPH. The information in the spreadsheet assumes constant speed.

The chart to the right shows lateral (sideways) force divided by vertical force (load) for each wheel as a function of acceleration. At zero acceleration the ratio is .37 and, you will note, is lateral acceleration (i.e., it is .37 g). Notice that the effect of acceleration is radically different between the front and rear tires.

In the case of the front tire, acceleration merely reduces loading because of weight transfer. Thus, traction is diminishing in proportion to that acceleration (i.e., traction is a function of the types of material that are being pressed together and the force pressing them together - since the load is diminishing due to weight transfer, so is traction.)

The effect of acceleration on the rear tire is quite different, however. You would correctly assume that weight transfer resulting from acceleration would increase traction on the rear tire. It does, during modest acceleration. But acceleration (increasing speed) is accomplished using the rear tire only. That is, there is no longitudinal acceleration affecting the traction of the front tire, just the rear one. Longitudinal acceleration and lateral acceleration are vectored, which means the resulting acceleration force is the square root of the sum of the squares of those forces. (In other words, more than either of them, but not as much as both.) As the rate of acceleration increases it quickly overwhelms the effect of increasing load on the tire (which increases traction) and begins to CONSUME THAT TRACTION FASTER THAN IT IS BEING ADDED. This is shown in the curved line in the chart.

So what do the lines ultimately show? If you assume that the coefficient of friction for your tires is approximately 1.1, then when either line reaches 1.1 on the chart that tire will lose traction and skid! The higher the line, the closer to a skid (i.e., the less traction is left.) If you increase speed or decrease the radius of your turn, your lean angle will get larger. When your lean angle gets to 45 degrees, the lines will start at 1.0 and even a slight acceleration will push the lines over 1.1 - which means you will soon be exploring the joys of road rash.

In summary, there are a few obvious reasons to care about weight transfer:

- Traction is directly proportional to the amount of weight carried by a tire -managing weight transfer is managing traction.

- Misloading your motorcycle can result in substantial handling problems -particularly in a curve.In order to manage weight transfer intelligently you need to have a good idea of where the center of gravity of your bike is and what happens to it when you add a passenger or luggage.
- Traction will probably be lost if tire load exceeds about 1.1 g. If you are in a curve and are leaning at 45 degrees, you already have 1.0 g tire loads. Enough is enough.
- Stopping with your elbows locked guarantees more weight transfer and a higher center of gravity - both undesirable from a control point of view.
- Rolling-OFF your throttle (or braking) if you are 'hot' in a curve is almost certainly more dangerous than simply leaning farther into the curve - because weight transfer will unload the rear-end which reduces rear tire traction.
- Under-steer and Over-steer both yield slides when load limits are reached -balancing the weight reduces the risk.

Delta V

Affects all motorcycles, not just 'crotch rockets' By James R. Davis

Following are two facts:

- Assuming that your speed remains constant while in a turn, you are accelerating constantly.
- Assuming you maintain the same speed in a turn as you had while riding in a straight line, your gasoline mileage goes down.

Though these facts do not appear to be true, they are. And if you will bear with me through a brief bit of physics you will learn why it is important to understand them.

Speed does not equal velocity. Speed is merely a measure of how fast you are moving. Velocity, however, is speed in a particular direction. Changing either speed or direction, therefore, changes velocity. Finally, the definition of 'acceleration' is changing velocity.

[Changing velocity, as any watcher of NASA activities knows, is called 'Delta V'.]

So? This is not some subtle play on words. There really is a significant difference between changing speed and changing velocity.

We all know that there is a limit to how much traction you can consume before you break loose a tire. We know that acceleration and braking (deceleration) eat up traction. It is important to understand that you do not have to roll-on your throttle to be accelerating! By changing direction you are definitionally changing velocity (Delta V) even if you maintain speed.

That means *you are consuming traction simply by being in a curve*. To make this crystal clear, when you apply any force to any mass you change its velocity (i.e., you accelerate it.) When you are in a curve you know that there is a force involved that is not there when you travel in a straight line - centrifugal. [Actually, the new force is centripetal. Centrifugal is only an apparent force.] Anyway, you can feel that force, you know it doesn't come from out of nowhere, and you know it is not 'free.' When you roll-on your throttle when traveling in a straight line, your head is forced backwards and you experience acceleration. In a car, if you maintain speed but travel in a circle, your head is pushed towards the outside. (i.e., you experience centrifugal force.) On a motorcycle, because you lean in a curve, even if you maintain a steady speed, you feel heavier. That is, you experience acceleration (called 'centripetal acceleration'.) If you have Excel on your system you may wish to click this link in order to access a model that shows this pretty clearly.

So, now you know that centrifugal force demonstrates acceleration.

Going back to 'Delta V' - if you acknowledge that acceleration IS changing velocity, then it follows that more energy is consumed (gasoline burned) in a curve than when riding in a straight line, even if both rides are at the same speed. [Note, however, that more energy is not actually being 'consumed'. Rather, more of it is being converted to heat, and your tires are getting warmer as a result.]

Again, so?

It is not an academic insight. If you generate more energy with your engine to maintain your speed while in a curve, then that energy MUST be consuming traction. [This, thanks to the law of 'conservation of energy'.] In other words, confirmation that you should think twice before aggressively rolling your throttle ON or OFF while in a curve.

[Just for a complete understanding, and so you do not think I pulled a fast one here, there is yet another reason why your gasoline mileage goes down if you maintain the same speed in a curve as when you drive in a straight line: You are riding on a part of the tire that has a smaller diameter while in a curve. Thus, the wheel has to make more revolutions in order to travel the same distance. That means, of course, that the engine must turn faster in order to maintain the same real speed. The speedometer will read high while riding in a curve.]