Why does a motorcycle sit up and run straight under heavy front braking?

This article, which is in two parts, explains why:

- **Part A:** This gives a non-technical description of what happens;

- **Part B:** This gives a more technical description of what happens, and why it happens.

Those interested in 'what happens' should read Part A; and those who want to know 'why' it happens should also read Part B.

Part A:

In this article I want to explore why a motorcycle leaning over in a bend sits abruptly upright and runs straight, if the front brake is applied hard.

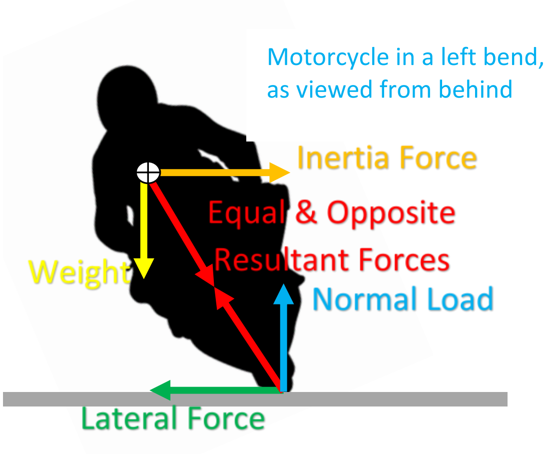
The 'white' curved paths show where the bikes go if cornered correctly. The 'yellow' straight paths show where they go if the rider applies the front brake, hard, whilst in the bends.

Correct application of SYSTEM allows the Rider to approach the bend at an appropriate speed determined by analysis of the Limit Point and application of the Safe Stopping Rule. (I.E. the Rider asks the question: *'can I stop in the distance I can see to be clear, whilst staying on my own side of the road?'*)

Very firm and sharp application of the front brake with the bike leaning off the vertical, is probably a 'knee-jerk reaction' to reduce speed quickly, for whatever reason.

It could be that on approach to a bend, the Rider fails to notice that the radius reduces as the bike runs deeper into the bend, making it sharper than at first anticipated.
Or it could be that the Rider has entered a double bend, or a series of bends, only to find that the second or subsequent bend is sharper than anticipated; whatever the reason, heavy front braking with the bike leaning off the vertical is probably the worst possible response, because the motorcycle ***immediately*** sits upright and runs straight, tangential to the intended path through the bend.

In a left bend on a UK road, the motorcycle is likely to cross to the centre of the road into oncoming traffic; and in a right bend, it is likely to run off the road into a nearside hazard, such as a wall or a tree: in either case, the end result can be serious!
So, why do motorcycles behave in this way?

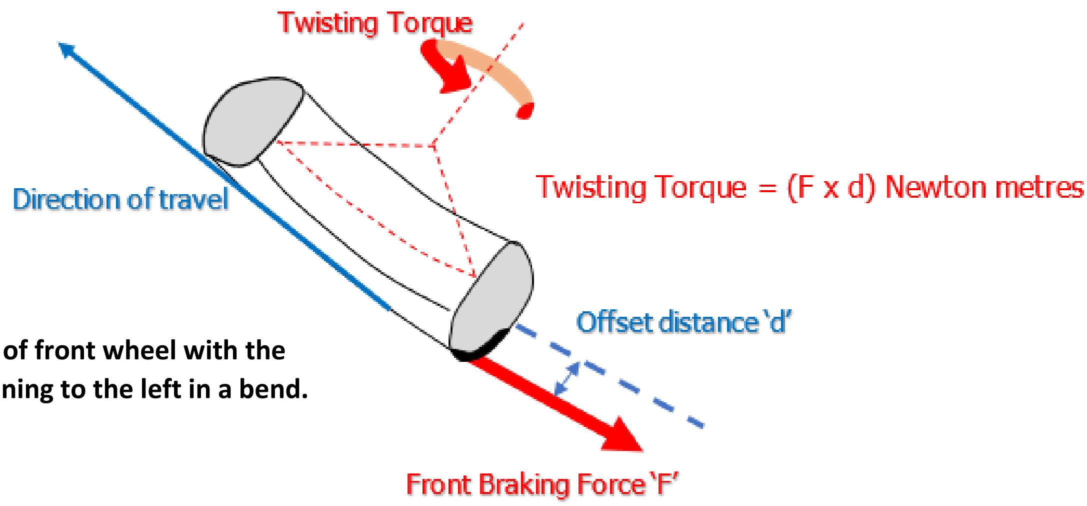


Consider the Stable State

Before considering why the motorcycle becomes unstable, let's consider the stable state when in a bend, as shown in the diagram to the right. The Normal Load on each tyre is a force equal in size, but opposite in direction to the portion of the Weight supported by the tyre: as such, the sum of the Normal Loads on the front and back tyres is equal to the Weight of the bike and rider. The Lateral Force acting on the tyre is shown by the 'green arrow'. 'Lateral' means acting at right angles to the wheel's direction of travel. This Lateral Force is the main component of the Friction Force (or 'grip') that prevents the tyre slipping out from under the bike; Lateral Force is therefore necessary to ensure stability in a bend. The bike leans into the bend until the Weight, which acts vertically down and the *Inertia Force, which acts laterally away from the centre of the turn, add together to produce a 'Resultant Force' (the downward pointing 'red arrow') that acts through the 'Roll Axis', which is the line joining the front and rear contact patches. At this point the bike achieves 'Dynamic Balance' in the bend and the Camber Angle (I.E. the lean angle off the vertical) remains steady, with the Normal Load and Lateral Force also adding together to provide the Newton's Third Law equal and opposite Resultant Force to that produced by the Weight and the Inertia Force, as shown by the upward pointing 'red arrow'. It should be noted that the Torques generated by these Forces are not the only ones acting on the bike; there is the Yaw Gyroscopic Moment, which is trying to keep the bike upright and the Twisting Moment, as a result of opposing Sheer Stresses on the Contact Patch, trying to make it lean more. Dynamic Balance is achieved when the various Torques balance out and the bike achieves a steady Camber Angle.

*Inertia is that property of a body that 'opposes any change in its state of rest or uniform motion'. In other words, Inertia resists any attempt to get a stationary mass moving and to stop a moving mass, once it gets going. The Mass of a body ***also*** opposes any change in its state of rest or uniform motion: Inertia is therefore Mass by another name. Inertia will always oppose any acceleration acting on a body and in accordance with Newton's Second Law the size of the resisting force it produces is equal to the Mass of the body multiplied by the Acceleration acting on it. Although Inertia per se is NOT a force, the 'Inertia Force' is the product of Inertia times the associated Acceleration. In the diagram above, the 'Inertia Force' opposes the Centripetal Acceleration, which points towards the centre of the bend, hence this 'Inertia Force' points away from the centre of the bend.

The Unstable State



Section of front wheel with the bike leaning to the left in a bend.

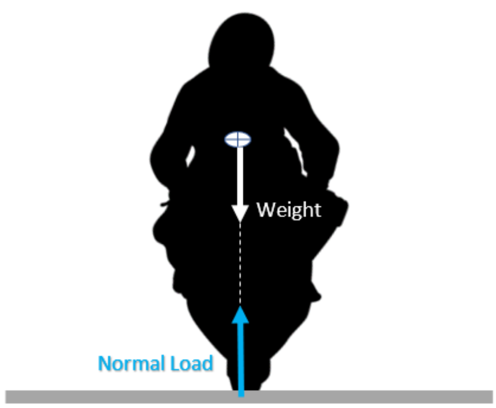
The diagram above shows a section of the front tyre, with the bike in a left bend.
If the rider brakes heavily with the front brake, the Braking Force 'F' Newtons, is applied to the left of the centre line of the tyre, by the offset distance 'd' metres. The Braking Force generates a Torque (F x d) Newton metres, which sharply twists the wheel to the left, trying to force it to turn around a smaller diameter circle. We know from experience that if you push away on the right handlebar end, the front wheel turns to the left, but the bike instantaneously turns to the right: we call this Positive Steering.
The Braking Torque (F x d) has the same effect as pushing away on the right handlebar end, however it has a far bigger and more aggressive effect than the Torque applied to the steering head by the gentle push used when Positive Steering. The bike instantly and aggressively reacts to the Braking Torque and tries to turn right. To achieve this, it must roll from left to right, through the upright position, ***but it never gets beyond the upright.***

Why is this?

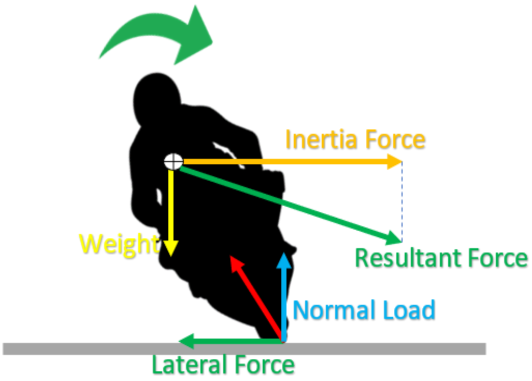
As the bike sits up, the point of application of the Braking Force moves to the centre of the Contact Patch reducing the offset distance 'd' to zero, which in turn reduces the Twisting Torque to zero.

I.E. (F x 0) = 0.

Without the Twisting Torque, the bike no longer tries to turn and roll to the right, so it stays in the upright position and runs straight.



At the same time, the Braking Force generates a big increase in the Inertia Force, which also makes the bike roll to the right into the upright position. I.E. the Braking Force generates the Twisting Torque, which turns the front wheel onto a tighter radius turn. This produces a big increase in both the Centripetal Acceleration pointing to the centre of the turn and the opposing Inertia Force pointing in the opposite direction away from the centre of the turn.



The net result is that the bike sits up and runs straight under the action of heavy front braking in a bend.

If you would like to follow a slightly more detailed analysis of why a bike sits up under heavy front braking, read **Part B** of this article below.

Part B

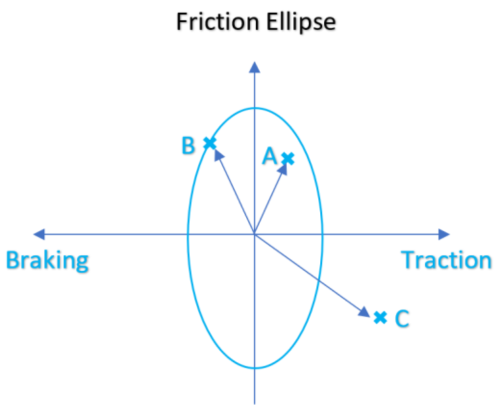
A slightly deeper insight into the reason for a bike sitting up under the action of the front brake when in a bend, can be obtained by considering the **Friction Ellipse**.

The edge of the Friction Ellipse traces out the Maximum Friction available at a Contact Patch and this depends on the tyre material; the nature of the road surface and the Normal Load on the tyre.

$$\boldsymbol{Friction} = \boldsymbol{\mu} \times \boldsymbol{Normal\ Load}$$

Where μ is the 'Coefficient of Friction'.

The **Friction Ellipse** therefore encloses all events that can be met by the Maximum Friction available between a tyre and the road surface. Events include braking, acceleration and steering, or any combination of the three, as they all have a demand for friction.

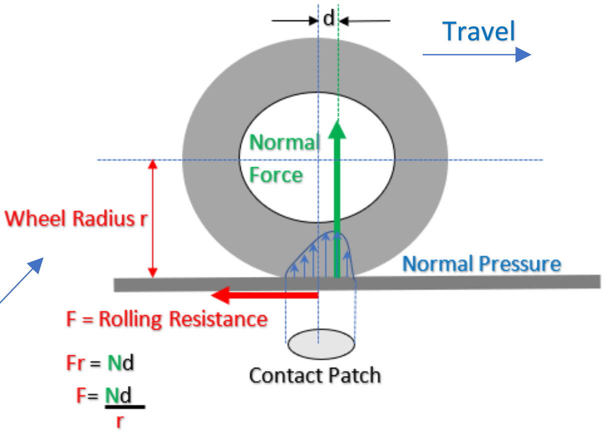


Point A is well within the Ellipse, therefore the events demanding this amount of friction can be met and the bike is stable. (I.E. skidding will not occur).

Point B is right on the limit of available friction. Events demanding this amount of friction can be met, but only just and any increase demand will result in skidding. Racers will frequently be near the limits of available friction for their machines.

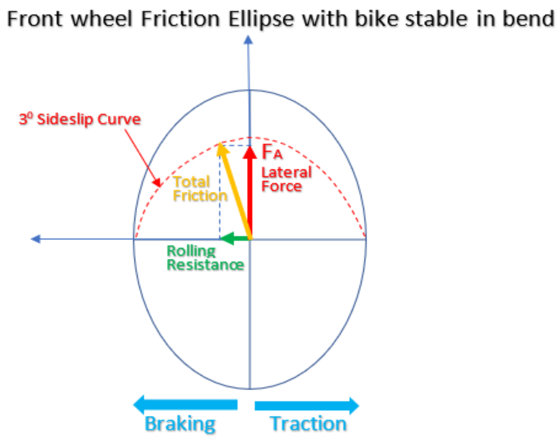
Point C indicates events that demand more friction than the tyres can provide. A rider with this demand for friction is in a serious situation, as the tyres have lost grip and the bike is out of control: oops!!!!

By convention, the horizontal axis of the Friction Ellipse shows forces acting in line with the bike's direction of travel, referred to as ***Longitudinal Forces***; they include the Driving Thrust, which only acts on the rear Contact Patch producing Traction; the Braking Forces, which act on either or both Contact Patches depending on which brake is applied and Rolling Resistance, which also acts on both Contact Patches.



Normal Load (N) is applied slightly forward of the point of contact of the wheel with the road surface (d), owing to the air pressure wave set up within the tyre, and this generates a small Torque opposing rotation. This Torque (Nd) is cancelled out by an equal and opposite Torque generated by the Rolling Resistance Force (F) multiplied by the radius (r) of the wheel: as shown in the diagram above, allowing us to determine the size of the Rolling resistance from the formula: $F_{Rolling\ Resistance} = \frac{Nd}{r}$

The Driving Thrust is shown on the Friction Ellipse as 'Traction', acting to the right, whereas actual Braking Forces and Rolling Resistance are collectively shown as 'Braking Forces', acting to the left. These directions are purely arbitrary with no correlation to the bike's direction of travel; the important point is that they are shown to act in ***opposite directions*** to each other.

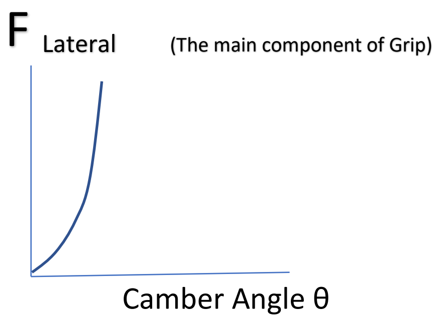


The Vertical Axis of the Friction Ellipse conventionally shows forces acting at right angles to the direction of travel and are referred to as ***Lateral Forces***. They include Camber Thrust, which is a force generated by the 'springiness' of the tyre when the bike leans into a turn and the tyre compound is scrunched up; it then acts like a compressed 'spring', pushing back against the road surface. Lateral Force on the Contact Patch is also produced by friction, when the tyre tries to 'slip sideways' across the surface of the road towards the outside of a bend. This Lateral Force increases in proportion with the lean angle, I.E. the Camber Angle, as shown by the formula:

$$F_{Lateral} = N \times Tan\theta$$

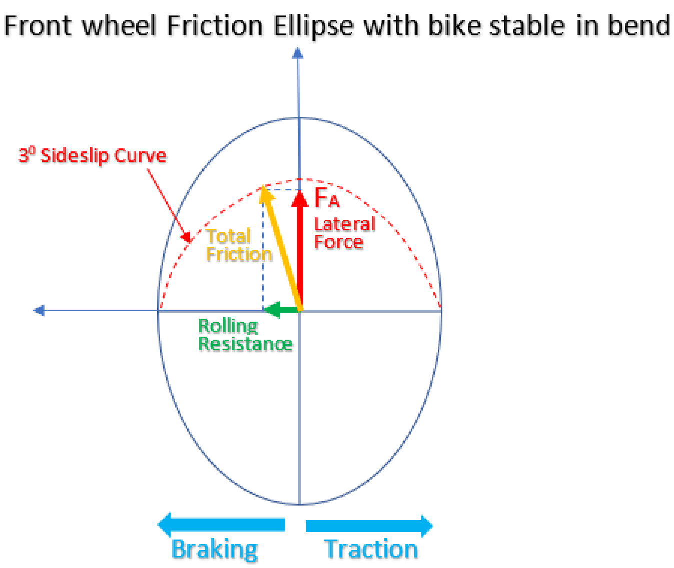
N is the Normal Load on the Contact Patch and θ is the Camber Angle.

The function Tan θ approaches infinity as θ approaches 90^0 but clearly the tyres cannot have 'infinite grip'! ***Grip therefore increases with Camber Angle, but only up to a point;*** if the Camber Angle increases above that point (which depends on the tyre construction and the road surface quality) the Contact Patch lets go and the bike slides from under the Rider.

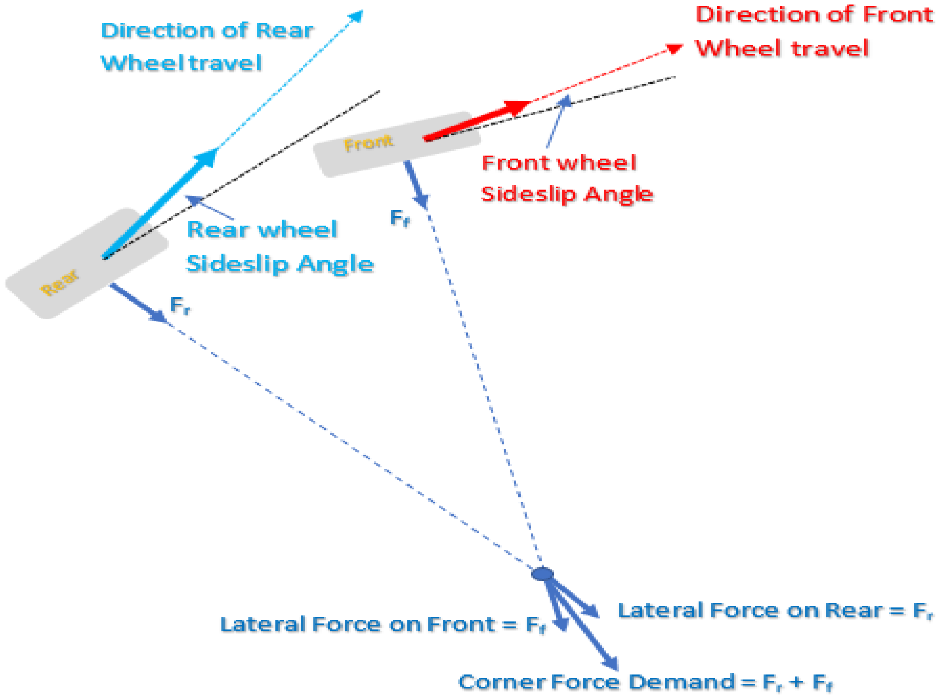


Racing motorcycles can lean about 50^0 - 60^0. Road going machines will not achieve such large Camber Angles, although 45^0 or more is not unusual for a Sports Bike with good tyres on a good road surface.

Here again is the Friction Ellipse for the Front Contact Patch. Note that there is no Driving Thrust, as this is only applied at the Rear Patch, however, there is Rolling Resistance on the front wheel, shown in the 'Braking' direction, as it opposes motion. The Lateral Force (F_A), when added to the Rolling Resistance, gives the Total Friction Force acting on the Contact Patch. This total Friction Force demand lies within the area of the Friction Ellipse and as such, the demand can be met by the available Friction at the Contact Patch and the bike is stable in Dynamic Balance. Take another look at the Friction Ellipse and you will see a 'red curve' which is the 3^0 Side Slip Curve for the front wheel; so, let's see the significance of this.



Plan view of motorcycle wheels in a right bend

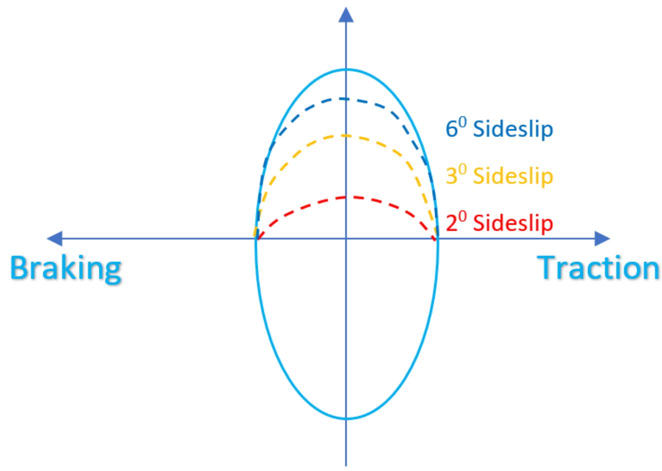


Both the front and rear wheels of a motorcycle slip sideways in a bend; the bike is effectively understeering in a controlled way. Each wheel usually slips by a different amount, referred to as the Rear Wheel Sideslip Angle and the Front Wheel Sideslip Angle.

It is the action of the tyres 'slipping' sideways across the road surface, that is responsible for the Lateral Force, which in turn is essential for Dynamic Balance in a bend. I.E. it stops the bike falling over!

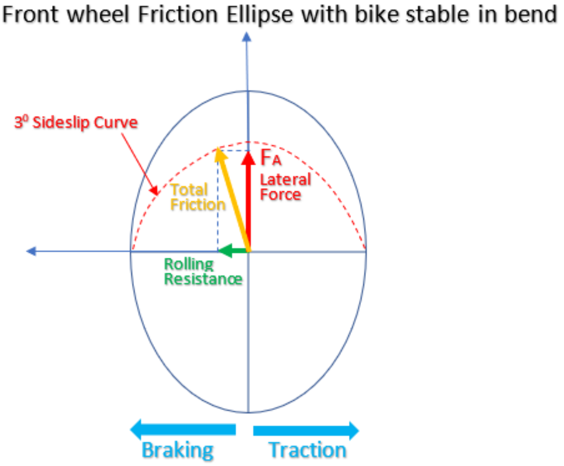
This Friction Ellipse shows just how much Friction is generated for Sideslip Angles of 2^0; 3^0 and 6^0.
The greater the Sideslip Angle, the greater the amount of Friction demanded to prevent the tyre from slipping out from under the bike as it leans into the bend.

Friction Ellipse



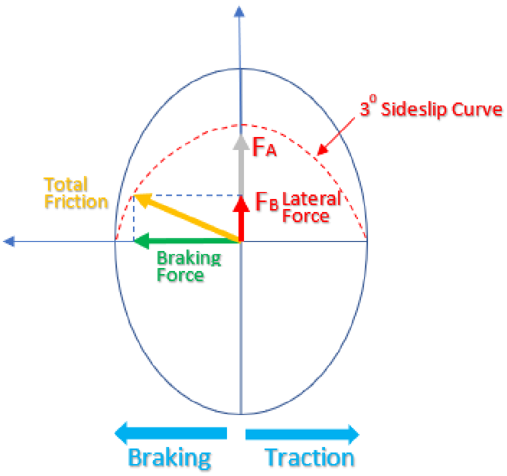
Let's see how the Friction Ellipse can be used to explain why the motorcycle sits up and runs straight, when the front brake is applied in a bend.
Assume the Sideslip Angle of the front wheel is 3^0, as shown in the diagram to the right.
Before the Rider applies the front brake, the motorcycle is in Dynamic Balance with the Total Friction demand lying on the 3^0 Sideslip Angle curve, well within the area of the Friction Ellipse.

Front wheel Friction Ellipse with bike stable in bend



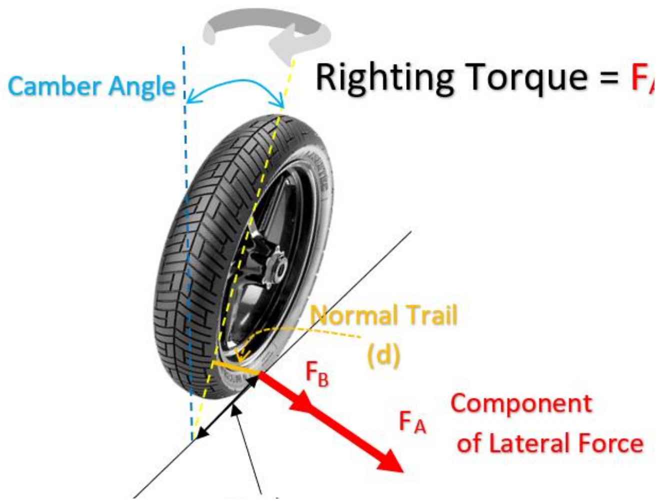
Now consider what happens when the front brake is applied hard! The front wheel initially retains the 3^0 Sideslip Angle and as such, the allowable values for Total Friction lie somewhere along the arc of the red dotted curve. For Dynamic Balance, the front wheel ***only needs*** Lateral Force F_B which is ***far less*** than the actual Lateral Force F_A acting on the Contact Patch at that instant. The Lateral Force is now far in excess of that required for Dynamic Balance and this excessive

Front wheel Friction Ellipse with heavy Front Braking



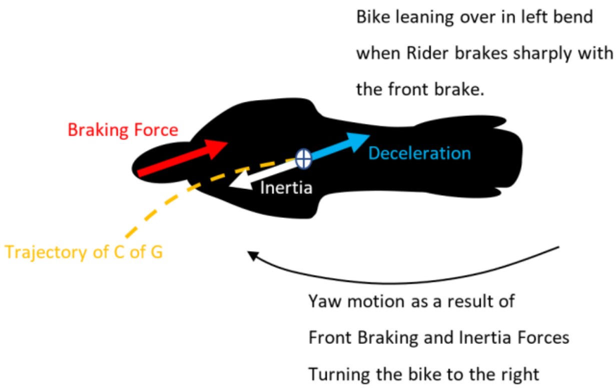
Force acts over the 'lever distance' of the Normal Trail, to produce a massive righting Torque, which drives the bike upright. In doing so, the Camber Angle (θ) is reduced and this results in a proportional reduction in the Lateral Force, which you may recall is given by the formula:

$$F_{Lateral} = N \times Tan\theta$$



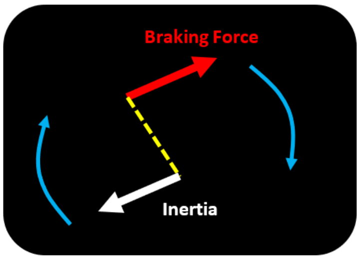
With the bike upright, θ equals zero which therefore means that the Lateral Force and the righting Torque are also reduced to zero. With no righting Torque the bike stays upright and as it no longer has a Camber Angle (I.E. it is no longer leaning into the bend) it runs straight.

In addition to the righting Torque generated by the excessive Lateral Force, the bike's Inertia and the Braking Forces act together to generate a 'Couple'. This is where two Forces act in such a way as to generate a 'turning effect' or Torque. Consider this diagram, which is a view looking down on a motorcycle in a left bend, leaning to the left, into the bend. Inertia is a Force that arises whenever a body with mass, such as the bike and Rider, undergoes Acceleration and the Inertia Force ***always*** opposes the Acceleration. When the Rider applies the front brake hard with the bike leaning over in the bend, the Centre of Gravity of the mass of the bike and Rider Decelerates, as shown by the blue arrow above. (A Deceleration is simply a negative Acceleration or an Acceleration, in the opposite direction, if you prefer!)



The Inertia Force opposes this Deceleration, as shown by the white arrow and both the Braking and Inertia Forces act on the bike and influence it to turn clockwise about some point off to the right of the bike: a motion known as Yaw. Before the bike can Yaw to the right, it must stop leaning to the left and sit up as it rotates about the imaginary Roll Axis joining the contact patches.

Couple generated by Braking and Inertia Forces



When added to the righting Torques generated by the Inertia Force and Lateral Force, as explained above, the bike ***rapidly*** sits up reducing the Camber Angle to zero!

There you have it, application of the front brake with the motorcycle leaning off the vertical in a bend results in an instantaneous righting Torque as a result of several independent actions and the net result is that they force the bike upright making it run straight.

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