Corner Force: what it is and how it is generated by car and motorcycle tyres

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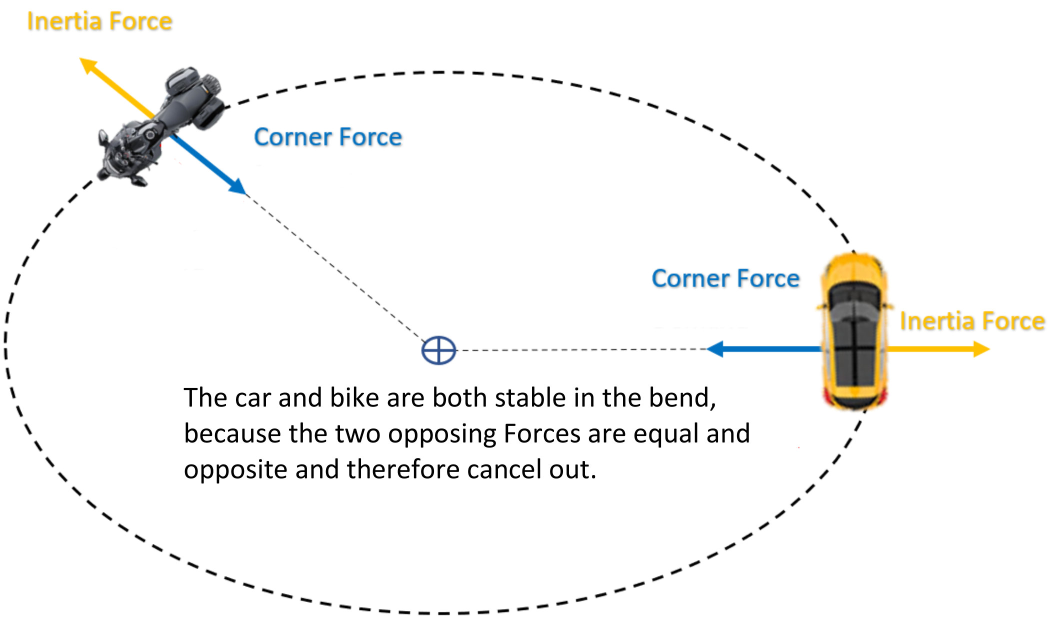
This article explaining Corner Force is presented in two Parts. Part A gives a less technical description for those who want to learn about Corner Force, without going into too much detail, whilst Part B (starting on Page 5) provides a deeper insight for those who want to learn more.

Corner Force Part A:

Cars and motorcycles experience acceleration towards the centre of a bend, even if their speed remains constant: odd as this may seem, it's a fact.

One of the greatest scientists of all times, Sir Isaac Newton, said that if something is accelerating there must be a force acting on it to make it accelerate. In the case of a car or motorcycle in a bend, the force responsible for acceleration is the **Corner Force**, which also acts towards the centre of the bend. Newton also said that every force has an equal and opposite reaction force, and in the case of a car or motorcycle in a bend, this is the Inertia Force, as shown in the diagram below. In this article we will use arrows to represent forces, velocities and accelerations. The bigger the arrow, the bigger the quantity represented and the direction in which the arrow points shows the direction in which the quantity acts.



If you enter a bend too fast, you will drift towards the outside of the bend. In a right bend you will be pulled towards the left kerb; and in a left bend you will be pulled towards the centre line and oncoming traffic. The reason for this is straight forward and can be explained by considering the opposing forces shown in the diagram above.

Corner Force is a ***demand*** on the car or motorcycle that must be met. It's a bit like the gas bill, another demand that cannot be ignored, and which must be met using the money in your bank: failure to meet the demand has unwelcome consequences. The Corner Force demand is met by Friction between your tyres and the road surface and under normal circumstances, you should have enough to meet the demand.

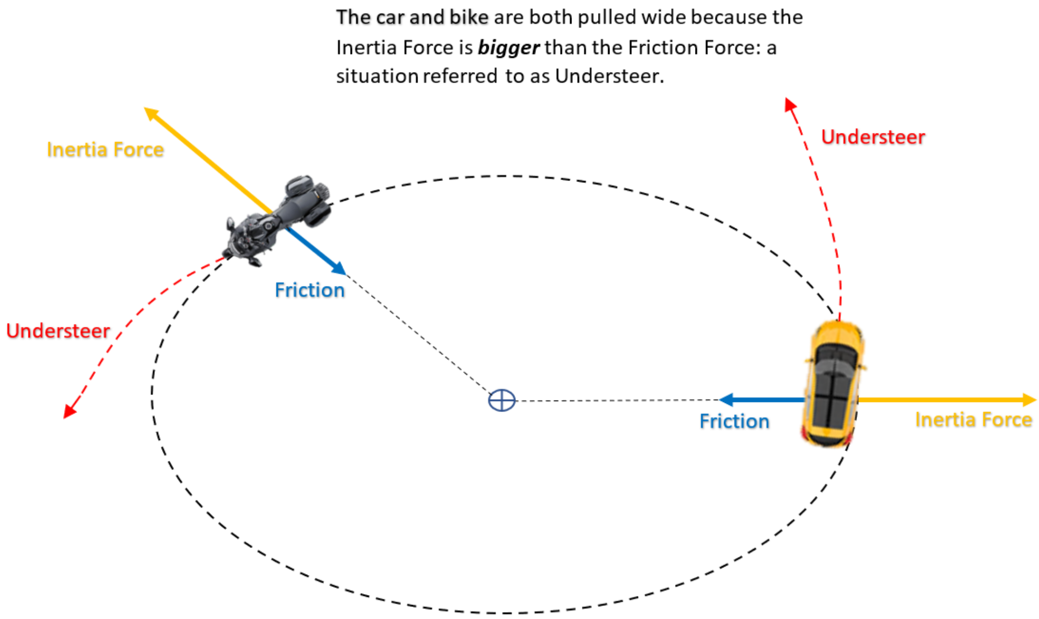
Friction can also be compared to the money in your bank: the amount you have depends on your circumstances (I.E. are you driving on ice or on a good grippy surface?); you ***can't*** have too much of it; you normally don't use it all at any one time, leaving some in reserve; and it's definitely limited, it's not infinite!

Here in lies the problem; there's no limit to how high your gas bill could be depending on how much gas you burn, whereas the money in your bank ***is*** limited.

Likewise, Corner Force demand increases rapidly as speed into the bend increases, or as the bend tightens up; there is no limit to how big it could be, whereas the Friction used to meet this demand ***is*** limited and if you don't have enough, there will definitely be unwelcome consequences!

If you are pondering the relationship between Corner Force and Friction, think of Corner Force as the ***'calculated'*** amount of force needed to keep the car or bike stable in a bend in accordance with the Laws of Physics, and think of Friction as the ***'actual'*** force between the tyres and the road surface, which must be big enough to satisfy the calculated demand. With good quality tyres and sensible driving or riding, there should always be enough Friction to meet the Corner Force demand.

To explain what happens when things go wrong, recall that the Inertia Force is the same size as the Corner Force demand, but acts in the opposite direction. I.E. the Inertia Force pulling you to the outside of the bend ***opposes*** the Corner Force -which is in turn provided by the Friction Force- trying to prevent you from being pulled outwards. When things go wrong, the calculated Corner Force demand and its equally big dance partner, the Inertia Force, are both bigger than the available Friction Force between the tyres and the road surface. When the force pulling you away from the centre of the bend (Inertia Force) is bigger than the force pulling you towards the centre (Friction Force), the car or bike ***understeers*** and runs wide, as shown below:



How cars and motorcycles generate Friction in a bend:

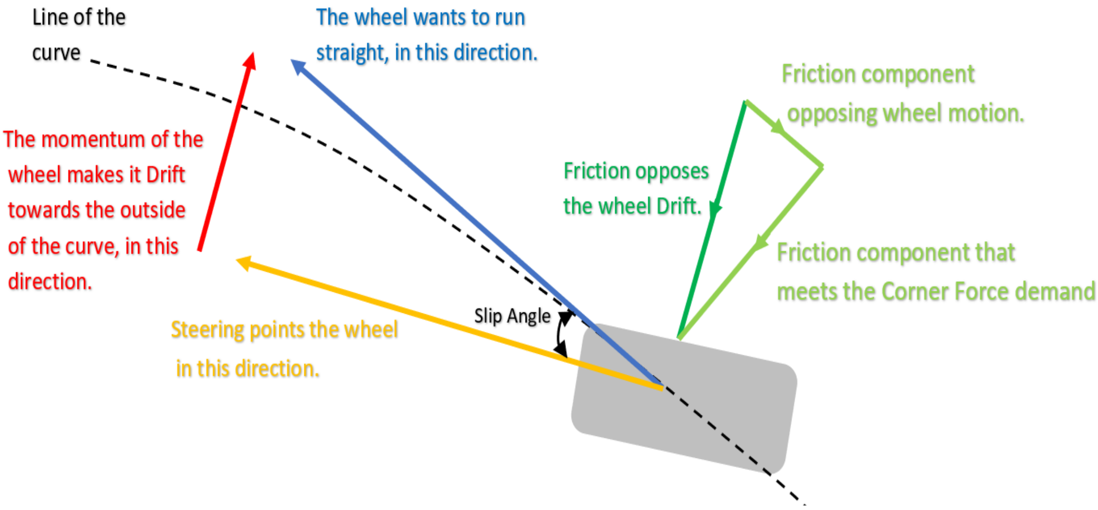
Stability in a bend is all about generating enough Friction to meet the Corner Force demand, so let's consider how Friction is produced. The forces acting on a car or bike in a bend are felt through the Contact Patch between the tyres and the road surface. Whereas a car has four points of contact with the road, a bike only has two and therefore must ***lean*** in a bend to stay stable; for that reason, car and motorcycle tyres have a different shape.

Car Tyre   Motorcycle Tyre

Common sense tells us that on entering a left bend you must steer left to follow the line of the curve; but what's ***not*** so obvious is that you must steer ***more*** than would appear to be necessary by an amount known as the Slip Angle, which can be up to about 20^0; any more than that and you will 'lose it' in the bend. You are unaware of this when driving and subconsciously rely on experience and visual feedback to follow the curve.

Cars and motorcycles want to keep going in a straight line when entering a bend, thanks to the Law of Conservation of Momentum; consequently, when steering is applied the front tyres drift towards the outside of the bend as they try to keep going straight.

In doing so, they generate Friction that opposes the drift: try pushing your stationary car sideways to experience the strength of this Friction Force for yourself. The Friction Force can be considered as having two components, one which opposes the forward motion of the car slowing it down in the bend, even if the gas is kept constant; the other component of the Friction Force points towards the centre of the bend, meeting the demand of the Corner Force.



The component of the Friction Force opposing the car's motion is the Drag Force and it's this Force that reduces the car's speed in a bend, even if the gas is kept constant.

The other component of the Friction Force points towards the centre of the bend and is responsible for meeting the Corner Force demand.

Motorcycle in a bend

When ***leaning*** into a bend, a motorcycle tyre is scrunched up at the contact patch and this generates an elastic restoring force known as **Camber Thrust.**

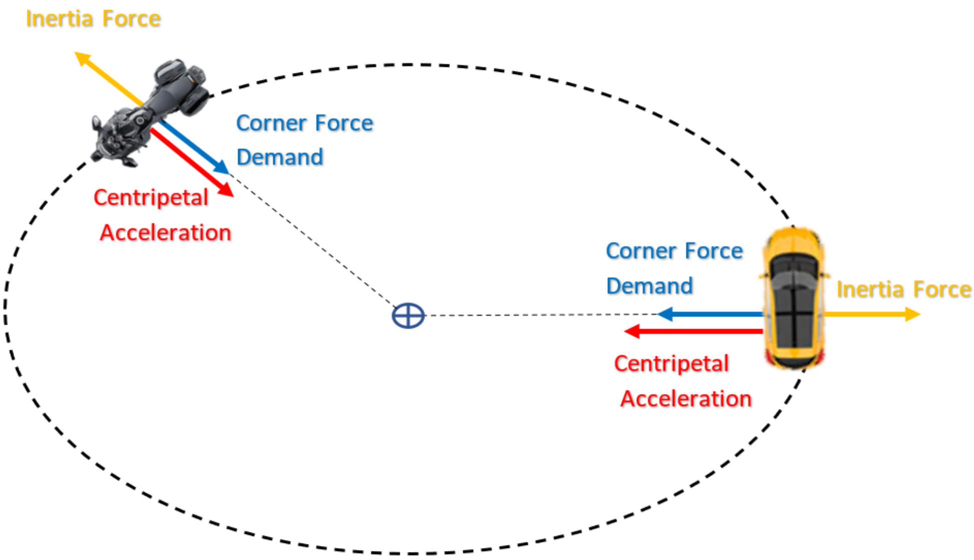
Camber Thrust is trying to return the tyre to its pre-loaded shape and therefore points towards the centre of the bend; as such it is the main Force responsible for meeting the Corner Force demand.

The motorcycle wheels also 'slip' sideways in a bend and this generates Friction, just as it does for a car. This Friction is referred to as the Slip Generated Force and it ***adds*** to the motorcycle's Camber Thrust in meeting the Corner Force demand. Consequently, a motorcycle steers ***less*** when following a given bend at the same speed as a car in the bend. This is because most of the Force needed to meet the Corner Force demand is provided by Camber Thrust and therefore ***less*** 'slip' is needed to generate Friction. Less 'slip' results in a lower Slip Angle, in other words less steering!

Corner Force Part B:

Cars and motorcycles experience **Corner Force** demand in a bend. This acts towards the centre of the bend as shown in the diagram below and is correctly known as **Centripetal Force**.

The **Inertia Force** is the Newton's 3rd Law equal and opposite Force caused by the car or motorcycle's Inertia (I.E. its Mass) opposing the Centripetal Force and the associated **Centripetal Acceleration**, which also acts towards the centre of the bend. When Newton wrote his 3rd Law: ***'Every Action has an equal and opposite Reaction'*** he certainly wasn't thinking about cars and bikes, but the underlying physics is as just as valid.



The Corner Force 'demand' must be met by real forces and in the case of a car or a motorcycle in a bend, the Force that meets the demand is partly due to Friction between the tyres and the road surface. ***All*** cars slip sideways in a bend-that is, they ***all*** understeer- and this generates the Friction required to meet the Corner Force demand. Motorcycle tyres similarly produce Friction by slipping sideways in a bend, but they ***also*** generate Force by leaning into the bend, deforming the tyres and generating restoring forces that contribute towards meeting the Corner Force demand.
Look at the difference between car and motorcycle tyres and how they generate the Forces required to meet the Corner Force demand.

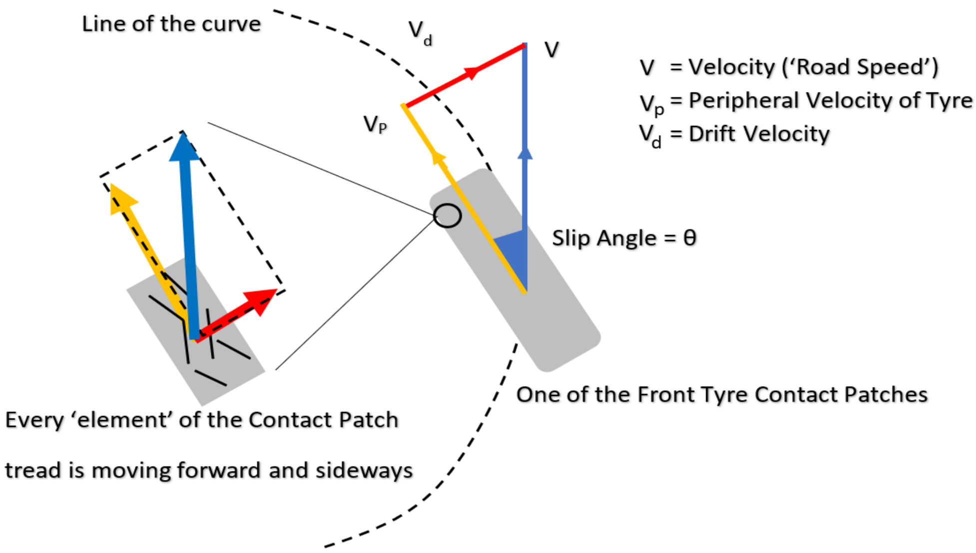
Car Tyre

Motorcycle Tyre

The rounded profile of the motorcycle tyre is essential for it to lean off the vertical when in a bend, whereas the Contact Patch of a car tyre effectively remains flat on the road surface.

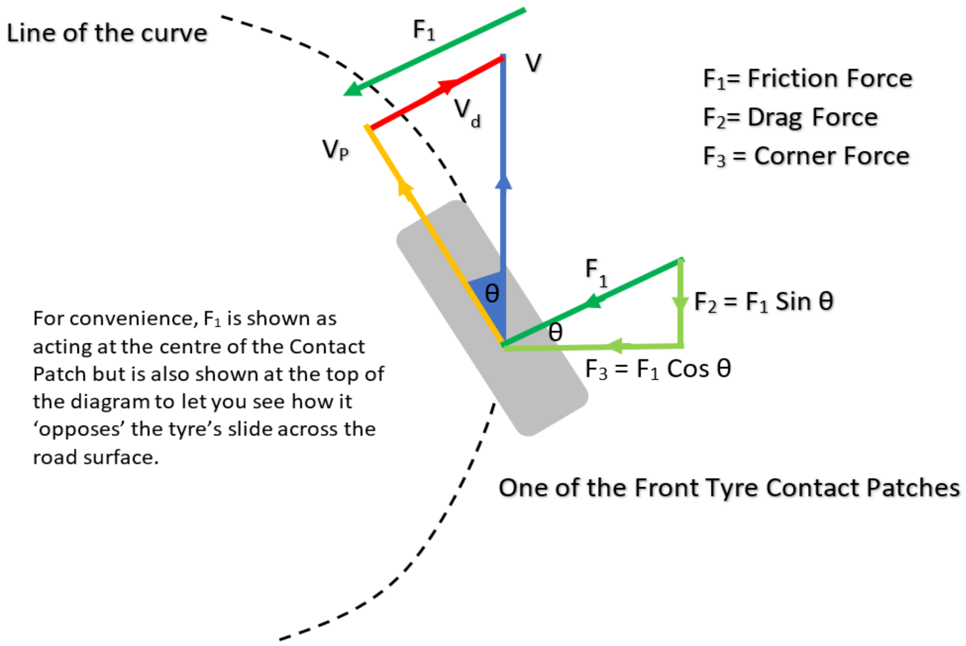
Slip Angle (θ)

For a car to follow a bend in the road, the driver must steer in by an amount equal to the **Slip Angle,** and as shown in the diagram below this is ***greater*** than the line of the curve. The Greek letter Theta (θ) is used in this article to represent Slip Angle. The front tyres therefore travel forward whilst at the same time slipping sideways with a lateral sliding velocity known as the **Drift Velocity**.



By steering left and sliding right, the car follows the desired line of the curve and it is a combination of experience and visual feedback that lets the driver know just how much steering to apply and when.

Consider the opposing **Friction Force F_1** generated as the Contact Patch 'drifts' across the road:



Friction Force F_1 opposes the car's drift across the road surface and is mathematically equal to component F_2 which directly opposes the car's Road Speed, plus component F_3 which is at right angles to the Road Speed. F_2 is equal to (F_1 Sin θ) and is known as the Drag Force. It is this Force that is responsible for a car or bike slowing down in a bend, even if the gas is kept constant throughout. For a given corner, Drag Force limits the maximum speed achievable from a given engine power, even if the grip of the tyre is not exceeded.

F_3 is equal to (F_1 Cos θ) and is the component of the Friction Force that meets the Corner Force demand on the car.

The car therefore ***needs*** to slide in the bend to generate the Friction Force required to meet the Corner Force demand. If the same bend were taken at the same speed on a very icy surface, the Corner Force demand would be the same, but there would be insufficient Friction between the tyres and the road surface to mee the demand and the car would understeer out of control and run straight on instead of following the line of the curve.

Motorcycle in a bend

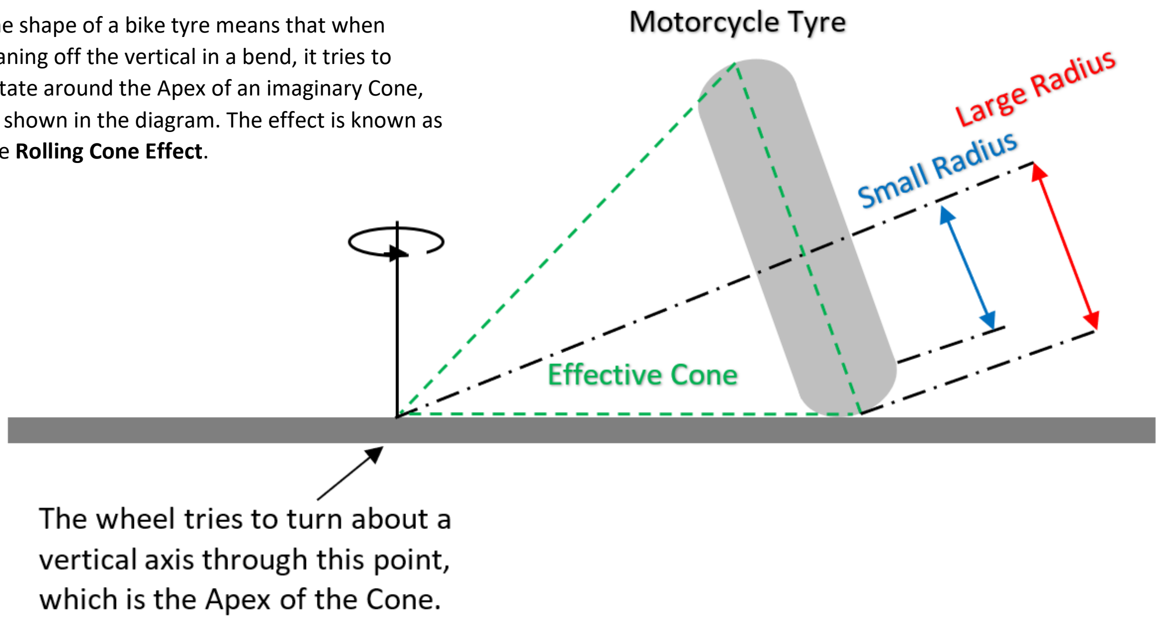
The Laws of Physics are the same for cars and bikes and they both experience Corner Force demand in a bend, which must be met by real forces to ensure stability.

A car wheel stays upright with its Contact Patch flat on the road surface and by slipping sideways in the bend it generates the Friction needed to meet the Corner Force demand. A bike ***leans*** into a bend and although it generates some Friction as a result of slip, as a car does, the majority of the force needed to meet the Corner Force demand comes from the restoring force produced by the elasticity of the tyre material pushing back like a spring, opposing deformation as the tyre leans into the bend.

This restoring force caused by the elasticity of the tyre material is known as **Camber Thrust** and it is very important for stability, especially at low speed where the Slip Force is small.

The Rolling Cone Effect

The shape of a bike tyre means that when leaning off the vertical in a bend, it tries to rotate around the Apex of an imaginary Cone, as shown in the diagram. The effect is known as the **Rolling Cone Effect**.



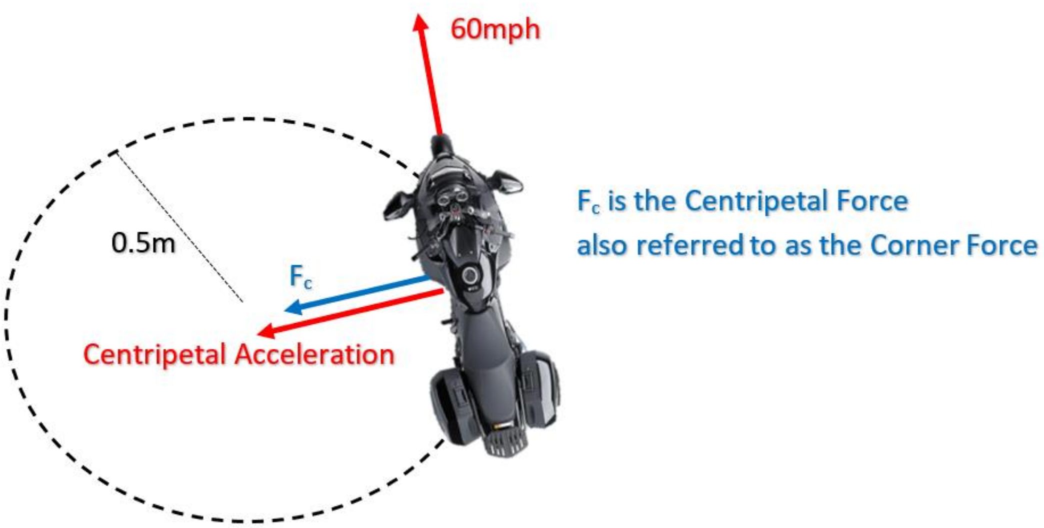
The Contact Patch of a motorcycle tyre flattens at an angle on the road surface owing to the tyre's rounded profile and it effectively becomes a slice of a Cone, which tends to turn around its Apex. The effective height of the Cone from Apex to base, depends on the Camber Angle. I.E. the angle the bike leans off the vertical. At small angles of lean, the height of the Cone is quite large. But when the bike is banked hard over, the Camber Angle is big, and the height of the Cone is small.

A typical sports bike might have a Cone height of 0.5 metres when banked over at 45^0.

Although the bike wants to turn around the Apex of the Cone it is an ***impossibly*** tight turn.

To see just how impossible it is to make such a tight turn, we will calculate the Corner Force demand on a bike and rider negotiating a bend of 0.5 metre radius at a speed of 60mph with a 45^0 lean.

We will then express the result as the 'g-force' acting on the bike and rider.



$$F_c = \frac{m\,V^2}{r}$$ Formula for Centripetal Force F_c

$$F_c = m\,a$$ But Newton's 2nd Law gives another formula for F_c

$$a = \frac{V^2}{r}$$ Equating the two force formulae gives a formula for acceleration

$$a\,r = \left(\frac{60 \times 1500}{3600}\right)^2$$ Convert the 60mph to metres / second

$$a = \left(\frac{625}{0.5}\right)$$ Divide both sides by Cone radius 'r'

$$Acceleration\ in\ g's = \left(\frac{625}{0.5 \times 9.8}\right)$$ 1g is 9.8ms^{-2} the Acceleration of Gravity, therefore dividing the acceleration by 9.8 gives the answer in 'g's'

$$\boldsymbol{Centripetal\ Acceleration\ in\ g's = 127.5g}$$

This is an impossibly large **Centripetal Acceleration** that neither you nor the bike can meet.

Your weight would be 127.5 times greater than normal for a start: that's a lot of doughnuts!

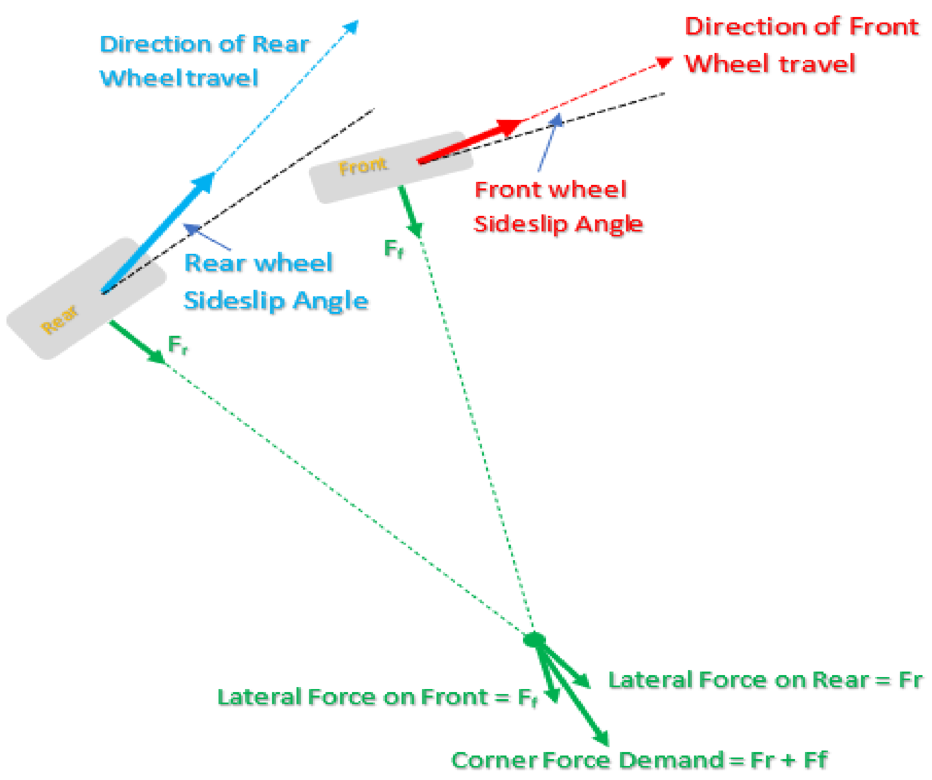
What happens in practice is that as you lean the bike over in a bend, the Camber Angle (I.E. angle of lean off the vertical) increases until the Corner Force demand F_c can be matched by the **Lateral Force** acting between the tyres and the road surface.

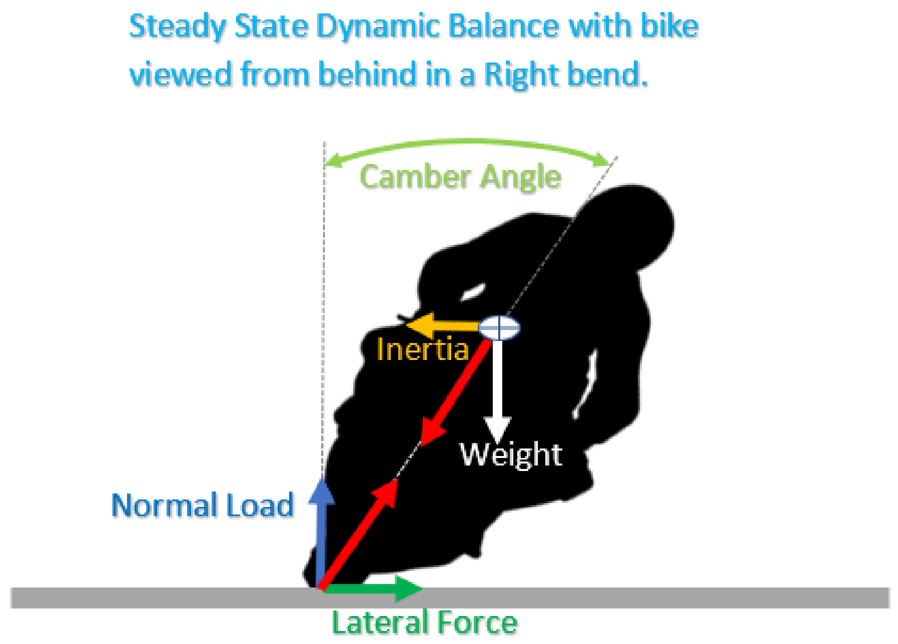
Lateral Force:

'Lateral' means acting at right angles to the direction of travel. The Lateral Force exerted by the tyre on the road surface depends on several factors, including the **Sideslip Angle** and the **Camber Angle**.

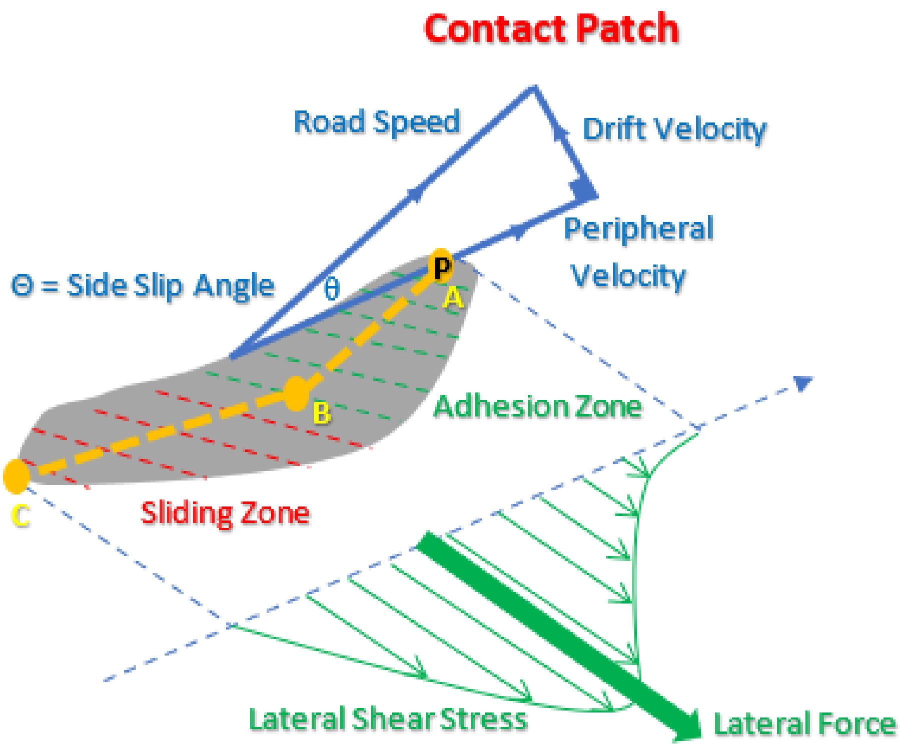
The first diagram below shows the **Sideslip Angle** and the second diagram shows the **Camber Angle** for a bike in a right bend.

Plan view of motorcycle wheels in a right bend





The tyre is deformed where it touches the ground, forming a **Contact Patch**. The shape is not symmetrical and depends on the material from which the tyre is made, as well as the Sideslip Angle, Camber Angle, the external load on the tyre due to the weight of the bike and rider, the inflation pressure and temperature. Any Driving, Braking or Lateral Forces will cause further deformation of the Contact Patch.



Consider some specific **Point P** on a tread meeting the ground at **Point A**. It then moves in a straight line to **Point B** at the Peripheral Velocity of the tyre, along a track parallel to the direction in which the tyre moves. When it reaches **Point B**, the elastic restoring shear stress, due to the deformation of the carcass and of the rubber elements in the tyre tread, becomes greater than the adhesion forces. This causes **Point P** to deviate in the opposite direction as it slides along the ground to the trailing edge of the Contact Patch at **Point C**.

The Contact Patch area therefore comprises two zones:

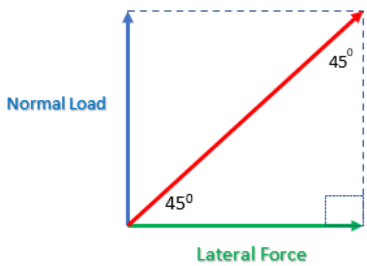
- An Adhesion Zone, where grip is generated.
- A Sliding Zone, where points on the tyre surface slide along the ground giving no grip.

As the Camber Angle increases (I.E. the lean off the vertical increases) the Sliding Zone gets bigger until at some critical angle of lean, which will differ from tyre to tyre and surface to surface, the Sliding Zone covers the entire area of the Contact Patch.

All grip is lost and the tyre slides from under the bike: agh!!!!

The 0.5 m bend in the example above was clearly impossible to achieve at 60mph, so we will now calculate the minimum bend radius for the bike travelling at 60mph, with a 45^0 lean, achieving Dynamic Balance.

At 45^0 Camber, the Lateral Force and the Normal Load are the same size



There is nothing 'special' about a lean angle of 45^0. However, it is often chosen when working out examples because of the geometry of the Force triangle. At this angle of lean ***and this angle only***, the Lateral Acceleration is 1g or 9.8 ms^{-2} and both the Normal Load and Lateral Force are the same size. This is a consequence of a 45^0 right angled triangle having two sides of equal length, as shown above.

$$a = \frac{V^2}{r}$$

Derived from formula for Centripetal Force above

$$1g \times r = \left(\frac{60 \times 1500}{3600}\right)^2$$

If the lean angle is 45^0 Centripetal Acceleration is 1g

$$r = \frac{625}{9.8}$$

1g is 9.8ms^{-2} the Acceleration of Gravity

$$\boldsymbol{r = 63.7\ metres}$$

This bike with a Cone Radius of 0.5m when banked at 45^0, will slip out until the Lateral Force meets the Corner Force demand. At a lean angle of 45^0, where the Lateral Acceleration is 1g, that distance is 63.7m from the centre of the bend.

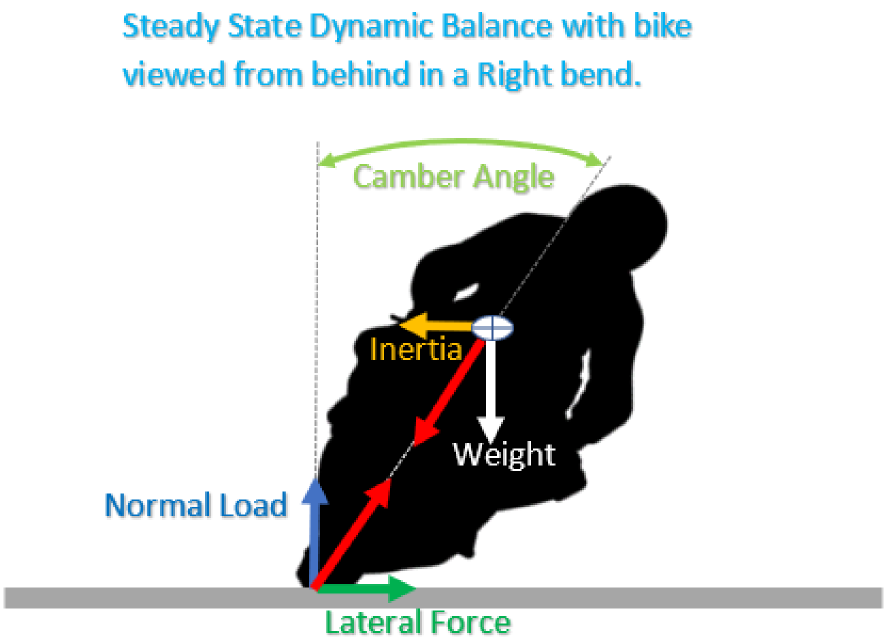
In summary, a car must slip sideways in a bend to generate the Lateral Force required to meet the Corner Force demand.

A motorcycle generally has ***two*** component Forces that combine to meet the Corner Force demand. The first and major contributor is Camber Thrust, the Lateral Force component generated by restoring forces in the tyre opposing deformation. Camber Thrust is generated in two distinct phases; first vertical deformation caused by the weight of the bike and rider and second, deformation caused by the Lateral Force of the Camber Thrust when the bike leans in a bend.

A consequence of the bike having more Lateral Force generating capacity than a car is that a bike has a smaller Slip Angle than a car when taking the same bend at the same speed.

This is because the bike does not simply rely on Drift Velocity to generate Lateral Force through Friction alone, as most of its lateral Force is generated by leaning into the bend and trying to go around the Apex of the Cone causing tyre deformation and restoring Camber Force. Consequently, a motorcyclist steers less than a car driver, when taking the same bend at the same speed.

Does grip continue to increase as the bike leans more off the vertical?



The diagram above shows the Forces acting on a bike in 'Dynamic Balance'. This state is achieved when the bike leans over enough to remain balanced and stable in a bend and it occurs when the Weight and Inertia Force vectors add together to give a Resultant Force (Red arrow) pointing down along a line passing through the Centre of Gravity to the Roll Axis of the bike. (I.E. the imaginary line joining the front and rear Contact Patches). At the same time, the Lateral Force and Normal Load vectors add together to produce the Newton's 3rd Law 'equal and opposite' Force to this Reaction

Force, shown by the Red arrow pointing up along the line passing from the Roll Axis to the Centre of Gravity.

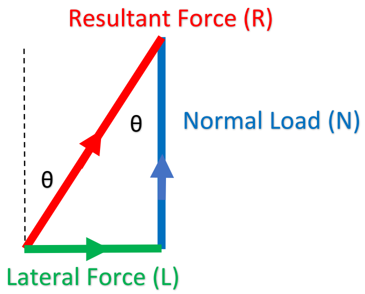
The relationship between Lateral Force and Camber Angle is determined from the Force triangle.

Let the Camber Angle be θ

The Force triangle opposite shows that:

$$Tan\,\theta = \frac{L}{N}$$

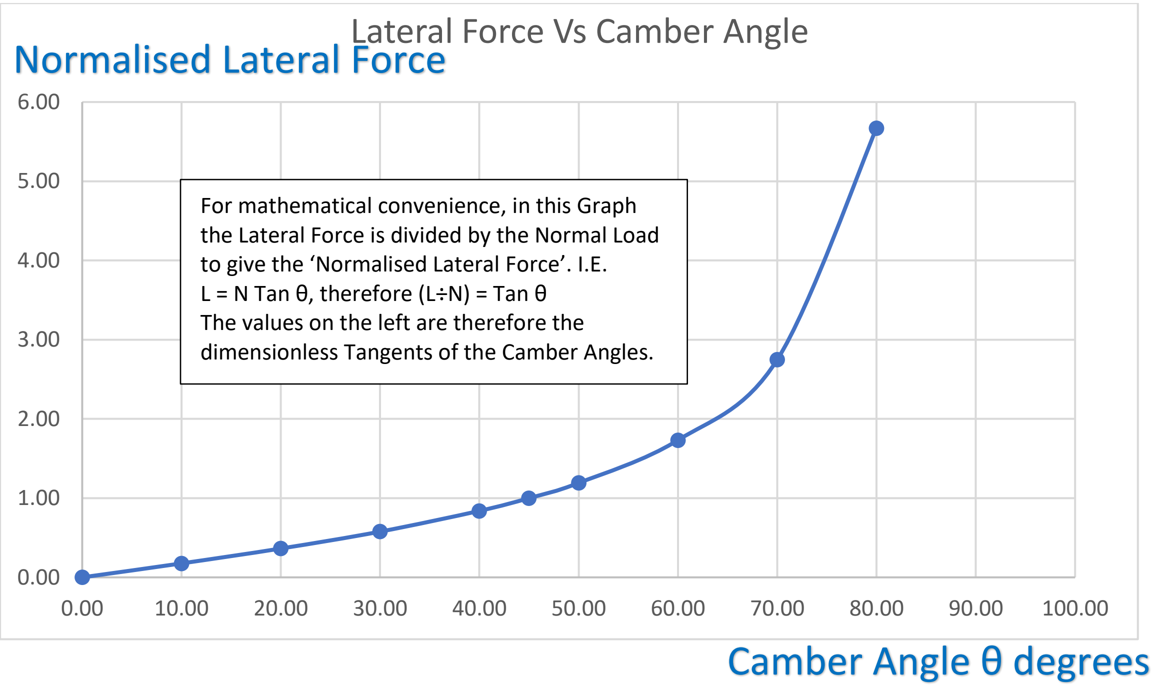
Therefore: $$L = N\,Tan\,\theta$$



This equation states that the Lateral Force (L) is the Normal Load on the Contact Patch (N) multiplied the Tangent of the Camber Angle θ.

The relationship between Lateral Force and Camber Angle can be seen better on a graph.

The shape of the Lateral Force with Camber Angle θ Graph is like that of the Tan θ Graph, as shown below:



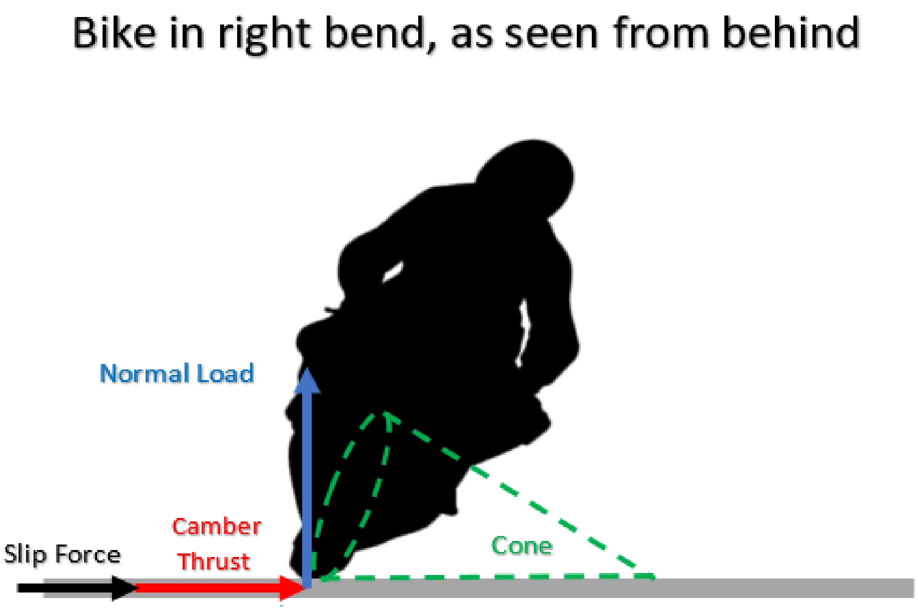
The Graph shows that as the Camber Angle approaches 90^0, the Lateral Force (I.E. 'grip'), ***in theory approaches infinity***. I.E. the Blue Curve goes vertical when the angle of lean approaches 90^0.

Clearly a motorcycle tyre cannot achieve infinite grip and a ***stable*** motorcycle in a bend cannot achieve a Camber Angle of 90^0.

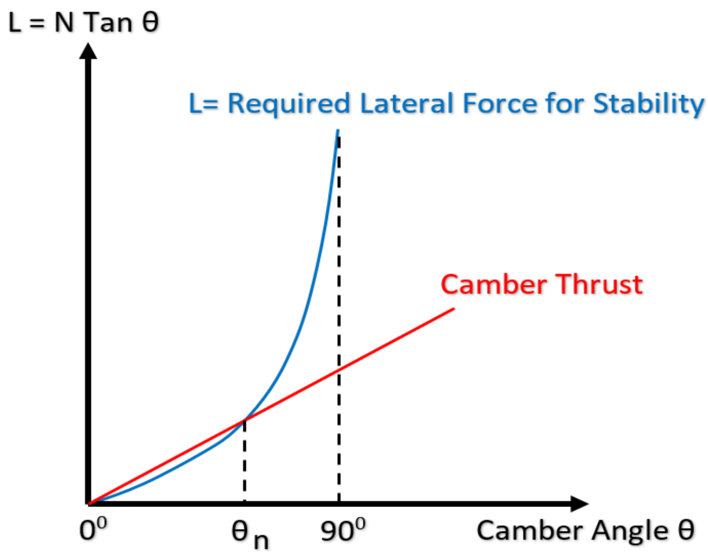
The Lateral Force required for stability in a bend depends on the Vertical Load, the Sideslip Angle and the Camber Angle. The main contributor to the force needed for stability is the Lateral Force of the Camber Thrust when the bike leans in the bend; however, Lateral Force is ***also*** generated as the bike tyres slip sideways in the bend, in the way that car tyres do, and this the **Slip Force.**

Camber Thrust varies with Camber Angle

Increasing the Camber Angle by leaning the bike more off the vertical in a bend, increases the tyre deformation responsible for the Camber Thrust component of the Lateral Force.



Over the range of realistic lean angles likely to be encountered when riding a motorcycle, Camber Thrust increases linearly with Camber Angle, as shown by the Red line in the diagram below.

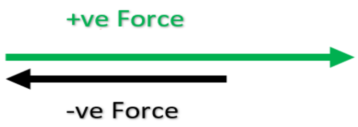


The Camber Thrust ***for this tyre and set of operating conditions*** (I.E. tyre pressure, load, Sideslip Angle, Camber Angle Etc.) is seen to be greater than the Lateral Force needed for stability over the initial range of Camber Angles from 0 to θ_n degrees. I.E. the Red line is higher than the Blue curve over this range, and the bike has too much Camber Thrust for stability. To fix this, the rider must introduce a ***Negative Slip Force, to detune the Camber Thrust*** so that when they combine, they will ***exactly*** match the Lateral Force required for stability.

When the Camber Angle equals θ_n degrees, ***all*** the required Lateral Force is provided by the Camber Thrust. At this point there is no requirement for Slip Force and the Slip Angle will be zero. When the Camber Angle is greater than θ_n degrees, the Camber Thrust is too small to meet the Later Force required for stability, so the rider must introduce a ***Positive Slip Angle and associated Positive Slip Force to add to the Camber Thrust*** so that they combine to ***exactly*** match the Lateral Force required for stability.

What are Negative and Positive Slip Forces and how are they generated?

A 'Negative Force' is one that acts in the opposite direction to some other Force, which has arbitrarily been assigned as a 'Positive Force', based on the direction in which it acts.



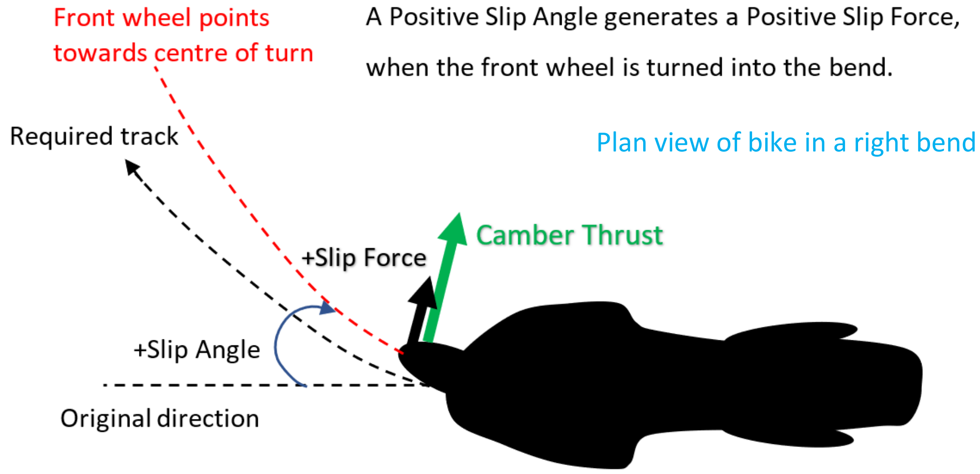
Forces have both size and direction properties.
If the 'green' force acting to the right is assigned a positive value, then the 'black force' acting to the left will have a negative value. It is as real as the 'green' force, it simply points in the opposite direction.

Camber Thrust opposes tyre deformation and always points towards the centre of the bend. Forces acting in this direction have arbitrarily been assigned positive values, which means that any force pointing away from the centre of the bend is a negative force.

Negative forces are as real as positive forces, but simply point in the opposite direction.

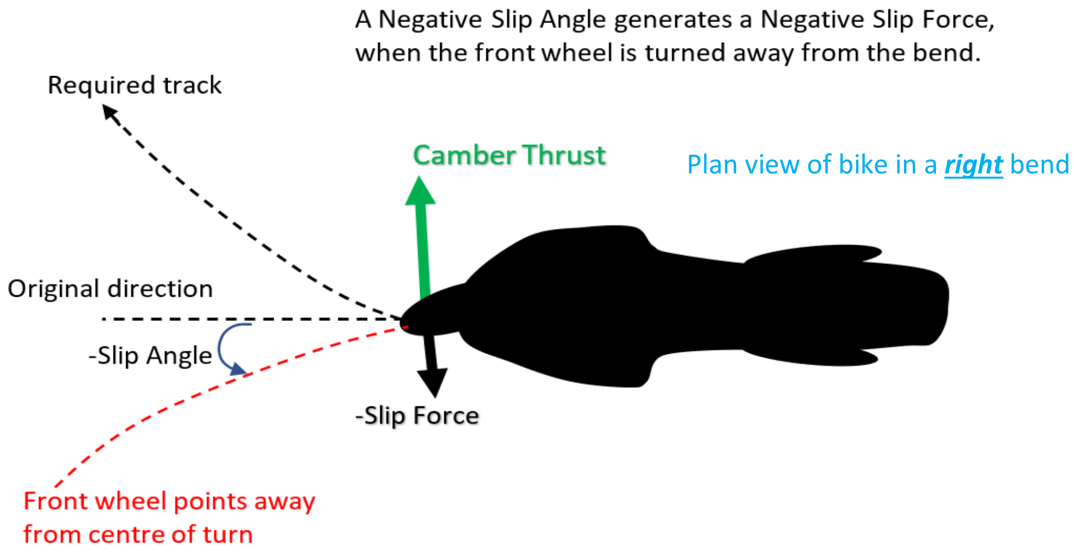
A Positive Slip Force is generated by a Positive Slip Angle when the rider turns the handlebars slightly in the direction of the centre of turn.

A Positive Slip Angle generates a Positive Slip Force, when the front wheel is turned into the bend.



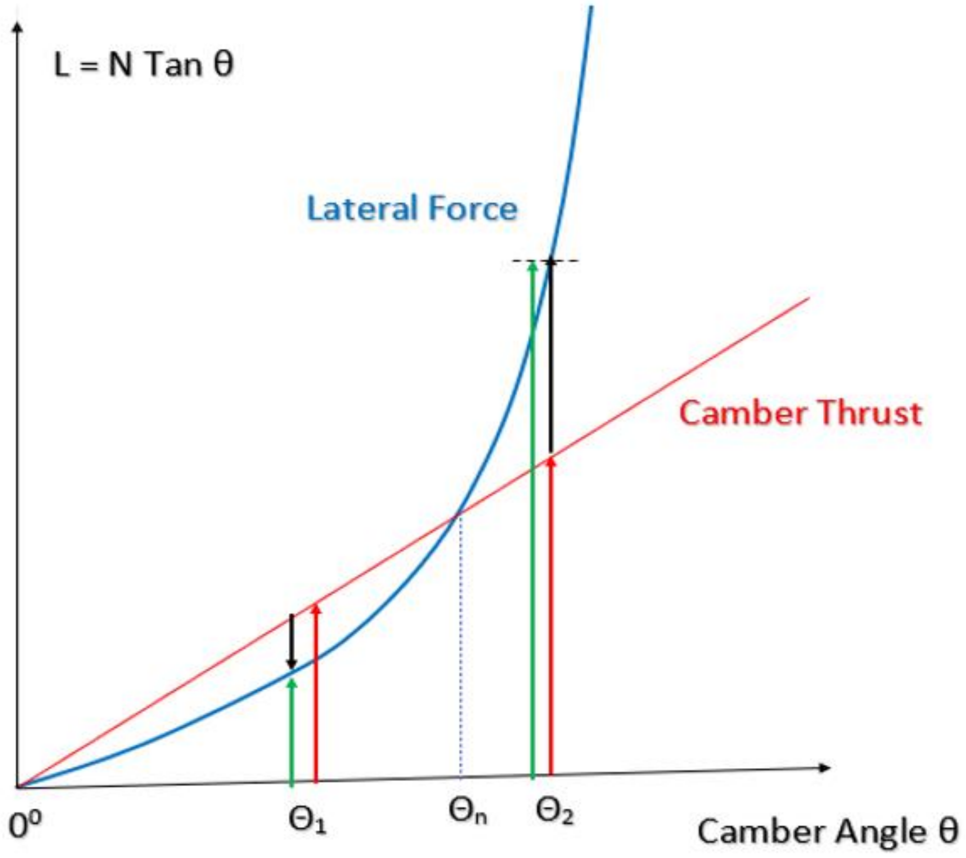
The Camber Thrust and Positive Slip Force add together to give the ***exact*** Lateral Force required for stability in the bend.

A Negative Slip Force is generated by a Negative Slip Angle when the rider turns the handlebars slightly away from the centre of turn.



In this case, the Camber Thrust is too big, so it is detuned by the Negative Slip Force so that when they are added together give the ***exact*** Lateral Force required for stability in the bend.

The following diagram 'exaggerates' the difference between Camber Thrust and the Lateral Force for visual ease.



For Camber Angle θ_1

Red + Black = Green

Camber Thrust + Negative Slip Force = Lateral Force

For Camber Angle θ_2

Red + Black = Green

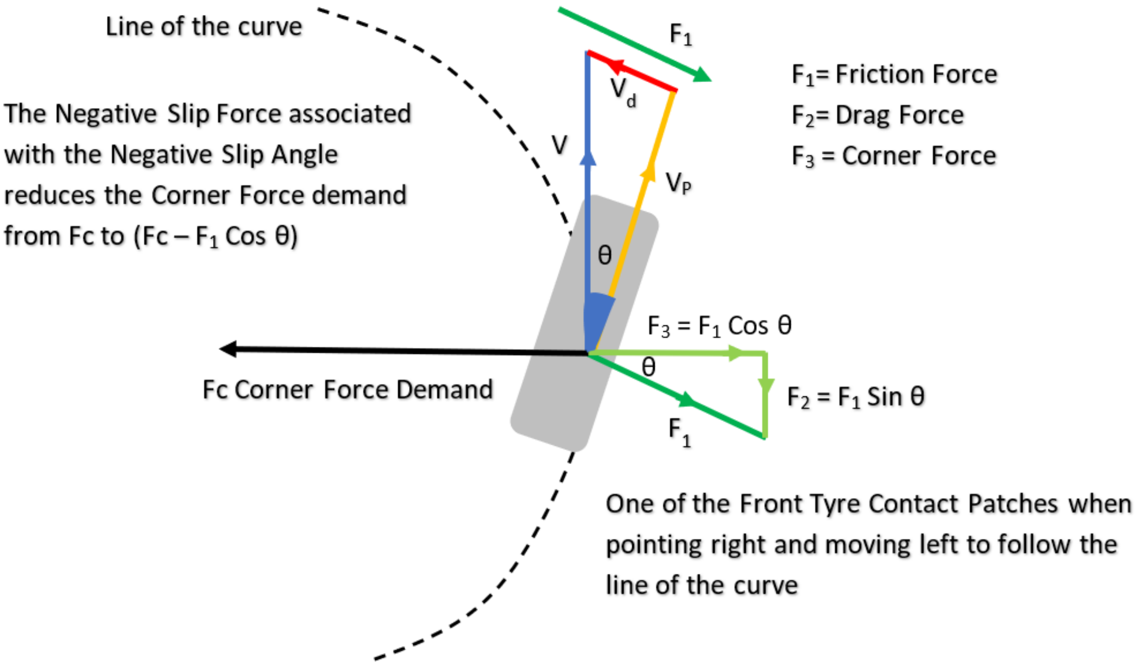
Camber Thrust + Positive Slip Force = Lateral Force

In the case of a Speedway Bike, the Camber Angle and associated Camber Thrust are both high. In the picture below, the rider is in a left bend with the front wheel pointing to the right, away from the centre of the bend. This produces a Negative Slip Angle and associated Negative Slip Force to detune the large Camber Thrust generated by the large Camber Angle.

Drifting in a bend

Watch a Rally Car in a fast bend on a loose gravel surface and you will probably see it 'drift' in the bend; also referred to as 'power sliding'. The driver does this by introducing a Negative Slip Angle, which in turn generates a Negative Slip Force to ***reduce*** the Corner Force demand so that it can be matched by available friction, as shown in the diagram below.

Car in ***left*** bend, with Negative Slip Angle



Conclusion

In this article I have discussed:

- Corner Force
- Slip Angles and Slip Force
- The Rolling Cone Effect
- Lateral Force
- Shear Stress in the Contact Patch
- Dynamic Stability for a motorcycle in a bend
- Negative and Positive Slip Forces
- Drifting

By reviewing the physics associated with cars and bikes in a bend is it is hoped that Observers and Associates have a better understanding of the topics listed above, and that -if nothing else- the content of this article stimulates debate.

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