Roll Center
Myths and Reality
by Wm. C. Mitchell

The Roll Center
"Roll Center" is the most misunderstood term in vehicle dynamics. A fairly simple concept - how much lateral force applied at the tire contact patch is transformed into vertical force - has generated a remarkable number of myths. The "roll center" is a simple measure, derived from symmetric production car design, extrapolated to asymmetric racing cars, which overwhelmed the underlying reality. The vary name "roll center" implies much more than it delivers.

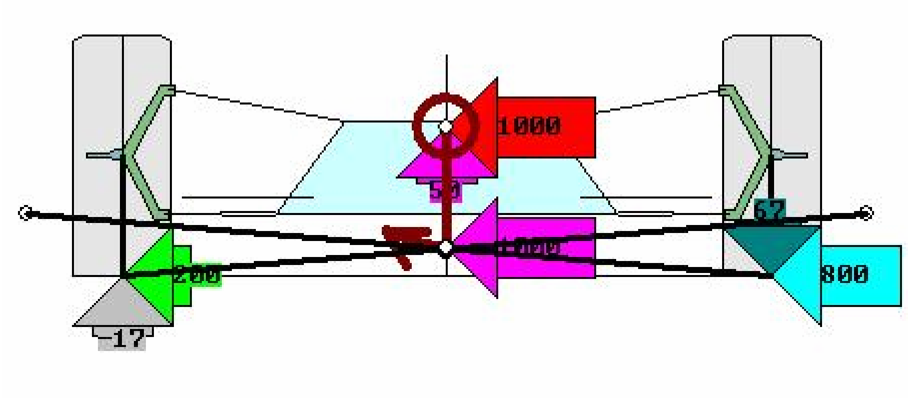
Tires generate forces which produce lateral and longitudinal acceleration. This process involves complex concepts ranging from molecular adhesion to the conformity of a soft tire to an irregular road surface. But the result is simple: a force in the plane of the road surface and a vertical force perpendicular to the road surface. The best analogy, due to tire author Paul Haney, involves a broom. If you hold the handle of the broom low it may glide over a washer lying on the ground. If you raise the handle it becomes harder to push but there is more vertical force pushing the bristles into the ground and more likely to dislodge that washer.

The reality of this analogy is the angle of the broom handle, not the height of the end. Cut the broom handle in half but maintain the angle and the effect is the same: the height of the end is irrelevant. "Roll center" is a measure of the height of the broom handle, not the angle. Reality is the angle snf the resulting forces.

The History
Most of vehicle dynamics theory was developed around production cars simply because there were many more production car engineers than racing engineers (and there still are). Production car suspensions are usually symmetric with the center of gravity near the centerline of the car.

Production cars are rarely subject to large lateral forces (outside of racing applications). Few drivers use more than 0.3g even in emergency situations. Consequently production car analysis is usually limited to low lateral forces. Under this assumption chassis roll and subsequent suspension movement can be ignored and the roll center is treated as a static point. Good vehicle dynamics texts, including Dixon and Gillespie, mention this.

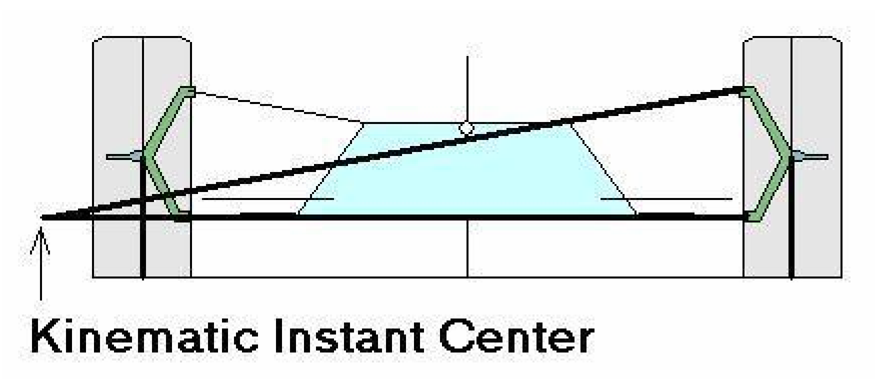
The roll center height is a useful concept because it defines the moment arm - the distance from roll center to center of gravity - acting to overturn the car. John C. Dixon writes: "… the roll-centre is a very useful idea, because the roll-centre height concisely summarizes the effect of the links. With known roll-centre heights it is easy to calculate the roll angle and the load transfer at each of the front and rear axles."



<<< Illustration 1: The moment arm is the distance from RC to CG >>>

The Kinematic Instant Center

Kinematic analysis gives us the four bar theory of movement which defines instant centers of motion. Applied to the double wishbone suspension four-bar theory establishes an instant center. The four bars are the two wishbones, the chassis, and the upright/hub/wheel/tire assembly. The upright/hub/wheel/tire assembly rotates about this instant center. This is a very useful concept because it explains camber change (for small displacements). We will later show it also explains jacking force. The instant center corresponds to the end of the broom handle in the earlier analogy.



<<< Illustration 2: The Kinematic Instant center >>>

The Kinematic Roll Center

The familiar roll center, shown in Illustration 1, is the intersection of lines drawn from the suspension instant centers to the tire contact patches. This is an application of 4-bar theory applied twice. The second application treats the theoretical lines from the kinematic instant centers to the tire contact patches as solid links. The other two links are the chassis (connecting the two instant centers) and the ground. The instant center of this mechanism gives the rotation point which minimizes tread change in reaction to chassis roll. This would be important if we were rolling the chassis in the shop where every bit of scrub would be expressed with the same screech you hear in car parks. But we are dealing with **moving** vehicles where tread change becomes a small toe change. The kinematic roll center is easily drawn (in two dimensions) and understood but analyzing the resulting movement is complex and leads to myths which are often wrong.

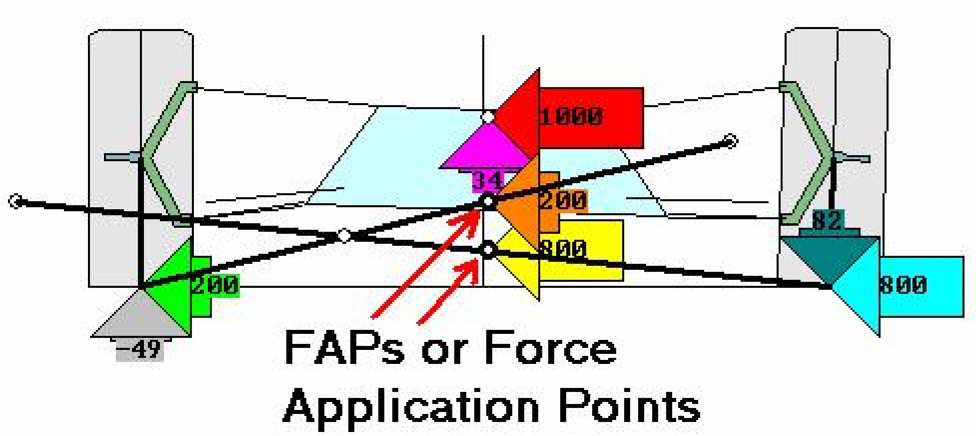
Why a Roll Center?

Important vehicle dynamics quantities including the loads on individual tires, the chassis roll angle, and roll couple depend on overturning moment. This depends on the forces operating through the suspension links and is ***measured*** by the roll center. As Dixon says "… the roll-centre height may be used as a summary of the load transfer characteristics of a suspension found by a detailed suspension analysis, or as the input specification for a simple handling simulation." [1]

Load transfer, jacking forces and overturning moment are forces and moments, not kinematics. Thus we should address the problem through forces and moments rather than kinematics. This leads to the "Force-Based roll center". This is calculated by solving a series of force and moment equations usually expressed as a matrix. In two dimensions it is a 3x3 matrix. In three dimensions it is a 6x6 matrix.

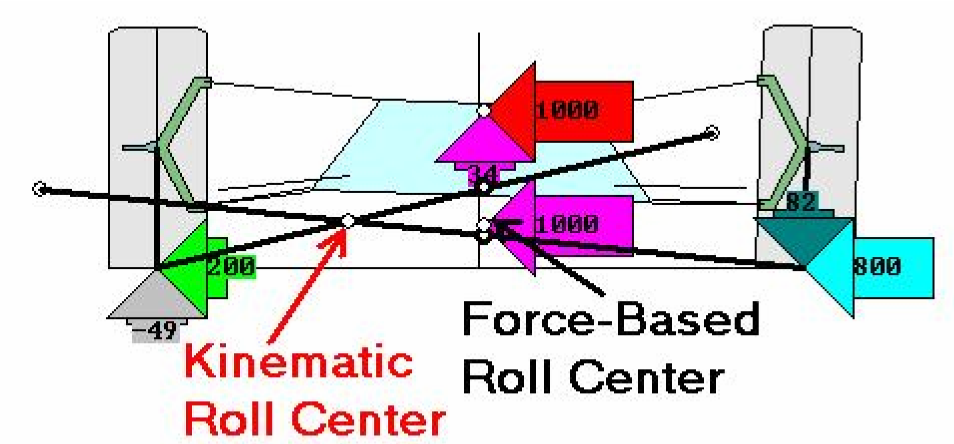
In the simple two dimensional case the kinematic roll center is identical to the force-based roll center for symmetric suspensions. For more complex cases we use the **Force Application Point**, which is the point on the line between the instant center and the tire contact patch under the center of gravity. For a symmetric suspension with the CG on the centerline of the vehicle the FAPs are identical to the kinematic roll center.

For an asymmetric suspension, and most symmetric suspensions became asymmetric when the chassis rolls, we have distinct FAPs for each side of the suspension.



<< Illustration 3: The FAP of Force Application Points >>

Determining a Force-Based Roll Center height requires knowledge of how the tire force is distributed between the two tires. This is unfortunate because it introduces an unknown variable. But it is easier to analyze the vertical movement of the FAP, which is always under the CG, for each side of the car than the kinematic roll center, which moves vertically and laterally.



<<< Illustration 4: The Kinematic and Force-Based Roll Centers. >>>

The FAPs and the Force-Based Roll Center are important. The Kinematic Roll Center is of little value.

But the roll center is a convenience, not a necessity. Dixon writes “With detailed computer simulations that consider the forces in the individual suspension links it is not necessary to use the roll-centre concept.”

The SAE Definition

SAE defines the roll center as “The point in the transverse vertical plane through any pair of *wheel centers* at which lateral forces may be applied to the *sprung mass* without producing *suspension roll*”. [2]. This sounds like a committee of academics compromising on a single valid expression with minimal meaning.

Note that this really defines a *height* rather than a point since there is no reference to lateral location. The roll center is often assumed to be on the centerline of the vehicle. Placing it under the CG would make more sense.

The Force-Based Roll Center in Three Dimensions

In the three dimensions most of us live in the force-based roll center yields a 6x6 matrix. Few of us can visualize a 6x6 matrix let alone it’s inverse. But with a little work we can understand what we need to know. Determining the instant center is a bit more complex because we must construct lines through the A-arms in the vertical transverse plane of the tire contact point. Often the ball joints will **not** be on this line. But once we understand the concept, and leaving the mathematical details to our ever-present computer, the instant center can be determined.

But there are five links from upright to chassis: the four A-arms plus the steering tie-rod. Some force, and more than many people expect, goes through the tie-rod. This contributes to the roll moment. The amount of contribution depends on where the tie-rod projected crosses the instant center axis which conects the standard instant center with the side-view instant center. But since the steering tie-rod is usually aimed near the IC axis the effect of the tie-rod is usually small. Those interested in the precise details may consult the author's SAE paper 2006-01-3617. But for most working engineers can ignore the difference (as long as they understand what they are ignorng).

For the necessary sixth equation we consider a vertical force at the tire contact patch which is often called the jacking force. As an alternative we can calculate the force going through the spring. This ignores the compression of the spring as well as the contribution of dampers, anti-roll bars and third springs.

What We Need to Know

The crucial concept is the FAP rather than the Kinematic Roll Center. This has the advantage that an independent suspension yields independent analysis. We can study each side independently. This is nice. The disadvantage is that we need to know the distribution of force between the tires. With a symmetric car the left and right FAPs are at the same point and the distribution of force drops out of the equation (though we still need it to calculate net jacking force).

Stability results when the FAP-CG moment arm remains constant as the vehicle rolls. The chassis "takes a set" rather than constantly seeking a new equilibrium. This can be expressed by minimizing the lateral movement of the KRC as the vehicle rolls. But this is an artifact: there are more direct ways to calculate this; namely with the change in FAP height resulting from ride. It should be one-to-one. (An easier way to visualize this is from the viewpoint of the chassis rather than the world. The FAP point should be constant as the wheels and tires move up and down.)

Confounding the Confusion

Everything we have written about lateral forces and the roll center applies to longitudinal forces and the pitch center. The principles and the analysis are identical except cars symmetric front-to-rear are extremely rare and sometimes longitudinal forces are generated at the axle rather than the ground. But engineers usually discuss anti-dive and anti-squat in percentage whereas few discuss lateral forces as an anti-roll percentage. Some even discuss acceleration as an angle rather than a percentage. The use of common terms would eliminate a lot of confusion while emphasizing the common elements.

Myth #1 - The Kinematic Roll Center

Several myths exist about keeping the kinematic roll center in a certain area. It should not be under the inside tire or not near the outside tire. It should be within the tires and not in the infield. Based on the analysis above, I know of no validity to any of these theories.

Myth #2 - The Roll Center should not go through the ground plane.

When the chassis moves to place the instant centers near the ground the kinematic roll center moves rapidly laterally. When one IC is above ground and one below ground the KRC is outside the track. Before I understood the limited role of the KRC I thought this was bad. One way to avoid it is to keep the ICs either above or below ground.

"Mea Culpa" (as the Romans said) or "My Bad" as the current generation say. Formula SAE/Formula Students occasionally present this theory and I have to explain why it is invalid while acknowledging my guilt in their error. Whoops.

Myth #3: The distance from the kinematic roll center to the CG is the moment arm.
If you believe in the kinematic roll center it is easy to consider the distance to the CG as a moment arm. A long distance from KRC to CG produces lots of chassis roll. The problem is that this line is not perpendicular to the lateral force. The FAPs, defined as being under the CG, yield a moment arm perpendicular to the lateral force. The distance from FAP to CG is a valid moment arm.

Myth #4 - The Chassis Rolls about the Roll Axis
The chassis ***moves*** in reaction to a lateral force: it does not roll about a point or axis. The movement includes chassis roll as well as vertical movement. The kinematic roll center concept clearly describes the roll yet neglects jacking force, which might be small for symmetric cases where both tires contribute equal lateral force. But for racing cars the majority of the lateral force comes from the outside tire. In some applications the inside tire may even be off the ground.

Dixon writes " … many authors introduce the roll-axis as an axis about which the vehicle actually rolls during cornering, the roll axis being the line joining the front and rear roll-centres. When a vehicle is actually moving on a road, the concept of a kinematic roll axis is difficult to justify in a precise way, especially for large lateral accelerations. Therefore the idea of the vehicle rolling about such an axis, although useful as a qualitative idea, should be treated rather cautiously, except in the special case of a stationary vehicle subject to loads in the laboratory." [1]

Summary
The Roll Center is important but you have to separate reality from myth. Kinematics are easy to visualize and that aids understanding. But forces move the race car.

References
1. Tyres, Suspension and Handling, John C. Dixon, Cambridge University Press (1991)
2. Vehicle Dynamics Terminology, SAE J670e, SAE, 1952, last revised 1976
3. Racing by the Numbers, Wm. C. Mitchell Software, 125 E. Plaza Drive, Suite 117, Mooresville, NC 28115 USA

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