Vehicle Dynamics through Multi-body dynamics

Introduction
Competitive motorsport at any level is a matter of the final 0.1%. What is meant by that is the winner will be only a faction better than the person who comes second and any competitive edge gained (even 0.1%) might be the difference between winning and losing.

Vehicle handling can play a crucial role in gaining this edge. The Dynamic events are designed to test the handling characteristics of the vehicle to the last detail. Clever vehicle handling design stems from strong understanding of vehicle dynamics. Multi-body dynamics simulation through Motion View and Motion Solve is a strong tool to help students and professionals alike to validate and test out their vehicle dynamics knowledge and vehicle design.

Tyres and rubber

Introduction
Any lecture/presentation/training talking about vehicle dynamics will start with a discussion about tyres. Tyres are the mechanical link between the vehicle and the road. Every non-aerodynamic force and moment that acts on the vehicle will be through the tyre and understanding the functioning of tyres is the key in understanding the dynamics of the vehicle.

Tyres are complicated rubber interfaces with the road. Multi-body dynamics, can involve computations of detailed mathematical models of the tyre. Fortunately we can develop our understanding with simple ideas about the tyre “contact patch” and later move on to more complicated mathematical tyre models.

The contact path
Tyres work because of rubber friction. The normal load applied by the weight of the vehicle deforms the rubber. There is a flattened piece of rubber in contact with the road which is called the “contact patch”. The contact patch is where all the tyre forces act. The rubber in contact with the road pushes on the road and static friction between the rubber in the contact patch and the road is responsible for the tyre force.

Frictional forces have their limits beyond which the rubber would start to slide and a lesser (than peak static friction force) frictional force will be applied at the contact patch. This is when the vehicle tyres at beyond their limits, slide around and the driver loses control. The maximum tyre force is also called “available tyre grip”. For maximum performance it is desirable that the tyre forces stay at the maximum grip levels while not sliding. When the tyre is sliding the driver has little control over the vehicle and the maximum force generated is less than the peak force when the contact patch is not sliding.
Friction Circle
It is important to understand that the tyre force produced by friction is resolved into 2 significant components. They are –

- **Longitudinal force**
  The force applied in the direction that corresponds to “straight ahead” for the tyre. This force is responsible for the acceleration and braking forces that are produced by the tyre.

- **Lateral Force**
  The force applied in the direction of the spin axis of the wheel. This force is responsible for the steering (lateral) forces which enable a vehicle to make a corner or turn.

It is important to note that these are components of the forces so they do not have independent peak (maximum) force values, the overall force has a peak value at a given vertical load. This implies that if the tyre at a given point of time is producing peak longitudinal force its peak lateral force producing capacity is very close to zero and vice-versa. More generally, more the lateral force a tyre is generating the peak longitudinal force comes down.

This can be graphically plotted as a plot of peak lateral force at different longitudinal force values. This plot forms a closed loop and is popularly known as the tyre friction circle. The tyre is considered to be on the limit when the point corresponding to the current lateral and longitudinal force produced by the tyre is on the boundary of this loop. If the point is inside it means that there can be more force (lateral or longitudinal) drawn, and if the point is outside it means that the contact patch is sliding.
Note: Usually the peak longitudinal force at zero lateral force is not the same as peak lateral force at zero longitudinal force. So the friction circle is more of a friction oval or a friction egg.

**Understanding Vehicle Handling**
The handling characteristics of the vehicle are also the function of the tyre force limits. If the front tyres reach their limit before the rear tyres the vehicle will “understeer” while if the rear tyres approach their limit before the fronts the vehicle will “oversteer”. Making the vehicle handle better involves doing 2 major things –

- Improve the “quality” of the contact patch to maximise grip available
- To maintain a balance between the combined grip levels for the front wheels and the combined grip levels of the rear wheels.

Typically in the design of the student competition vehicle, initially the front suspension of the vehicle is designed separately from the rear. During this phase half car models (front half and rear half) are built for simulation and focus is on the improvement of the quality of the contact patch.

Later the front half and the rear half car models are built up as one and the balance of the vehicle is improved.

**Wheel Alignment**
While designing suspensions there is often talk about wheel orientations. Terms like caster, camber and toe feature often as referred to during vehicle design. Here is a brief introduction of each term as per Wikipedia
Camber

Camber angle is the angle made by the wheels of a vehicle; specifically, it is the angle between the vertical axis of the wheels used for steering and the vertical axis of the vehicle when viewed from the front or rear. It is used in the design of steering and suspension. If the top of the wheel is farther out than the bottom (that is, away from the axle), it is called positive camber; if the bottom of the wheel is farther out than the top, it is called negative camber.

Toe

Toe angle is the symmetric angle that each wheel makes with the longitudinal axis of the vehicle, as a function of static geometry, and kinematic and compliant effects. This can be contrasted with steer, which is the anti-symmetric angle, i.e. both wheels point to the left or right, in parallel (roughly). Positive toe, or toe in, is the front of the wheel pointing in towards the centreline of the vehicle. Negative toe, or toe out, is the front of the wheel pointing away from the centreline of the vehicle. Toe can be measured in linear units, at the front of the tire, or as an angular deflection.

Caster

Caster angle or castor angle is the angular displacement from the vertical axis of the suspension of a steered wheel in a car, bicycle or other vehicle, measured in the longitudinal direction. It is the angle between the pivot line (in a car - an imaginary line that runs through the centre of the upper ball joint to the centre of the lower ball joint) and vertical. Car racers sometimes adjust caster angle to optimize their car's handling characteristics in particular driving situations.

Significance of wheel alignment

Wheel alignment determines how the tyre is in contact with the road, hence severely impacts the quality of the contact patch. All the parameters are equally important but for the purpose of this document we will talk only of camber.

Camber Effects on Contact Patch

A tyre is designed to run perfectly vertical with respect to the road. This is usually the situation when maximum grip is available. Any tilt in the tyre will reduce the grip. How much the grip will reduce by is a function of the tyre design and construction.

The reason for this is that the upright tyre has a uniform contact patch, in other words the pressure distribution in the deformed area is uniform. This ensures a large portion of the rubber is in contact with the surface and most of the rubber is producing static friction. When the pressure in the contact patch is uneven as the tyre nears the limits of its grip levels, some portion of the contact patch that is experiencing low pressure will start sliding, lowering grip levels.
Therefore it is safe to conclude that it is in the best interest of the designer to keep the camber at zero irrespective of the suspension travel. It is important to understand that is with respect to the road and not the chassis.

**Camber Change with Wheel Travel**
Depending on your suspension geometry, camber of the wheel will tend to change with wheel travel. Understanding this is one of the key aspects to understanding vehicle suspension design. Multi-body Dynamics simulations through Motion View and Motion Solve can be a powerful tool to visualise, analysis and optimise the change in camber along with other suspension parameters.

The suspension can be thought of a kinematic mechanism where the wheel is one of the links. The chassis is the ground body and all observations are made with respect to the chassis, making it easy to visualise. For this the concept of Instant Centres must be revisited.

**Instantaneous centre (IC)**
Instantaneous Centre (sometimes called Instant Centre) is a more general concept but with respect to suspension design it is the virtual point about which the wheel appears to rotate with respect to the chassis when there is wheel travel (Suspension moves up or down).

The instantaneous centre (IC) is the location found by the virtual intersection of the suspension links when projected on to a two dimensional plane. The suspension when projected on to the two dimensional plane rotates about this location.

The front view instantaneous centre is the virtual intersection of the suspension links when projected onto the front view plane. Therefore for an observer sitting in the chassis the wheel will appear to rotate about the Instant Centre as it moves up or down due to suspension travel.

It is important to remember that for most suspension types the IC keeps moving around with suspension travel and is not constant. Also, if the two suspension links are parallel the IC is at infinity and there will be no rotation of the wheel with respect to the chassis with wheel travel.

![Pressure Distribution Across Contact Patch](image-url)
The rotation of the wheel with respect to the chassis directly affects the orientation of the wheel with respect to the road. Then the vehicle hits a bump both the wheels travel up together with respect to the chassis and when the vehicle rolls one side moves up and the other moves down. As these movements happen, the camber of the wheel changes with respect to the road. The plot of the camber with respect to the road verses vehicle roll and wheel travel in bump are popularly known as Camber Curve.

**Demonstration of effects of the Camber Curve**

First let us consider the situation where the suspension is designed such that the Instant centre is at infinity. This means that the camber gain in bump is zero. That is, when the wheel moves up and down with respect to the chassis the wheel still stays upright.

In this situation let us look at the situation where the vehicle is braking. Braking causes the vehicle to pitch forward (dive). It’s easy to notice this while driving any car or while observing a car come to a stop. This pitching causes the body or the chassis of the vehicle to dip in the front. This lowering of the chassis with respect to the wheels will cause the wheel to rotate about the IC, but since the IC is at infinity there is no rotation and hence no camber gain.
This is a very desirable situation. The car is optimised in terms of camber gain to handle braking manoeuvres, the wheels stay upright, the contact patch is still flat on the road and maximum longitudinal force is available for breaking.

Now let us consider the same car while cornering. The vehicle will roll while cornering. This means that with respect to the chassis one of the wheels will go up and the other down depending on the cornering direction. With respect the chassis the wheel is still upright.

In reality of course the inner tyre does not go below the ground and the outer tyre above, the car chassis is rotated. On the road the cornering situation looks like this
Both the wheels are not upright with respect to the load. This will reduce the maximum lateral force that the tyres can produce. The maximum speed at which the vehicle can turn a corner of a certain radius will be lesser than the situation where the wheels would have been upright.

Suppose we want to design a vehicle which is good at cornering, then we need to make sure that the IC of the suspension would not be at infinity. We need to make sure that the IC is such that the wheel rotates around an arc relative to the chassis as it moves up or down.

In this situation during roll the wheels will still stay upright. This is very desirable as now during cornering the wheels can provide maximum grip. This will greatly improve the maximum speed at which a vehicle can make a corner.
Again, in the roll situation the wheels are actually on the ground and the chassis rotates, so the camber is still zero with respect to the road. As the next diagram illustrates –

Now let us observe what happens if we look at the same suspension configuration during braking and other straight line events.
We observe that now during the braking manoeuvre when the both the wheels move up with respect to the chassis. The wheels rotate with respect to the chassis such that they maintain the defined arch. This causes the wheels to be tilted with respect to the road and thereby reducing the maximum available grip in the braking and acceleration.

This means that neither of the 2 suspension configuration is the correct solution and a compromise needs to be found. A parallel configuration of the control arms will cause the vehicle to perform better in straight line events and the IC close to the centre of the vehicle will improve the cornering speeds but have an adverse effect on braking performance. The correct compromise is a designer choice based on a lot of factors which include expected terrain, performance strengths of the car, driver preference, etc.

**Multi-Body Dynamics Simulations**

Multi-body Dynamics Simulations using Motion View and Motion Solve are a powerful tool to visualise and analyse these suspension parameters. Camber Curves and other related information can be obtained by running half car simulations on a suspension models. Roll analysis and ride analysis will give accurate camber cures for both the situations. More information about how to conduct these simulations is available in the Half Car Analysis user guide.

The example here is just one of the design decisions and trade-offs that need to be made. Many similar trade-off decisions can be significantly aided by MBD simulations.