The Physics of SUV Rollover Accidents

- Can you calculate your vehicle speed in feet per second? (multiply mph by 1.47. For example, 60 mph = 88 feet/second.)
- Can you square that number? (like 88^2 = 7744.)
- Can you estimate the radius of a curve in a road? (like 250 feet).
- Can you divide the first by the second? (like 7744/250 or 31). This gives the LATERAL ACCELERATION of the vehicle. (like 31 ft/sec^2 or 0.97 G).
- Then you already know nearly everything you need to know whether your vehicle will roll over in that sort of turn!
- You DO also need two measurements of your vehicle. One is called the Track, which is the distance between the two tires on an axle (like 60”). The other is called the height of the center-of-gravity (like 30”).
- You then take TWICE the second number and divide it by the first (like 30 * 2 / 60 or 1.0) and multiply that by the acceleration you had gotten above. (like 31 ft/sec^2 * 1.0).
- IF that number is ABOVE 32, the vehicle WILL roll over. If it is BELOW 32, it will not.
- This example (31) would be extremely close to great danger.
- There IS the possibility that the tires might not have enough traction to the road, so the tires could break loose and slide straight, which could change the problem from a rollover to the vehicle going out of control.
- Pretty simple, huh? But that is essentially all that is needed to calculate an APPROXIMATE idea of whether YOUR vehicle is stable or not at any speed and around any turn! There are some additional factors, but they all make the situation worse and never better.

The reasons why SUV rollover accidents happen so often are simple High School Physics. With a high center-of-gravity and a comparatively narrow track, such vehicles are relatively unstable as a natural fact. Unless either the Track is greatly widened or the center-of-gravity lowered, the situation cannot be improved.

Near the end of this presentation, I suggest the possibility of using an extremely old technology of automatically changing the height of the vehicle suspension. That was popular in luxury cars in the 1970s for leveling out the ride when back seat riders were in the car. I see that as a simple and obvious solution for SUVs and other tall vehicles now. At LOW speeds, like for off-roading, the suspension could be as high as is popular on SUVs. But as the vehicle sensed greater road velocity, as on a highway, the suspension could smoothly lower down to a height where the vehicle
was far more stable and even UNLIKELY to be able to rollover. Not very expensive to add to vehicles, old and proven technologies, but something that would certainly save many lives. From the vehicle manufacturer's viewpoint, also greatly reduce the number of lawsuits they constantly face!

A 2001 PBS FrontLine program about SUV vehicle rollover accidents amazed me that no one, among the carmakers, among the legislators, or among the researchers, seemed to understand the very basic Physics involved! When I taught High School Physics, I gave problems comparable to that to the students!

In that FrontLine program, they showed an "expert" (in that case, from Ford) comforting the Judge in a Court Case by informing the Judge that they had fully analyzed the situation and they would widen the track of their SUVs BY TWO INCHES, and that that change would completely solve the problem! The Judge seemed comforted, but only because the Judge did not know enough Physics to realize that would produce a very MINIMAL improvement, and the basic danger would still remain. It has always been my understanding that when anyone is Sworn in in Court, and then knowingly and intentionally LIES about important facts, that is supposed to be called Perjury???. Maybe I am wrong about that, that "experts" are allowed to alter the truth!

This presentation will describe the physics (and math) of what occurs, for NON-physicist-types!

First, whenever a vehicle turns, Newton's First Law indicates that it wants to go straight, so the tires must therefore create a lateral "centripetal force". This is entirely due to friction between the tires and the roadway. If the road is icy and slick, there is generally not a high enough "static frictional coefficient" to cause the force described here. The vehicle would then not roll over but slide straight, possibly having DIFFERENT problems! A rollover situation can only occur if there is enough friction between the tires and road to create sufficient centripetal force.

Sidebar regarding Centrifugal and Centripetal!

Virtually all non-Physicists regularly talk about Centrifugal force. That drives Physicists crazy, because there is actually no such thing! Circular motion can only occur for any massive object, if there is a CENTRAL force, or what is called a Centripetal force. A vehicle going around in fast donuts (circles) (kids, don't do this at home!) are able to do that because the tires have enough traction to provide the necessary Centripetal force to enable the vehicle to keep turning. Ah, but Newton told us that all (massive) objects try to go in straight lines unless a force is applied to them. Therefore, YOU, sitting IN that vehicle doing circles, are actually trying to go off on a straight line, at every instant! The vehicle keeps scooting sideways out from under you (due to the Centripetal force provided by the traction of the tires on the road). From YOUR point of view, where you tend to consider the seat of the vehicle to be a "reference frame" (a high-class term!), then you definitely feel that you are constantly "being thrown outward by Centrifugal force". Nope! Didn't happen! But the seat-belts are certainly applying strong (centripetal) forces to your body to cause you to go in the same circle that the vehicle is going.

There are all sorts of things where we imagine that a Centrifugal force is existing, but in every one of those cases, the reality is that the effect is just due to Newton's INERTIA trying to cause an object to keep its current motion, like a speed, in whatever direction it is now pointed. So there really is no such thing as Centrifugal force, even though even Physicists occasionally mention it!

More advanced: (be warned!) A constant velocity circular motion can be described in a coordinate plane...
as $\theta$ (angular position) * $r$ (radius of the circle), as giving a location on that plane. In familiar x-y terms, we could say that the POSITION is $x = r \cos(\theta)$ and $y = r \sin(\theta)$. (where $\theta$ constantly increases at a constant rate in time, and we can specify that rate of change of $\theta$ as $\omega$, an angular velocity) The position vector is then from the origin to a point on the circle at position-angle $\theta$. We could do a simple Calculus magic of Differentiation of this, to get VELOCITY quantities, which are $dx/dt = -\omega \cdot r \cdot \sin(\theta)$ and $dy/dt = \omega \cdot r \cdot \cos(\theta)$. (where $\omega$ is the angular velocity). We could do that same Differentiation a second time to find the ACCELERATIONS along the x and y axes, which are $dx^2/dt = -\omega^2 \cdot r \cdot \cos(\theta)$ and $dy^2/dt = -\omega^2 \cdot r \cdot \sin(\theta)$. (These are the rates of changes of the speeds along those axes, in other words the accelerations.) By comparing these acceleration values with the position values, we can see that they are identical, except for a constant factor of $-\omega^2$.

**What this means is that this acceleration, required for the constant speed circular motion, is negative, meaning that it is opposite the direction of the position vector, which means it is always exactly toward the origin, in other words a CENTRAL acceleration. We even know that that acceleration (for a circular motion) is always exactly $-\omega^2 \cdot r$.** Newton also told us that an acceleration times the mass involved equals the force, which means we are talking about a Central (Centripetal) Force for this circular motion. We have even just proven that the (centripetal) acceleration is exactly proportional to the square of the angular speed $\omega$. Therefore, we have proven that circular motion can only occur under the influence of a central (Centripetal) force, and even the equation for calculating it!

Below, you will sometimes see this presented as $v \cdot v$ (square of velocity) / $r$ in the equations, which is just the same thing because $v = r \cdot \omega$. Therefore, $-\omega^2 \cdot r = v^2/r$, and either describes the centripetal acceleration for circular motion.

We show the tire-road frictional force as the red arrow to the right in the drawing above. This represents a turn to the right. That force, acting on the vehicle, is just the simple $F = ma$ (force equals mass times acceleration, as Newton said), expressed for a curved motion. For this example, we will consider a vehicle turning in a circular course, to the right, approximately like circling clockwise in an intersection, with a circle radius of 25 feet. Say the vehicle weighs 3200 pounds, and we will consider it moving at 20 mph. (20 mph is equal to about 29.3 feet/second). And the acceleration due to gravity is 32 feet/second/second. Now you know everything necessary! (Metric: $r = 7.6$ meters; $m = 1450$ kilograms; $v = 8.9$ meters/second, and $g = 9.8$ meters/sec$^2$.)

With the force due to the tire-road friction being to the right, there is an effect, often called centrifugal force, that then also seems to exist to the left. It is actually just the condition of the vehicle wanting to go straight (in accordance with Newton's Laws) and so this apparent centrifugal force (to the left) is exactly equal in size with the (actual) centripetal force (to the right) making the vehicle turn the corner. Sorry about the confusing two words! The driver feels as though there is a force on him to the left. The reality is that the vehicle and seat are moving to the right underneath him, and the driver has that sensation (of centrifugal force) only because his body is trying to go straight.

The $F = ma$ for a circular motion is in the (familiar) form $F = (W \cdot v \cdot v)/(g \cdot r)$ or (the more scientifically correct form) $F = (m \cdot v \cdot v)/(r)$. [W = vehicle weight; v = velocity/speed; r = circle radius; and g = acceleration due to gravity. In the English system, m is an odd unit called slugs which describes MASS. Our
example vehicle has a mass of 100 slugs, but we will try to avoid mentioning slugs very much, because few people have ever heard of them except in Physics classes!]. That version of Newton's Law is very straightforward. (It's actually in the sidebar box above) This gives a centripetal force for our example: \( F = \frac{3200 * 29.3 * 29.3}{32 * 25} \) or around 3400 pounds! In the version that uses slugs, it is \( F = \frac{100 * 29.3 * 29.3}{25} \) which is the same 3400 pounds.

When people do this calculation in the metric system, some seem to misunderstand one part of it. So it might be clearer (in either system) to focus more on the ACCELERATION involved and not worry quite as much about the FORCE. So we have \( a_{\text{centripetal}} = \frac{v^2}{r} \). In the English system, for our example, this would be \( (29.3 \text{ f/s})^2 / 25 \text{ feet} \), or about 34 ft/sec\(^2\). In the metric system, the comparable numbers would be \( (8.9 \text{ m/s})^2 / 7.6 \text{ m} \), or about 10.5 m/sec\(^2\). They are the same. The English system has that goofy unit of mass called the slug, which virtually no one has ever heard of! The familiar Weight in pounds is equal to the mass in slugs times the acceleration due to gravity (32), so our 3200 pound vehicle has a MASS of 100 slugs. We could have used more precise science and simply multiplied the centripetal acceleration times the mass is slugs, and got 34 * 100, or the same 3400 pounds that we just calculated above. But virtually everyone would have their brain short-circuits by the reference to slugs! Therefore, we presented the far more common version of the centripetal force formula that has WEIGHT in it and not MASS. The specific situation of pounds and slugs is probably the BEST argument for the US going to the Metric system, to avoid this sort of confusion, which happens regularly in students!

We probably caused a little extra confusion above by using the most common version of the centripetal force formula which uses WEIGHT. In any case, that strange problem does not occur in the metric system so there is a factor of 9.8 which does NOT exist in the metric formula.

That is the force that the tires traction must exert sideways on the vehicle to make it turn in the circle rather than going straight the way it would have normally wanted to go. (On an icy surface, tire traction is poor and nowhere near that much side force can be applied, and the vehicle slides straight instead of going around the turn. Now you know why!)

By the way, in nearly all vehicles, if you try to turn really fast circles (doughnuts) to try to rollover a vehicle, the tires nearly always break free of the pavement before enough side force can be produced. But when a vehicle is ALREADY traveling at speed, and a sudden and extreme side turn is made, the tire traction can exist long enough to cause a rollover. This is related to the fact that there are TWO different frictional coefficients between the tires and the roadway. A STATIC coefficient of friction is usually slightly higher than the DYNAMIC coefficient of friction. As long as traction is maintained, then the higher STATIC value applies, but as soon as the tires start sliding, the lower DYNAMIC value applies. Now you also know why once you lose traction, it is so hard to get it back!

With switchback turning (zig-zagging) the (static) tire traction can be plenty for such a rollover. And this is the source of the danger being considered here. We are going to downplay the Physics of the two different coefficients of frictions, as well as the fact that different roadway surfaces and whether it is covered by dew or rain or snow or motor oil, all can affect what those coefficients are. And also that new and old tires also tend to have different coefficient of friction, and even different chemical formulations of the rubber in the tires can affect those coefficients. We leave such subjects for a different venue!

We have shown this force acting at one point of the vehicle, often called the center-of-gravity. That statement is technically not precisely true in actual calculations, because the vehicle has three different ROLL AXES (each of which has to pass through the center of gravity point). This presentation focuses on the SIDE ROLL AXIS, which is an imaginary LINE that passes through the vehicle from front to back, at the height and lateral location of the center-of-gravity. (For other purposes, the roll axis that passes laterally through the center-of-gravity is used to calculate the bucking-bronco rocking of a vehicle, used in designing
shock absorbers and suspension; and the roll axis that passes vertically through the vehicle is used to calculate vehicle handling and weight distribution matters. Again, different subjects for different venues!)

Since the vehicle is considered here as one solid object, it can be mathematically treated as though all of its weight is at that one point. We are now going to change our position and look at the vehicle from the front, and we see the red spot that indicates the center-of-gravity.

OK. That's the sideways force that has to be acting on the vehicle, by the tires' grip on the road, in order for it to go around that-sized circle at that speed. Now we need to look from the front of the vehicle. We see the points where the tires contact the road. The distance between them is called the "track". A red point is marked up on the body of the vehicle, on its centerline. This is called the "center of gravity" of the vehicle. It is the line through the length of the vehicle on which the entire vehicle could be balanced. Imagine a giant barbecue spit rod going through the vehicle at that point. As that rod would be turned, the vehicle would stay balanced and would turn smoothly.

In other words, the entire weight of the vehicle acts as though it was at that point/line, height. Viewing from the front, we're looking at the end of that line, so it looks like a point in our drawing.

Now, we have that all of the weight (mass) of the vehicle acts as though it is at the height of the center-of-gravity, and that there is a lateral force, the centripetal force being applied by the tires and road AT THE HEIGHT OF THE ROAD SURFACE on that weight, to the left in our drawing. This horizontal force does NOT act directly at/on the center-of-gravity directly because it is at the wrong height. Therefore, it not only acts to push the weight/center-of-gravity sideways but it also acts to try to twist the vehicle around the center-of-gravity. This twisting action is where the problem arises.

In basic Physics, forces can be analyzed for the separate effects of translation (straight-line motion) and rotation. This can be done equally correctly in different frames of reference. So far, we have been considering the force acting ON the vehicle as seen from the ground, and so we would draw our horizontal arrow TO THE LEFT in this drawing at a height of the bottom of the tires. This would represent the ACTUAL centripetal force acting on the vehicle by the road, and would be analyzable as to both translation and rotation effects. I think it may be easier to understand if we look at this in a different, but exactly equivalent way. Instead of saying that the centripetal force is acting to the left (in our drawing), at the height of the tires, we can say that there is an identical force to the right, acting ON the center-of-gravity. The effect is exactly the same, regarding the action to rotate/twist the vehicle, but I am hoping that the arrows and discussion might better show why this acts to roll the vehicle over sideways.

Here is the (3400 pound) sideways force that is acting on the vehicle, as seen from the front, and still acting on the center-of-gravity. In this drawing, you can see that if the (outer) rightmost tire is held from sliding sideways to the right (by friction with the roadway), then the force arrow will act to try to roll the vehicle over (to the right in the drawing). This all happens because the height of the center-of-gravity and the height of the frictional force with the road are at different heights, which then allows the twisting effect as a result.

Now, this does not mean that every turn results in a rollover! All (three or more-wheeled) vehicles are "meta-stable" because they have contacts with
the roadway which are spaced apart sideways. In the case of conventional vehicles, these are the tires on the left and right sides of the vehicle. Where a bicycle does not have this advantage, and can easily be pushed over sideways (being naturally unstable). The sideways spacing of the tires on conventional vehicles, called the "track", makes for better stability regarding rolling over. Again, looking at this drawing, you can see that the force arrow shown would actually have to LIFT UP the weight of the vehicle (a little) in order to roll it over. Consider this drawing with the vehicle tilted up balanced on those rightmost two tires and you will see that the center-of-gravity has raised up, to be straight above the point of contact of the tires with the road. This necessity of "lifting" the vehicle weight up is what provides the meta-stability for normal driving. However, with ANY vehicle which has its center-of-gravity above the road, in other words, ALL actual vehicles, if sufficient lateral force is applied by the tire-road friction, the vehicle can rollover. We are going to proceed with the analysis of this now.

Maybe we can describe this in yet another way that might be useful. We had earlier examined the ACCELERATIONS which are present. In our example, we saw a HORIZONTAL acceleration of 34 ft/sec² due to the attempt to follow a circular path. We also had the natural (VERTICAL) acceleration due to gravity of 32 ft/sec². We will shortly examine an SUV which happens to have this drawn angle at exactly 45°. The basic point being made here is that the angled line we show just below has ONE (VERTICAL component of the) acceleration which is trying to keep the vehicle shiny side up, gravity, of 32 f/s² and a SECOND (HORIZONTAL component of the) acceleration which is trying to roll it over, the centripetal force, of 34 f/s². In this specific case, foregoing the drama, the rollover acceleration (force) will win!

In physics, the angled force shown just below can be thought of as a "resultant force" which is a combination of two "component forces."

We know that the tire treads are going to somehow be involved, especially since we know that on icy roads, the vehicle does not turn. So we know that the sideways force must be being applied between the tire treads and the roadway.

Our (horizontal) force in the previous drawing can therefore be thought of as a combination of two separate component forces. One of the component forces is directly toward the tread of the tire, as shown here. This component is actually the portion of the force that actually acts to give the vehicle sideways force (through the tires' friction with the road) to make it turn. More to the point here, this component does NOT act to try to rotate/twist the vehicle.

This is the physics way of showing how the tire treads are able to transfer a sideways force to the vehicle, to make it possible to turn corners.

More Technically Presented:

In actual Physics, this subject of rotational effects is described in terms of something called "moments". A moment is a Force acting on an "arm" to cause a torque or a tendency to rotate. In this case, there is one moment that is due to the weight of the SUV, and in our example that moment is a Vector aimed toward the FRONT of the vehicle (don't ask!) of $\mathbf{W} \times \mathbf{r}$ which has a magnitude $W \times r \times \cos(0)$. The moment that is
due to the horizontal lateral force is a vector aimed toward the rear of the vehicle of $F \cdot r$ which has a magnitude $F \cdot r \cdot \cos(90° - \theta)$ or $F \cdot r \cdot \sin(\theta)$. In the situation of being just about to roll over, these two must be equal, or $F \cdot \sin(\theta) = W \cdot \cos(\theta)$, or $F \cdot \sin(\theta) / \cos(\theta) = W$, or $F \cdot \tan(\theta) = W$. $\theta$ is the angle between the two red arrows shown in the two drawings above, and $r$ is the actual (angled) distance between the center-of-gravity and the tire tread. If $F$ is any greater than that amount, the vehicle will roll over.

An equivalent description in physics considers that $F$ acts to rotate the vehicle (to the right in our drawings) at a height of the center-of-gravity (which is $r \cdot \sin(\theta)$); and the weight $W$ acts to rotate the vehicle (to the left, around the outer, rightmost tire) at a horizontal distance of half the tire track (which is $r \cdot \cos(\theta)$). You can see that this gives the exact same equations.

Since the height of the center-of-gravity of a particular vehicle is known, as is its weight and its tire track width, $F$, the maximum sideways force before rollover is easily known for any vehicle. It would be totally incompetent if Ford engineers, for example, did not know this value, as they testified in court!

Actually, documents show that they were fully aware of these matters! Around 1980, when the Ford Bronco was first being developed, Ford engineers used a term Stability Index, because they were already aware that tall vehicles like that have a tendency to have rollover accidents. That Stability Index was simply the fraction of the track width dimension divided by the height of the center-of-gravity. Actually, that concern was known even earlier, with the Jeep CJ-7. Jeep had even made an incredible blunder in making and airing a TV commercial, where an eagle-eyed viewer eventually noticed that the Jeep in the commercial had nearly rolled over during the commercial! The viewer had noticed that one of the Jeep's wheels had lifted off the ground!

At that time, the Stability Index of the CJ-7 was 2.04 and the design that had been chosen for the Ford Bronco was slightly worse at 2.03. Ford's early testing with the Bronco therefore also found regular problems in the danger of rollovers. But the Ford Executives did not seem that interested! Around 1981, Ford engineers were challenged to find solutions to the rollover danger. They came up with five potential solutions. Three of the solutions would have provided substantial improvement in safety, one even increasing the SI to 2.25. But Ford Executives rejected the better solutions, because they would have required extensive re-design and also changed the overall appearance of the vehicles. So a design that had an SI of 2.03 was chosen. There were extensive testing programs planned for this design, but early on, test drivers became terrified at having to test the Bronco, and the testing was soon stopped. For the first six years that the Bronco was sold on the market, essentially no actual safety testing had been done on it!

Later, the terminology changed, and the term became Static Stability Factor. Part of the reason for that change was that there were also DYNAMIC factors involved in rollover accidents. Specifically, larger Ford vehicles use a front suspension called a Twin I-Beam Suspension. That design has some advantages, but it causes dynamic disadvantages regarding rollover accidents. The action of that particular suspension has the effect of (dynamically) bringing the front two wheels closer together (reducing the Track) while also jacking the vehicle UP higher (increasing the height of the center-of-gravity). BOTH of these dynamic effects INCREASE THE DANGER of rollover accidents (per the calculations presented in this page). These added dangers of the Twin I-Beam Suspension were known as early as 1965. However, the dynamic aspects are much harder to experimentally measure. Therefore, it was apparently decided that simply describing the STATIC Stability Factor, would be sufficient. This new SSF is exactly half of the older SI value, HALF the Track divided by the height of the C-G.

Manufacturers seem to never want to describe the heights of the C-G of their vehicles! So even though the Track is easy to find or to measure, getting the correct value for the C-G height is hard to do! The government
and some independent organizations present data from crash testing, which can include the number for the SSF for vehicles. For example, the 2009 Ford Escape has an SSF of 1.13. A 2009 GMC Envoy is 1.17. More standard shaped vehicles have greater values, which indicates their much better stability and less rollover danger. For example, a 2009 Chevy Impala is 1.39 and a Chevy Malibu is 1.41.

We will continue this discussion with separate references to Track and height of the C-G, as is usual in Physics.

The other component force (of the horizontal lateral force discussed above) is at right angles to the component between the C-G and the tire tread, and so it is aimed upward and outward, as shown here. This component acts to roll the vehicle over, around that (outer) tire tread.

We are concerned about the extreme situation where the vehicle actually WOULD roll over sideways. From our front view, we then need to know the force necessary to act AT the center of gravity, AROUND the outermost tire treads, as shown in this drawing. Let's call this $F_{\text{unknown}}$. This force is upward at a $(90 - \theta)$ angle, which depends on the geometry of the vehicle. You can also see that the magnitude of this component, $F_{\text{unknown}}$, is $F_{\text{horizontal}} \times \sin(\theta)$. (We already know the value of $F_{\text{horizontal}}$)

You can see that this is the direction that a force would have to act in order to "roll" the vehicle over that tire's point of contact with the road. It represents the "torque" around that outer tire tread, due to the turning.

We're not quite done! This angled force component can now be considered to be a combination of a vertical and a horizontal force. If the vehicle is going to be about to roll over, the UPWARD part of it (shown as a yellow arrow) is what we are interested in and it must be at least exactly equal to the weight of the vehicle. That would then LIFT the weight of the vehicle up off the roadway. The (red) upward angled force gets a leverage advantage around the tire tread, and so it is able to have a lifting effect greater than its own strength, actually, equal to its strength divided by the cosine of $\theta$. If the vehicle is about to roll over, this lifting effect must be equal to the weight of the vehicle. $F_{\text{unknown}}$ therefore equals Weight $\times$ cosine($\theta$), (or Weight $= F_{\text{unknown}} / \cos(\theta)$). The cosine can never be more than 1.00, so this means that its leveraged (lifting) effect is always greater than its true force.

Standard geometry is then all that is needed to get actual numbers! It tells us that this angled (red) $F_{\text{unknown}}$ must therefore be the weight of the vehicle times the cosine of the angle shown ($\theta$, between the red and yellow arrow).

We already found that the force we have been calling $F_{\text{unknown}}$ is equal to the horizontal force times the sine of the angle we mentioned earlier. Since these two would be equal for the situation where the vehicle is just barely rolling over, we find that $F_{\text{horizontal}} \times \sin(\theta) = \text{Weight} \times \cos(\theta)$. Writing this differently, we now know that the actual upward lifting force on the vehicle, which must then be equal to W, is equal to the horizontal force times the sine/cosine or the tangent of the ($\theta$) angle we have been describing. That's all there is!

For a rollover to begin to occur,

$$F_{\text{horizontal}} \times \tan(\theta) > \text{Weight}.$$
We learned $F_{\text{horizontal}}$ up above, as ONLY depending on the speed and radius of the turn and the weight of the vehicle. The only part not yet known is the angle $\theta$.

Now let's look at determining that angle. The wheel spacing (track) on most domestic vehicles is less than around 60" apart (center of tread to center of tread) (The specific vehicle shown here has about a 56" track). The center of gravity of a vehicle is always very close to its centerline, so it is around half of the track-width sideways (inward) from either tire. Rather than using a 56" track, we will use a more generous (and more stable) 60" track for our example calculations. Half of that easy-to-measure distance is therefore 30". This is the horizontal green line shown here.

The center of gravity is always above the ground. For a fairly tall vehicle like an SUV, it can commonly be 30" (or more) above the ground. Vehicle manufacturers used to divulge the height of the center-of-gravity of their vehicles, but they no longer do. For the vehicle illustrated, we believe that the center-of-gravity is probably around 34" above the road surface. Rather than using that value, we will again use a more generous (and more stable) 30" height for our example calculations. This is represented by the vertical green line shown here.

Now, look again at the force acting between the tire tread and the center-of-gravity of the vehicle (in red). This force is at an angle which has a horizontal component proportional in length to half the track of the vehicle. It also has a vertical component that is exactly proportional to the height of the center-of-gravity above the roadway. We KNOW both of these distances! Therefore, the angle at the CG (which we have been calling $\theta$), between the red and green lines, is the angle whose TANGENT is equal to (Height of the CG)/(half the track). In the case of this example, that vertical side is 30" and half-the-track is also 30". This means that the angle we have been describing has a tangent of 30/30 or 1.000, and so our angle $\theta$ is 45°.

Since we now know the angle $\theta$ in the triangles we have been dealing with, we can do the final calculations. Using the specific dimensions (tread track and center-of-gravity height) of ANY vehicle, it is therefore VERY easy to quickly calculate at what speed it would roll over! No "expert", from Ford or anyone else, could possibly get away with testifying in court that he "does not know!"

We have already determined that the actual lifting force on the center of gravity of the vehicle is the centripetal force times the tangent of that angle, in other words in our example, 3400 pounds times 1.000 or 3400 pounds vertical lifting effect!

Now, since the vehicle only weighs 3200 pounds, there is only 3200 pounds of gravitational force holding the vehicle down, and so this 3400 pound lifting force is enough to lift it up and roll it over. Our example vehicle would roll over in making that moderate turn at just 20 mph!

That's all there is to the calculations! This is actually all way easier to do in math, than the very comprehensive way we felt necessary to present it here so that full and deep understanding might be had. Doing these calculations a second time should only take a minute or two! If the resultant vertical lifting force is less than the weight of the vehicle, it will not roll over; if it is more, it is certain to roll over.

In our example, at just 20 mph, our SUV vehicle would roll over when trying to turn in our 25-foot radius circle!

Actual SUVs are much heavier than we have used. However, the heavier weight increases the centripetal force proportionally, which increases the force that acts to roll the vehicle, EXACTLY in the same proportion...
that the necessary lifting force is increased for the heavier vehicle. The actual overall weight of the vehicle does not alter these results! It is not actually necessary to know the weight of the vehicle. Just being able to calculate the accelerations involved is all that is necessary. Heavier vehicles are no more or less stable than identical lighter ones. The track-width, the center-of-gravity height, the turning radius, and the vehicle speed are the ONLY necessary variables!

Now, a rollover accident at 20 mph might not be that dangerous. The problem arises when a higher speed tall vehicle makes a sudden steering adjustment, such as to avoid a deer or some object in the roadway. At 60 mph, the sideways (centripetal) force is NINE TIMES as great, because it depends, as explained above, on the SQUARE of the speed and we have tripled the speed. This means that, even if the radius of curvature of a sudden turn is NINE TIMES AS GREAT (225 foot radius, half a block), the vehicle WILL suddenly roll over! At 80 mph, it is 16 times as dangerous, and a 400-foot-radius (nearly one full city block radius) turn will result in the vehicle rolling over. Such steering actions may NOT seem very extreme to a driver, and many are totally surprised when the vehicle suddenly is out of control and about to roll over.

In other words, an SUV at 80 mph, simply changing lanes fairly quickly on an Interstate highway, can result in a sudden and unexpected rollover! And, at such a speed, whether the SUV hits any other vehicles or not, very bad results are likely for the occupants.

(Feel free to duplicate the calculations above but for 80 mph and a 400 foot radius circle.)

You have seen semi trucks and trailers laying on their sides. The center-of-gravity is even higher for such vehicles, but their Track cannot be much wider. And so when a truck driver needs to suddenly change lanes at highway speed, many of those drivers are totally surprised that their vehicle is suddenly out of control and in the process of rolling over. It is the very same Physics and the same calculations.

Long ago, Ralph Nader wrote a book "Unsafe at any Speed" about the poorly designed Corvair cars. It is hard to see how that is not even more true today about SUVs! Since some States now have Interstate highway speed limits of 75 mph, SUVs can commonly be traveling at 80 mph and higher. The families inside them have NO idea of what a dangerous situation they are in! The worst part of all this is that all of the SUV manufacturers have always known this simple Physics! In order to sell the extremely popular SUV vehicles, they have chosen to ignore the amazing danger, and deny the public the information involved in driving in and riding in them!

IF the driver is TOTALLY AWARE of these dangers, fine. A very careful and cautious driver can probably avoid all situations where a sudden lane change might ever be necessary. But that seems to almost require a year-long driver-training course for SUVs! Younger and more inexperienced drivers rarely have any idea of the danger they really should be guarding against!

It is hard to see how the vehicle manufacturers will be able to financially respond to hundreds of thousands of lawsuits by people who will get injured inside SUVs. As of now (2002), they simply are aggressively working at keeping the publicity of all those crashes as quiet as possible, in a way reminiscent of the way the tobacco companies insisted that cigarettes "had never been proven to be dangerous". In both cases, the manufacturers certainly DID know for many years how terribly dangerous their products are. And, in both cases, the companies involved are so huge that the American economy could not handle their going out of business. Therefore, we still have tobacco companies prospering (and now with total immunity from litigation and with strong support from all State governments due to their large incomes from the tobacco settlement. It is hard to see how the SUVs could result in anything different.

The really sad part is that countless thousands of people are going to die while the SUV manufacturers continue to deny all culpability. At least, with the Corvair, Mr. Nader got public outrage started after only a few hundred people died from their failings. This SUV situation will cause the deaths of far more people, and
already has! But they are so popular, and the buyers and drivers of them BELIEVE they are safer inside them, that SUVs will continue to be extremely popular, until gasoline prices get so high that people start buying smaller vehicles.

(I realize that the above paragraphs are essentially an Editorial Opinion, and not usually heard from a Physicist, but it seems outrageous that so many people are dying just because giant corporations insist on selling popular products, even though they are extremely dangerous. If that is not a deja vu regarding cigarettes, I don't know what is!)

Back to science and Physics!

In the case of a sudden turn, the effect is actually greater than this, because there are momentary dynamic accelerations and forces involved, which are greater than the constant circle forces we have calculated here. The calculations for that get a little more complicated, but it always acts to make a vehicle even MORE prone to rollover accidents. In this case, heavier vehicles actually have a greater inertia, and so the increase in danger due to these dynamic accelerations is greater for them than for lighter vehicles.

The point of much of this discussion is that it is relatively simple to calculate these things! It would not be necessary to keep doing road tests with vehicles constantly going up on two wheels, as the government and testing labs keep seeming to do.

The general form of the calculations above is vertical LIFT = centripetal force * Tangent(θ). In our case, that was 3400 * (1.000) or 3400 pounds lift. The 3400 pounds of centripetal force was easy to calculate, using Newton's formula based simply on the speed and the radius of the turn. θ is easy to calculate from two simple measurements of any vehicle. Why do "experts" claim to not understand such things, and even testify to such ignorance in Court?

The PBS FrontLine program included some "manufacturer's experts" claiming that widening the track by two inches would do miracles. That was clearly a lie! Isn't that Perjury when someone knowingly and intentionally lies in a Courtroom? It is easy to do this math again to show that it would only make an incremental difference. In our example, widening the track by 2" makes our horizontal 30" into 31", while leaving the center of gravity height of 30" the same. It is easy to check that this geometrical change makes our 45 degree angle now become 44.06 degrees. The tangent of that angle is 0.9677. When put in our problem, we would now have 3400 * (0.9677) or 3290 pounds, STILL making the vehicle roll over! The dangerous lift is only minimally reduced, from 3400 to 3290 pounds! A two inch wider track would have a VERY slight benefit as to safety from rollovers. A benefit, true, but so small as to not provide significant extra safety for passengers. Actually, where our original vehicle could have made our circle at up to 19.3 mph while being on the verge of rolling over, the one with the two inch wider track would be able to do it at 19.6 mph instead, less than half a mph improvement!

Sports Cars

For comparison sake, a (much lower) sporty car, also 3200 pounds, making the same circles as described above, but with a center of gravity 14" above the ground, would have the same centripetal force, 3400 pounds.

But that angle θ would be around 25 degrees, and the lift calculation would be 3400 * (0.4667) or 1587 pounds. Absolutely no danger of rollover, as 1587 pounds vertical lift is FAR less than the 3200 pound vehicle weight. This explains why cars rarely roll over while the taller SUVs do so far more often.
Recovery is Very Difficult, even for a Professional Driver

Once a rolling action has begun, everything gets a lot worse, very fast. This drawing shows the situation once a vehicle has tilted only 10 degrees sideways. With some soft vehicle suspensions, and under-inflated tires, this much of a (body roll) tilt is nearly possible while all the wheels are still on the pavement.

Let's look at how the forces we have been discussing change.

To start with, this doesn't look all that different.

But compare this drawing with the similar ones above. You can see that the center-of-gravity has gotten a little higher. At a 10° tilt, it is actually raised up by 5.2". And if the tire's low pressure allows it to deform horizontally, then it is less far horizontally from the tire footprint. We will estimate 2". These two effects combine in making that important $\theta$ angle bigger. We would now have (vertical) 30 + 5.2 or 35.2" and (horizontally) 30 - 2 or 28". The tangent is now 35.2/28, or 1.257. Our 3400 pound horizontal centripetal force then would have the effect of 3400 * 1.257 or 4274 pounds of vertical lift!

The (initial) 3400 pound lifting/rolling effect has already gotten FAR greater, above 4200 pounds already. Even worse, there is now no realistic chance of recovery. Where the problem began with a lifting force just a little more than the vehicle weight, as soon as the vehicle starts tilting, the geometry gets catastrophically worse. An experienced driver would tend to immediately try to straighten the wheels out. In many vehicles, and if the driver reacted fast enough, this can resolve the rollover situation safely. However, the driver had had to steer the vehicle toward a direction that might not be safe or acceptable! He might even then have to again make a fast steering change to cause a second start of a rollover. But in tall vehicles such as SUVs, there is a common tendency for a driver to rock the vehicle back the other way (inertia, momentum, etc) (again depending on what obstacles are nearby) and the action of trying to recover tends to cause even faster steering actions and therefore can cause the SUV to roll over to the opposite side. So, even experienced drivers have great difficulty in recovering from incipient rollovers in tall vehicles. Imagine a less experienced soccer mom!

FYI: This is why test vehicles always have those "training wheels" arms on them, because once a rollover begins, it gets so much worse so fast that even professional drivers have great difficulty in recovering.

(Once a rollover has begun, the geometry actually gets even more complicated, but always WORSE, involving the dynamic rotational inertia of the vehicle and the fact that the effective weight of the vehicle becomes less (even zero as it crosses above the tire tread), but this last calculation essentially shows how the problem gets far worse as the rollover proceeds. These complicating effects all act to make the rollover effect even worse. All of the earlier "level vehicle" calculations were exactly correct. They represent the most generous analysis regarding stability.)
Passengers and Luggage

There are additional dangers that can be involved. We have been considering a vehicle that is essentially empty, where the center of gravity is as low as it can be. If an SUV is fully loaded for a vacation, with six people riding in it, the effective center of gravity of the vehicle actually rises! Seated up on the seats, a human's weight may have a "personal center-of-gravity" around 42" (or more) above the road. Six two-hundred pound men then adds 1200 pounds of weight at this higher center-of-gravity. The effect is to RAISE the net center-of-gravity of the vehicle. A few hundred pounds of luggage up on top of the roof luggage carrier similarly greatly raises the effective center-of-gravity of the vehicle. These things each make the vehicle even MORE unstable, as it decreases that angle we have been discussing. It is easy for anyone to follow the logic above and calculate the rollover speed if the center of gravity was effectively six inches above the empty center of gravity, and it is frightening how much even more dangerous it becomes.

Low Tire Pressures and Soft Suspensions

Such vehicles tend to have very harsh suspensions, and so the "ride" is very rough. The manufacturers feel the need to use such stiff suspensions to MINIMIZE body roll, in acknowledgement of the stability issues being considered here. However, manufacturers such as Ford chose to give a recommendation of an unusually low air pressure for the tires for such vehicles, in order to create a smoother ride. The many deaths caused by accidents of their vehicles in association with Firestone tires, were directly related to this, for at least two very clear reasons. Since the tires had such low pressure, they have a tendency to "roll" (distort) more due to the centripetal force exerting a side force on the tire treads in causing the vehicle to turn. The low pressure actually allows the tread portion of the tire to shift inward sideways a fraction of an inch, relative to the rim of the wheel. This acts to LOWER the wheel, a substantial amount. This effect both tilts the vehicle sideways and changes the basic geometry of these calculations above, resulting in greatly increasing the vertical lifting force on the vehicle due to a specific centripetal force. This greatly increases the rollover danger. That aspect has nothing to do with any inherent flaws in the tires, but in the extremely poor engineering involved in recommending low tire inflation pressures for vehicles that were so unstable to begin with.

The other reason that the recommended low tire inflation pressures caused the accidents and deaths has to do with the normal way a tire functions. Each time a tire rotates, its sidewalls have to bend/flex/deform as that part is in contact with the road, as it must briefly support the weight of the vehicle. This causes the sidewalls of the tire to flex every single revolution. This flexing ALWAYS creates frictional heat within the sidewalls of the tires. After a long highway drive, you may have noticed that the tires are too hot to touch! They can be as hot as 240°F! When the tire pressure is low, this flexing is greatly exaggerated, resulting in much more internal heating of the sidewalls of the tires. This is the primary reason why a tire that is extremely low on air pressure quickly blows out, because the sidewalls flex so much that they overheat and then fail, permitting the internal pressure of the tire to suddenly burst out.

When tires have abnormally low air pressure in them, on long trips of high-speed highway driving, they are especially susceptible to the sidewalls overheating in this way. For this reason, it is quite understandable that many tires failed and caused terrible accidents on those Ford vehicles and on all other SUV vehicles that recommend low tire pressures. This is actually an effect whether the vehicle is traveling straight or turning. If a particular tire had even a hint of a problem on its own, that situation would ensure that it would fail. So, whether or not the Firestone tires had any drastic flaw, even if they have a tiny additional inclination of a flaw as compared to other brands, the effect would have been tremendously magnified by the circumstances of the low recommended tire air pressures in those vehicles.

And then if a tire has a blowout, the situation arises where the driver has to very suddenly move the steering
wheel, to try to control the vehicle. The natural instability of the high center-of-gravity vehicles therefore added to the problem, to cause the many rollovers once the vehicle got turned a little sideways.

The driving public seems to think that these problems have "gone away". Or been fixed. They have not. All of the millions of NEW SUVs being manufactured and sold, still have this tremendous tendency toward rollover accidents. Just widening the track a few inches will not make them materially safer, as shown above. The very nature of a tall vehicle which is intended for use at high speed and in potentially abrupt maneuvers, ensures continuing danger. It seems amazing to me that so many millions of mothers entrust their children to regularly riding in such vehicles! They clearly have very little idea of how dangerous they actually are. They seem to ASSUME that just because the vehicle is so BIG, that it is a "tank" and therefore excellently safe for their children. That is not remotely true! It would seem that the manufacturers must be doing an effective effort at minimizing publicity of the many accidents! It's hard to imagine how they will be able to financially survive once hundreds of thousands of settlements for millions of dollars each will start being necessary.

Interestingly, the manufacturers cannot claim to not be aware of these matters! For example, Ford's various SUV vehicles have wider track dimensions VERY much in line with these calculations! For example, their very tall Excursion (77.2" tall) has a MUCH wider track (64" compared to 56") as compared to their own Explorer Sport SUV, which is 68.4" tall. It is obvious from that that they are VERY aware of needing a wider track dimension for the even more unstable taller models. That means that they have always known what they were doing to begin with! And, assuming that their Engineers were capable of the High School Physics presented here, they have been aware of the instabilities that are direct consequences of their decisions. This seems to imply an intentional knowledge that they were going to cause many injuries and deaths, which I see as far worse than just incompetence or unpredictable accidents.

For some years, I have seen what seems to be an extremely obvious solution to this danger. It is not even complex or expensive!

Around 30 years ago, I owned a Cadillac that had a feature where the suspension was self-adjusting regarding vehicle height. The car had very soft suspension to start with, and when several people would get in the back seat, the car initially tilted where the headlights were then pointed somewhat skyward. This feature sensed this and switched on some small electric motors that pumped a little hydraulic fluid into the shock absorbers. You would hear these little motors run for a few seconds as the vehicle leveled itself back out.

Regarding SUVs, it seems to me something very obvious to add! If the vehicle speed is UNDER 30 MPH, a dashboard switch could be flipped to raise the vehicle to the high ground clearance that all SUVs now have, for doing off-road exploring. However, at all other times, the vehicle suspension would lower the entire SUV by maybe six inches vertically. That still leaves plenty of ground clearance for highway driving, but it importantly LOWERS THE CENTER OF GRAVITY BY SIX INCHES.

This would essentially eliminate the tendency of rolling over! You can do the math based on the equations presented above to see this! For our hypothetical vehicle discussed above, the CG is now at 24" high instead of 30". This makes our angle 38.6° rather than the 45° we had above. As a result, our vehicle could withstand a lateral (centripetal) force of 4,000 pounds instead of the 3,200 it could before. We have really increased the stability of the vehicle to rollovers by 25%, quite a large effect. It still would not eliminate ALL possibility of rollover accidents, because it still has an high CG, but a 25% improvement in stability would be a spectacular improvement.

And this is using only 30 year old technology, meaning virtually NO Research and Development costs, and relatively cheap application to vehicles!
How come none of the SUV manufacturers have ever used such an obvious idea?

Readers of this page may use this information in any way you wish, with a single exception. IF my concept of automatically adjusting the vehicle height is to be used or marketed, I consider that to be MY concept, and therefore NOT available with a Contractual arrangement!

Please pass the rollover information here along to the families of the victims of the rollover accidents, and to the government regulators.

Given how simple these calculations are, it is really disappointing that no one seems to be in a position to challenge the "engineering" of the carmakers! To watch in that PBS program, an "expert" representing a carmaker testifying that he just didn't know how great the benefit would be of widening the track two inches, was appalling! Tell them to get any high school Physics student to explain it to them! The calculations above show how simple those calculations are! There ARE no "complicated" calculations to do! This is all of it!

This presentation was first placed on the Internet in January 2002. The text has been edited from time to time since then.

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Automotive-related presentations in this Domain

Physics in an Automotive Engine
Physics in an Automotive Vehicle
Battery-Powered (and Hybrid and Hydrogen) Vehicles
Hydrogen as an Automotive Fuel-source
Physics of SUV Rollover Accidents (first presented on the Internet January 2002)

An Absolutely GREEN Transportation and Freight System Which Is 20 times More Efficient than Cars and Trucks and Airplanes, Cheaper and Faster! (invented in 1989)
A Super-Inter-Cooler High-Efficiency Engine (first presented on the Internet in 2002)
An Inexpensive and Simple Dynamometer for Vehicles (invented around 1966)
Road Talker Ridge Patterns in Highways for Warning Messages (invented in 1995)
A Simple System to Eliminate Hi-Speed Police Chases (invented in 1997)
Automotive Diagnostic Device Based on Vibrations (invented in 1998)
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Fuel Efficiency Effects of Driving with Headlights On
A Simple Oil Change Alert Monitor (invented in 1998)
The Physics of How Police Radar Works
A Different Tire Construction Concept, for softer ride (first presented on the Internet 1998)
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E-mail to: Public1@mb-soft.com

C Johnson, Physicist, Physics Degree from Univ of Chicago