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Physics of Automobile Rollovers

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You need the free Amaya browser/editor to see the math in this XML/MathML document. Download it at http://www.w3.org/amaya .

Introduction

The National Highway Traffic Safety Administration (NHTSA) of the Department of Transportation of the United States government recently promulgated rollover resistance ratings (http://www.nhtsa.dot.gov/cars/testing/ncap) for automobiles. A parameter called the Static Stability Factor (SSF) is assigned to each vehicle. It is defined as one-half the track width divided by the height of the center of gravity. It is called "static" because SSF is essentially the tangent of the slope angle for a vehicle to just roll over while sitting on the slope. Another, slightly less static, way to look at SSF is "equal to the lateral acceleration in g's at which rollover begins in the most simplified rollover analysis of a vehicle represented by a rigid body without suspension movement or tire deflections" (Taken from http://www.nhtsa.dot.gov/cars/rules/rulings/Rollover/Chapt05.html.) Note the words "at which rollover begins".

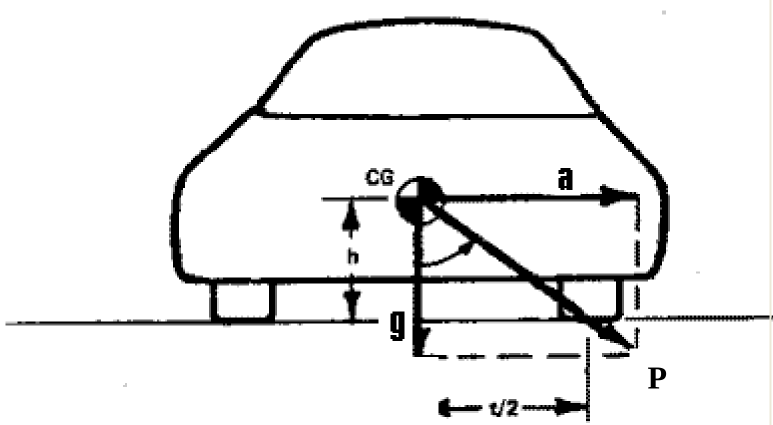

Figure 1: Components of ... own at Critical Lateral Acceleration

Fig.1 (from that web site) depicts the lateral vehicular acceleration vector *a* to the right and the downward gravity acceleration vector *g*. The vehicle will just start rotating about the pivot point P at the right tire when tan ? = a/g

Static Stability Factor = SSF = *tan ? = t /2h = a/g*; whence *a = g · SSF*

One needs SSF to be as large as possible in order to make the lateral acceleration required to cause a rollover to be large.

In a real situation a vehicle is usually moving when it rolls over, not standing still on a slope. We consider two types of idealized moving rollover situations:

1. A vehicle is moving (sliding) sideways and the wheels strike a solid obstacle that provides a pivot point for a possible rollover. Rollover occurs when the ensuing rotation causes the force of gravity vector to pass through the pivot point.
2. A vehicle is moving, without slipping, around a circular curve at a constant speed high enough to just cause rollover. Rollover occurs when the force of gravity vector passes through the pivot point.

It should be emphasized that the effects of suspension movement, tire movement or electronic/mechanical stability control may be very important in the rollover tendency for an vehicle. Suspension and tire movements would likely increase the tendency for rollovers, while electronic/mechanical stability control should make it less likely that a vehicle would get in a situation where rollovers occur. These analyses do not account for such and, thus, can only compare vehicles as rigid unintelligent bodies.

Rollover Physics for a vehicle Sliding Sideways

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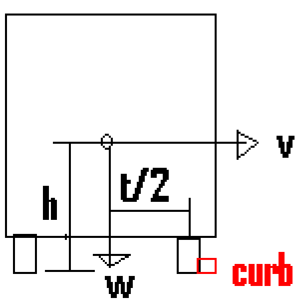
<td>
</td>
<td>Consider a vehicle sliding sideways until both side wheels strike a solid obstacle, such as a curb. The curb provides a pivot point for the car to rotate. The half track t/2 and the height h of the center of gravity are shown in this diagram at the point when the vehicle strikes a curb at sideways speed v.</td>
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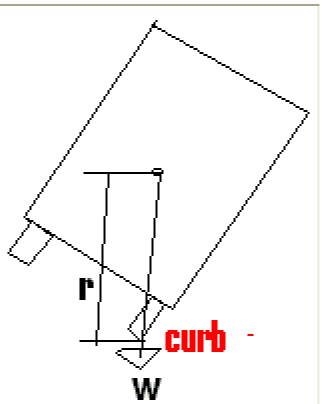
<td>
</td>
<td>Here the vehicle is at the critical point for rollover. If the speed is greater than zero at this point, rollover will occur. If the sideways speed just goes to zero at this point in the rotation, the vehicle is just on the verge of rollover (the critical point),

The height of the center of gravity at the critical point has increased to r = $\sqrt{\left(\frac{t}{2}\right)^2 + h^2}$, by Pythagorus theorem as the hypotenuse of a right triangle with sides t/2 and h.</td>
</tr>
</table>

Energy conservation requires that: energy before hitting the curb = energy at the critical point, where energy = kinetic energy ($\frac{1}{2}mv^2$) + gravitational potential energy (mg × height above surface):

Therefore, at the critical point where v = 0,

$$\frac{1}{2}mv^2 + mgh = mg\,r = m\,g\sqrt{\left(\frac{t}{2}\right)^2 + h^2} = \text{mgh}\sqrt{1+s^2}$$, where $s = SSF = t\,/\,2h$.

Therefore, the initial speed that just produces the critical point is

$$v^2 = 2\,gh\,\left(\sqrt{1+s^2} - 1\right)$$

This is the square of the initial speed, when hitting the curb, that yields zero speed at the critical point, the condition to just begin a rollover; call this initial speed the **critical speed**. Thus, we see that the critical initial speed depends not only on the SSF, but also on h and t/2. In fact, it is better not to even consider SSF, but both h and t/2 instead.

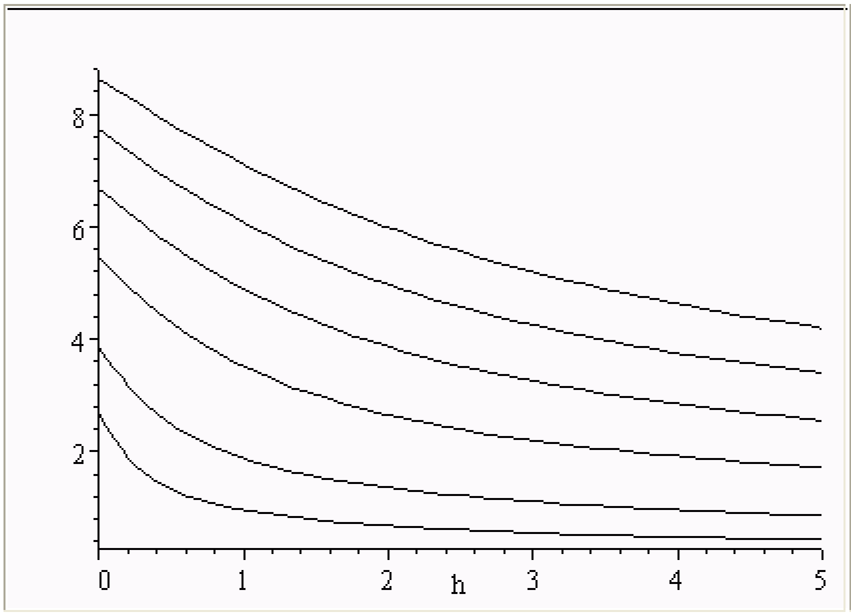
For s = 0 (i.e., t = 0): $v^2 = 0$

For s = 1 (i.e., h = t/2): $v^2 = 2\text{ g h } (\sqrt{2} - 1) = 0.828\text{ g h} = 0.414\text{ g t}$

For s = 8 (i.e., h = 0): $v^2 = \text{g t}$

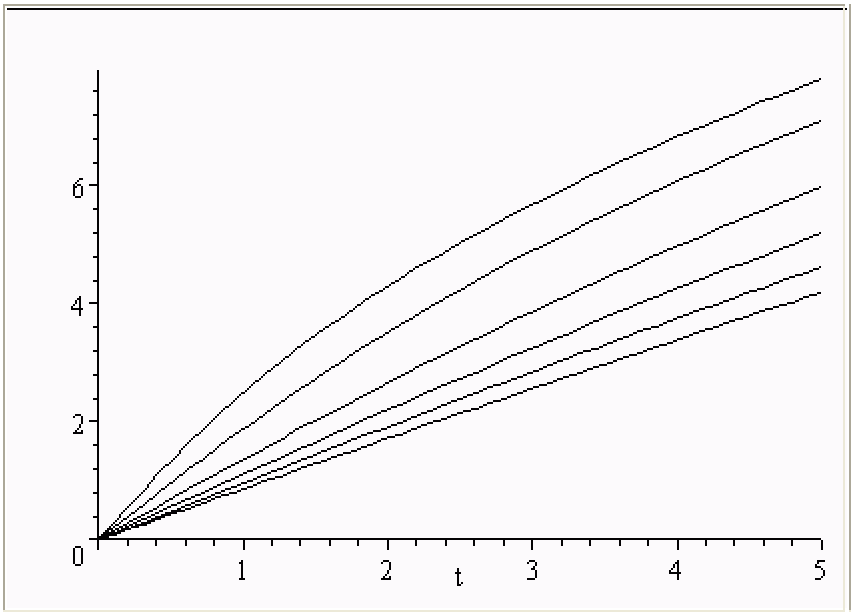
Most vehicles were rated at 1.0 < s < 1.5 in the NHTS ratings (http://www.nhtsa.dot.gov/cars/rules/rulings/roll_resistance/appendix1.html). (It is interesting to note that the incidence of rollovers is about five times greater for s = 1.0 vehicles as it is for s = 1.5 vehicles.)

Of course, energy is not strictly conserved, so the actual critical initial rollover speed will be larger than this calculated speed. However, rollovers often occur after the vehicle has left the road bed and is on the downward slope beside the road bed, which would decrease the critical initial rollover speed.



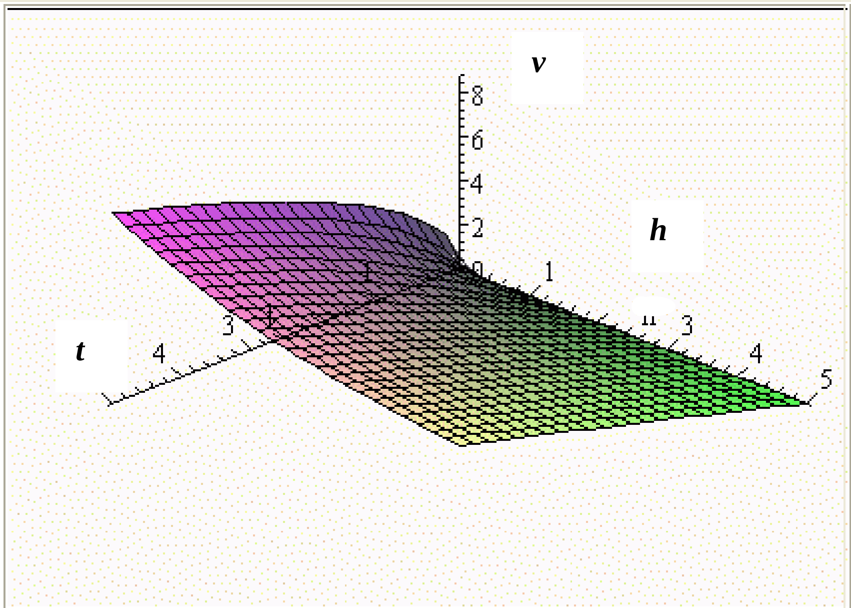
This is a plot of the critical-point initial speed v in miles/hour versus h in feet for different values of t.

(Bottom to top: t = 0.5, 1 , 2 , 3 , 4 , 5 feet). One wishes *v* to be as large as possible. Therefore, one would want *h* to be as small as possible.



This is a plot of the critical-point initial speed v in miles/hour versus t in feet for different values of *h*.

(Bottom to top: *h* = 5, 4 , 3 , 2 , 1 , 0.5 feet). One would want *v* to be as large as possible. Therefore, one would want *t* to be as large as possible.



This is a 3-D plot of the critical-point initial speed *v* in miles/hour versus *h* and *t* in feet. One wants *h* to be as small as possible and *t* to be as large as possible. Note that it is more effective for producing the desirable high *v* to decrease *h* (center of gravity) than to increase *t* (track).

Classifying Automobiles for Rollover Safety

A better way to rate vehicles for sideways rollovers is by calculating critical-point initial speed from *t* and *h*, instead of by static stability factor *s* = *SSF* = *t* /2*h*, from the expression

$$v^2 = 2g\left[\sqrt{\left(\frac{t}{2}\right)^2 + h^2} - h\right] = 2gh\left[\sqrt{s^2 + 1} - 1\right]$$

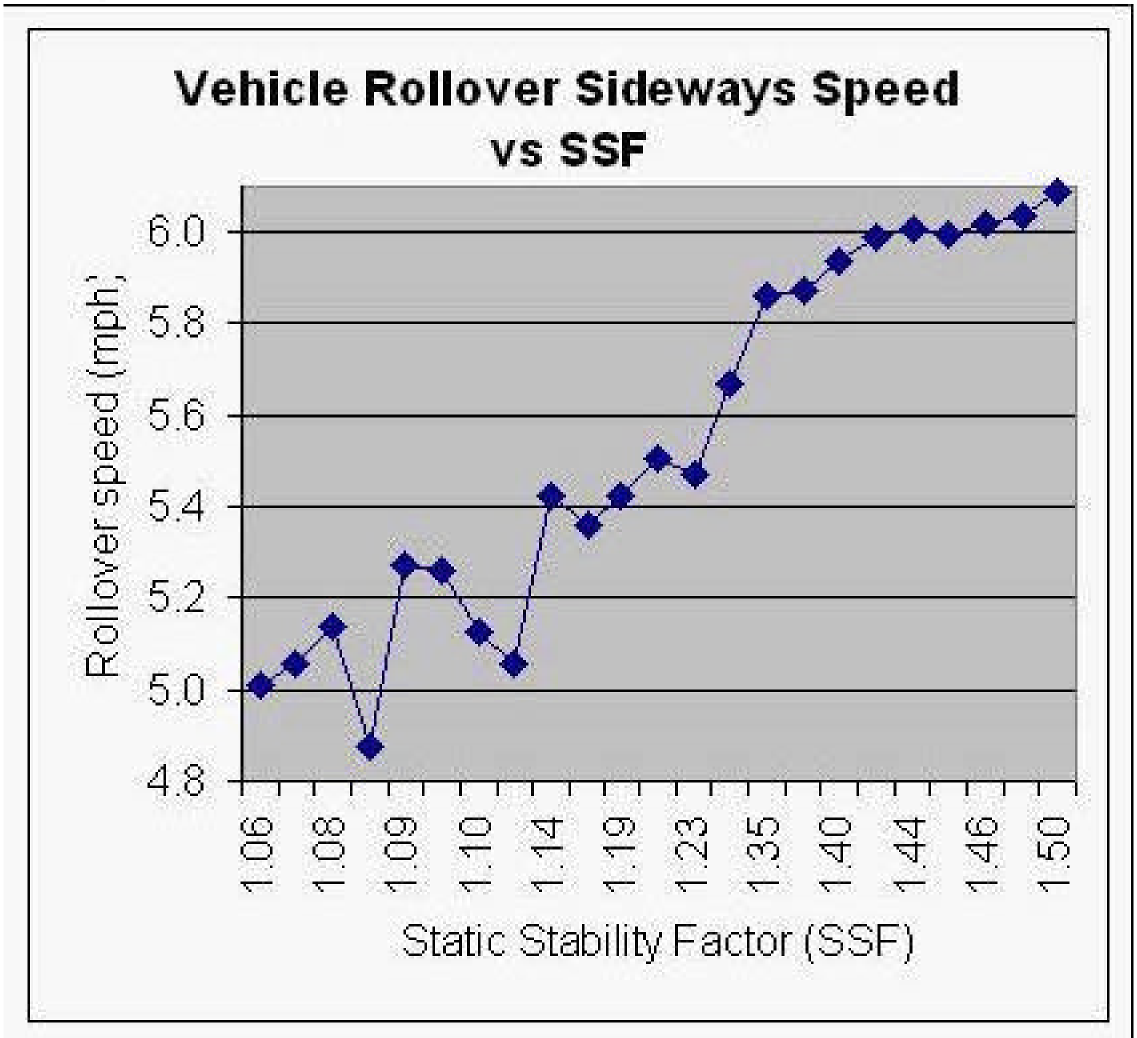
Critical-point initial speed also has the advantage of being a value with units (miles/hour) to which people can relate. For example:

a) for h = 2 feet and t = 4 feet (s = 1); v = 5 mph
b) for h = 2 feet and t = 6 feet (s = 1.5); v = 7 mph

In case these appear to the reader to be low speeds for a vehicle, remember that they are lateral (sideway) slipping speeds, not forward speeds.

Values for s for various vehicles are given in http://www.nhtsa.dot.gov/cars/rules/rulings/Rollover/Appendix.html, but the track and center-of-gravity values are not given there. I was able to find track/tread values for some of the listed vehicles on the Internet. (Ford Motor Company did not list the track for its vehicles.) I used them and the SSF, I calculated the height of the center-of-gravity. (It is not clear on the web pages what is meant by "track width" and "tread width"; it appears that some or all those who use the term "track" really mean "tread". In every case I have assumed that they meant the width to the outside edges of the tires; I therefore subtracted off 6" for the approximate width of the tire.). Then I calculated the critical-point initial sideways rollover speed, as shown in the following table, sorted by increasing SSF:

vehicle	SSF	Track (ft)	Track/2 (ft)	Center of Gravity (ft)	Sideways Rollover Speed (mph)
Honda Passport	1.06	4.48	2.24	2.35	5.01
Jeep Grand Cherokee	1.07	4.46	2.23	2.32	5.05
Jeep Cherokee	1.08	4.33	2.17	2.24	5.14
Chevrolet Suburban	1.08	4.96	2.48	2.53	4.88
Chevrolet Blazer 2WD	1.09	4.06	2.03	2.09	5.27
Chevrolet Blazer 4WD	1.09	4.08	2.04	2.14	5.26
Nissan Pathfinder	1.10	4.56	2.28	2.30	5.13
Chevrolet Astro van	1.12	4.93	2.46	2.42	5.06
Chevrolet S-10 pickup	1.14	4.04	2.02	1.99	5.42
Mazda MPV van	1.17	4.57	2.28	2.17	5.36
Honda CR-V SUV	1.19	4.53	2.27	2.11	5.43
Jeep Wrangler	1.20	4.33	2.17	2.01	5.51
Dodge Caravan van	1.23	4.79	2.40	2.15	5.47
Toyoto Tacoma pickup	1.26	4.27	2.13	1.89	5.67
Saturn SL sedan	1.35	4.20	2.10	1.74	5.86
Toyoto Corolla sedan	1.36	4.28	2.14	1.76	5.87
Nissan Sentra sedan	1.40	4.33	2.16	1.72	5.94
Honda Civic sedan	1.43	4.33	2.16	1.69	5.99
Dodge/Plymouth Neon	1.44	4.33	2.16	1.68	6.01
Nissan Maxima sedan	1.44	4.48	2.24	1.73	5.99
Toyota Camry sedan	1.46	4.54	2.27	1.73	6.02
Honda Accord sedan	1.47	4.57	2.28	1.72	6.04
Chevrolet Camaro	1.50	4.55	2.28	1.68	6.09



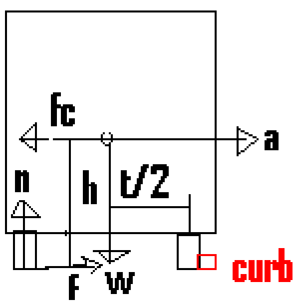
The graph above shows the critical-point initial rollover sideways speed plotted against the static stability factor (SSF). Note that, at high SSF, the two are essentially equivalent measures of relative rollover tendency, but at low SSF they differ considerably in the rankings. For example, the Chevrolet Suburban is fourth from lowest in SSF rankings, but lowest in critical-speed rankings. Just above the Suburban, four vehicles have their rankings reversed when one uses critical speed instead of SSF. There are three reversals of two vehicles at higher SSF.

I believe that this shows convincingly that critical-point initial speed should be used, rather than SSF, in ranking vehicles for rollover tendency, since it embodies the physics better and does not always agree with SSF rankings.

Of course, in a real sideways rollover, there will not be a solid curb providing a fixed pivot point. Instead, the pivot point may actually be moving, say in soft earth or pavement friction. Then the critical speed will be higher than the calculated value for a fixed pivot point. Nevertheless, the critical speed calculated for a fixed pivot point is a good comparative measure of the rollover hazard for different vehicles. Most rollovers occur as sideways rollovers (http://www.nhtsa.dot.gov/hot/rollover: "Most rollover crashes occur when a vehicle runs off the road and is tripped by a ditch, curb, soft soil, or other object causing it to rollover."). There is usually a forward speed, as well as the sideways speed that causes the rollover, which greatly increases the likelihood of damage to the vehicle and its occupants during rollover.

Rollover Physics for an Automobile in a Circular Path

Consider an vehicle moving at initial speed v when the driver suddenly turns the steering wheel such that the vehicle's wheels move in a circle of radius r with no slipping.



The centripetal force acting toward the center of the circle is provided by the friction of the road bed with the tires and causes ($f = ma$) a centripetal acceleration toward the center of the circle with value $a = v^2/r$. This force acts at the places where the tires touch the road bed, but the acceleration acts through the center of gravity, as does the gravitation force w (weight) downward. There is also a normal force *n* of the road on the tires. The forces *f* and *n* act at all four tires, although they are shown at only one tire in this diagram. The force of gravity is W = mg, where the acceleration of gravity is g = 32.2 ft/s^2. $?_c$ = arctan (2h/t) is the initial angle between the vehicle floor and the vector to the center of mass from the pivot point.

The fact that the tires-road frictional force *f*, causing the centripetal acceleration *a*, is offset from *a*, contributes to a torque about any point other than the tires-road point. The normal force *n* also contributes to the torque. These torques, if large enough, can cause the vehicle to rotate about a point of contact with the road, in addition to the circular motion.

The frictional force *f* depends on the coefficient of static friction μ between the tires and the road; "static" because the tires are not slipping. The usual assumption is that $f = \mu n$; that is, the frictional force can take on any value from 0 to μn, depending on what is needed to provide the centripetal acceleration *a*.

We treat the two inner tires as one tire and the two outer tires as one tire. Since, relative to the earth, the vehicle will rotate around the point where the outer tire touches the earth, we take that point as the point about which to calculate torques. We call the force doublet (f, n) at the inner tire (f_i, n_i) and the force doublet at the outer tire (f_o, n_o).

Balancing forces:

$$S\ f_x = ma = m\,v^2/r = W\,v^2/(g\,r) = f_i + f_o = \mu\,(n_i + n_o)$$

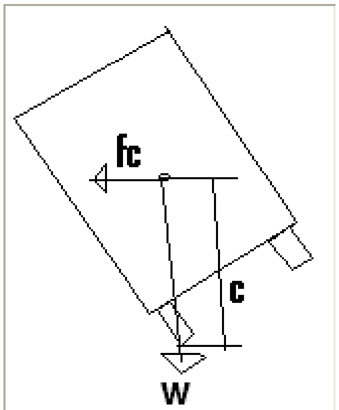
$$S\ f_y = n_i + n_o - W = 0$$

The centripetal acceleration term, *ma*, can be considered as a fictitious force, f_c, acting outward through the center of mass in the reference frame of the moving vehicle. It is called the "centrifugal force". In fact, it must be so used when calculating the torques in the reference frame of the moving vehicle. Balancing torques counter-clockwise about the point of contact of the outer tire with the road bed:

$$S\ t = I\ a = f_c\ h - W\ t/2 + n_i\ t$$

where *I* is the moment of inertia, and the angular acceleration a is taken counter-clockwise about the point where the outer tire touches the road bed. The inner normal force, n_i , can be any value from 0 to *W/2* ; it can never participate in any rotation about the outer tire, because it cannot move. As f_c increases n_i decreases to maintain balance until it reaches 0. The angular acceleration will be zero according to $f_c\ h - W\ t/2 + n_i\ t = 0$ until $n_i = 0$. Then $f_c\ h - W\ t/2 = 0$ and the inner wheel no longer has a normal force; i.e., the inner wheel has just lifted off of the road bed. Then: $f_c\ h = ma\ h = mg\ t/2$ and therefore:

$a = t / (2\ h)\ g = s \cdot g = SSF \cdot g$. This is the reason that SSF was chosen by the NHTSA as the parameter to compare vehicles for rollover tendency. One would want this **critical centripetal acceleration** to be as large as possible. However, this value of acceleration only gives a measure of the tendency to begin a rollover, not to actually rollover. This defines a **critical circular speed**: $v = \sqrt{r \cdot s \cdot g}$, the speed required to lift the inner tire from the road bed. This speed depends on the turning radius *r*.



The more relevant situation for rollover tendency is when the center of gravity is over the point of contact of the wheel that is touching the road bed. Then the only force producing a torque about the point of contact is f_c. At this point any value of centripetal acceleration would cause the vehicle to roll over. Let us call this situation the "**critical point**" to produce a rollover. This critical-point rollover angle is given by tan $?_p$ = $t/2h = s$ = SSF. This is another reason why SSF was chosen by the NHTSA as the parameter to compare vehicles for rollover tendency. For maximum safety, one wants this angle to be as large as possible; i.e., one wants large *t* and small *h*.

In the diagram above, the height of the center of gravity above the road surface is

$$c = \sqrt{\left(\frac{t}{2}\right)^2 + h^2}$$

At any intermediate angle between 0° and $?_p$, the centripetal acceleration required to balance the torques lies between $(s \cdot g)$ and *0*, such that *t = m a (h cos ? + t/2 sin ?) + W (h sin ? – t/2 cos ?)* - > $a = g\frac{s - \tan q}{1 + s\tan q}$

Thus $a = 0$ at $? = ?_p$.

Once the inner wheels are off of the ground, the vehicle will continue to perform the rollover unless the driver reduces the speed or decreases the turning radius, which a driver would instinctively do unless there was insufficient time to react (within hundreds of milliseconds).

In the equation above, it appears that the centripetal acceleration $a = v^2/r$ is constant, but that is not strictly true. Energy is assumed to be conserved, so that v^2 must decrease to

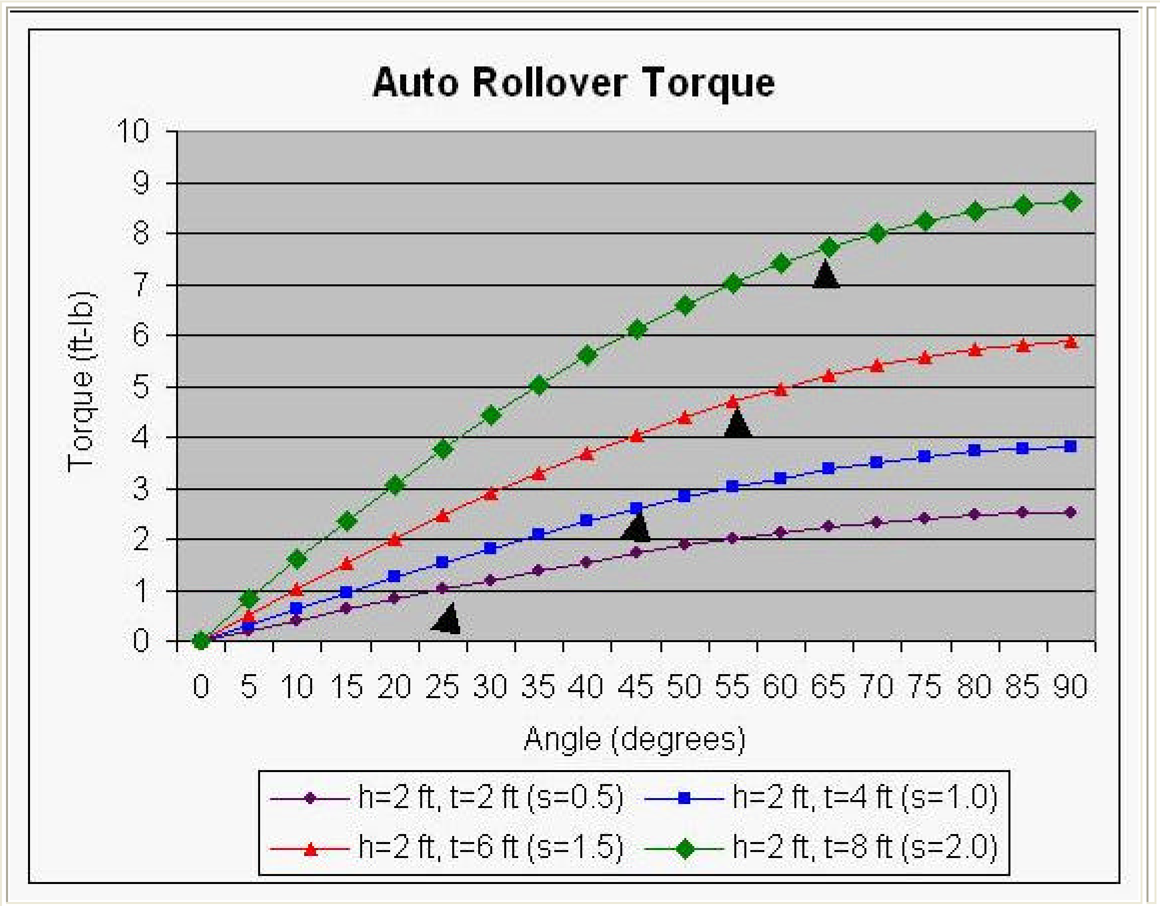
$$v^2 - 2\,g\,\sqrt{\left(\frac{t}{2}\right)^2 + h^2}$$

as the center of mass rises initially from h to $\sqrt{\left(\frac{t}{2}\right)^2 + h^2}$ at the critical point of rollover.

Also, since the wheels are locked to move in a circle of radius r, the radius of the center of mass changes from initially r to $r + t/2$ at the critical point of rollover. As a function of *?*, denoting the angle between the vehicle floor and the road bed, the torque/weight ratio may be expressed as

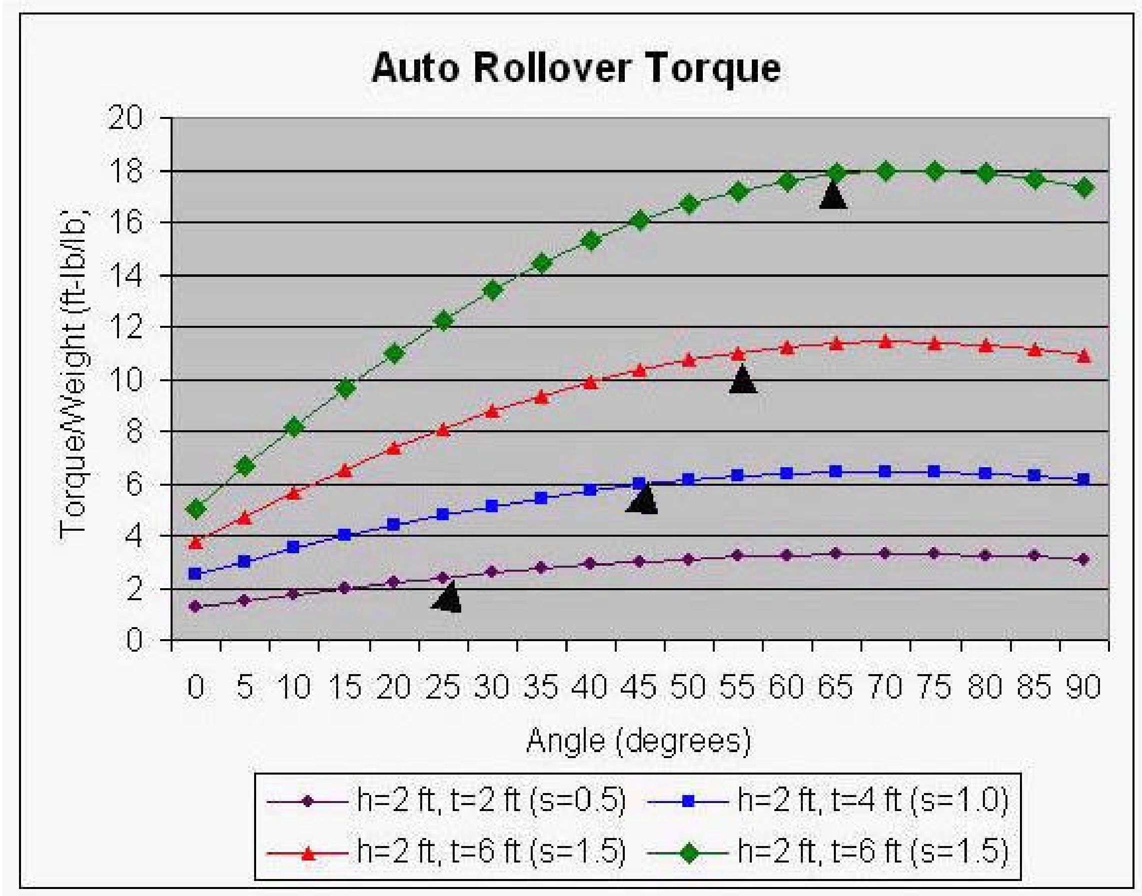
$$\frac{t}{W} = \frac{v^2 - 2g\left[h(\cos q - 1) + \frac{t}{2}\sin q\right]}{g\left[r + \frac{t}{2}(1 - \cos q) + h\sin q\right]}\left(h\cos q + \frac{t}{2}\sin q\right) + h\sin q - \frac{t}{2}\cos q.$$

(For the derivation of this equation, see torque.)



The graph above shows the rollover torque as a function of angle for different values of h and t up to complete rollover on the side (? = 90°) at the critical initial circular speed and r = 40 ft. Any speed slightly above the critical initial circular speed will cause a rollover. The tip-over angle, given by tan $?_p$ = t /2h = s = SSF , is shown for each case by an arrow head. The critical initial circular speeds for these cases are:

h = 2 ft, t = 2 ft (s = 0.5); v = 17.3 mph
h = 2 ft, t = 4 ft (s = 1.0); v = 24.5 mph
h = 2 ft, t = 6 ft (s = 1.5); v = 30.0 mph
h = 2 ft, t = 8 ft (s = 2.0); v = 34.6 mph



The above graph shows the rollover torque as a function of angle for circular speed for 50% above the critical speed and r = 40 ft. These graphs make it very clear, that once the initial circular speed is above the critical speed and, thus, the torque is above zero at zero angle, the rollover is certain since the non-zero torque causes an angular acceleration which then moves the vehicle to a larger angle where the torque is even larger.

If we assume that the system does not lose any energy to the environment during the course of going from initiating the rollover to the critical point of the rollover, the energy-conservation analysis carries through exactly as above for a sideways-slipping rollover when hitting a curb.

The energy-conservation initial critical speed is given by: $v_{ec}^2 = 2\,g\,\left(\sqrt{\left(\frac{t}{2}\right)^2 + h^2} - h\right)$

For the two examples given above:

a) h = 2 feet, t = 4 feet (s = 1); v_{ec} = 5 mph
b) h = 2 feet, t = 6 feet (s = 1.5); v_{ec} = 7 mph

As the torque is zero at *? = 0*, the initial speed required is then given by

$v^{2'}{}_{t=0}$ = g [r + t/2 (1 - cos ?) + h sin ?] t/2 cos ? - h sin ? · h cos ? + t/2 sin ? +
+ 2 g [h (cos ? - 1) + t/2 sin ?]

$$v_{t=0}^2 = g\left[r + \frac{t}{2}(1-\cos q) + h\sin q\right]\cdot\frac{\frac{t}{2}\cos q - h\sin q}{h\cos q + \frac{t}{2}\sin q} + 2g\left[h(\cos q - 1) + \frac{t}{2}\sin q\right]$$

The critical circular initial speed for barely initiating a rollover (*? = 0*, *t = 0*) is

$$v_{ir} = \sqrt{r\cdot s\cdot g}$$

Equating the two critical initial speeds for energy conservation and for barely initiating rollover, we get the following for the critical turning radius *r* required for barely initiating rollover in circular motion of the type described herein:

$$r = \frac{4h}{t}\left[\sqrt{\left(\frac{t}{2}\right)^2 + h^2} - h\right]$$

For the two examples used above:

a) $h = 2$ feet, $t = 4$ feet ($s = 1$); $r = 1.66$ feet
b) $h = 2$ feet, $t = 6$ feet ($s = 1.5$); $r = 2.44$ feet

These radii are much smaller than any vehicle can steer. Larger, more realistic radii, give a larger critical speed for initiating a rollover, which definitely would cause a complete rollover, once the inner wheels leave the road bed.

For the two examples, a realistic turning radius *r* of 40 feet yields:

a) $h = 2$ feet, $t = 4$ feet (s = 1); $v_{ir} = 24.5$ mph
b) $h = 2$ feet, $t = 6$ feet (s = 1.5); $v_{ir} = 30$ mph

For this kind of rollover, *s* is a good measure of the tendency to roll over. However, most rollovers are not of this kind (http://www.nhtsa.dot.gov/hot/rollover). Some rollovers may be a combination of sideways sliding and circular motion.

Conclusion

If a single measure of rollover-tendency ranking of vehicles is used, it should be the critical-point initial speed, given by

$$v^2 = 2g\left[\sqrt{\left(\frac{t}{2}\right)^2 + h^2} - h\right]$$

rather than the static stability factor, $s = SSF = t/(2h)$. The latter is strictly for sideways rollovers, not for circular-motion rollovers; however, that is the case for most rollovers according to NHTSA.

I suspect that a reasonable fraction of rollovers involves some circular motion, as the driver tries to maneuver out of trouble, as well as sidewise motion. Circular-motion rollover tendency depends monotonically on SSF. So, perhaps one should average the rankings for critical-point initial speed and SSF.

The rankings of the vehicles given above for the three ways to rank are as follows:

(In decreasing degree of tendency to rollover)		
SSF Rankings	**SRS Rankings**	**Average Rankings**
Honda Passport	Chevrolet Suburban	Honda Passport
Jeep Grand Cherokee	Honda Passport	Jeep Grand Cherokee
Jeep Cherokee	Jeep Grand Cherokee	Chevrolet Suburban
Chevrolet Suburban	Chevrolet Astro van	Jeep Cherokee
Chevrolet Blazer 2WD (tie)	Nissan Pathfinder SUV	Nissan Pathfinder SUV (tie)
Chevrolet Blazer 4WD (tie)	Jeep Cherokee	Chevrolet Astro van (tie)
Nissan Pathfinder SUV	Chevrolet Blazer 4WD	Chevrolet Blazer 2WD (tie)
Chevrolet Astro van	Chevrolet Blazer 2WD	Chevrolet Blazer 4WD (tie)
Chevrolet S-10 pickup	Mazda MPV van	Chevrolet S-10 pickup (tie)
Mazda MPV van	Chevrolet S-10 pickup	Mazda MPV van (tie)
Honda CR-V SUV	Honda CR-V SUV	Honda CR-V SUV
Jeep Wrangler	Dodge Caravan van	Jeep Wrangler (tie)
Dodge Caravan van	Jeep Wrangler	Dodge Caravan van (tie)
Toyoto Tacoma pickup	Toyoto Tacoma pickup	Toyoto Tacoma pickup
Saturn SL sedan	Saturn SL sedan	Saturn SL sedan
Toyoto Corolla sedan	Toyoto Corolla sedan	Toyoto Corolla sedan
Nissan Sentra sedan	Nissan Sentra sedan	Nissan Sentra sedan

Honda Civic sedan	Honda Civic sedan (tie)	Honda Civic sedan
Dodge/Plymouth Neon (tie)	Nissan Maxima sedan (tie)	Dodge/Plymouth Neon (tie)
Nissan Maxima sedan (tie)	Dodge/Plymouth Neon	Nissan Maxima sedan (tie)
Toyota Camry sedan	Toyota Camry sedan	Toyota Camry sedan
Honda Accord sedan	Honda Accord sedan	Honda Accord sedan
Chevrolet Camaro	Chevrolet Camaro	Chevrolet Camaro

In all the above calculations, the effects of suspension movement, tire movement or electronic/mechanical stability control were neglected. Suspension and tire movements would likely increase the tendency for rollovers, while electronic/mechanical stability control should make it less likely that a vehicle would get into a situation where rollovers occur.

Auto makers should be required to publish the height of the center of mass for each automobile made, so that one can easily calculate the SSF. Better yet, they should be required to publish the SSF itself.

An industrial economist, Joe Kimmel, has developed a formula for predicting the probability of rollovers in accidents given the track width t, height h and weight W of an automobile. The formula is given at http://ads.usatoday.com/money/consumer/autos.nayti698.htm. However, there is a slight error in the formula as given there. The correct formula for the % probability of rollover is:

$$P = 0.091\,(550000\,\frac{h}{tW} - 90)$$

The values for 189 model year 2001 automobiles are given at:

http://cgi1.usatoday.com/money/consumer/autos/mauto695.htm.

Rollover risks for some 2001 luxury AWD automobiles are:

Model	Acura MDX	Acura MDX Touring	Audi A6 Avant	Audi Allroad	BMW X5 6cyc	BMW X5 V8	Lexus RX300	Mercedes ML320	Mercedes ML430	Volvo V70 XC
height (in)	68.7	71.3	58.2	60.1	67.5	67.5	67.7	69.9	69.9	61.5
track (in)	66.4	66.4	61.3	62.2	60	61.4	61.3	60.4	60.4	61.6
weight (lbs)	4323	4383	3787	4167	4519	4828	3924	4586	4696	3699
Risk %	3.79	4.07	4.36	3.42	4.27	3.21	5.90	4.44	4.14	5.32

			height	62.7						
			Risk %	3.92						
Head Air Bags	no	no	yes	yes	yes*	yes*	no	yes	yes	yes

Two values are listed for the Audi Allroad because it has a variable height/ground-clearance capability between the two values shown. The last line indicates whether the vehicle has head air bags that extend from the front to the back of it; this is very important for protecting the occupants during a rollover. *All except the BMW are curtain air bags; the BMW has a cylindrical head air bag apparently only for the front seats, which I judge to be not as good as curtain air bags. (I own an Audi A6 Avant and a Volvo V70 XC.)

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