Rollover of Sport Utility Vehicles

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Recently, the respected PBS program "Frontline"[1] examined the history of the development of the sport utility vehicle (SUV) and the efforts to force car makers to design SUVs that are less prone to rollover. The dangers of SUV rollovers were spotlighted in the fall of 2000, when the sensational Ford-Firestone scandal prompted Congress to launch a series of hearings focusing on deaths and injuries related to faulty Firestone tires mounted on Ford Explorers. However, during the same 10-year period in which Ford-Firestone rollover crashes caused some 300 deaths, more than 12,000 people — 40 times as many — died in SUV rollovers *unrelated to tire failure*.[1]

This issue will soon be brought to the forefront of media attention by the new five-star rollover rating system (also called the "Rollover Resistance Rating") of the National Highway Traffic Safety Administration (NHTSA). This rating system is primarily based on the Static Stability Factor (SSF) of a vehicle.

In this paper, the SSF will be linked to the maximum possible speed to round a given curve. The SSF will also be linked to the maximum coefficient of static friction between the rubber of the tires and dry concrete pavement. Finally, the SSF is not a smooth variable, where small differences imply little change in vehicle handling characteristics. We will demonstrate that there is a critical value of the SSF such that vehicles with values less than this critical level are inherently unstable and prone to rollover, while vehicles with larger SSF values will spin out during cornering.

The danger of loading SUVs to full capacity can be illustrated, since it results in a demonstrable raising of the center of gravity, and thus a dramatic decrease in the SSF — possibly even below the critical value.

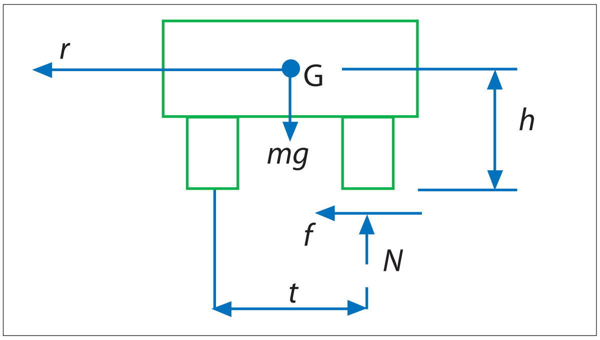

Fig. 1 Free-body diagram showing back view of car rounding a curve. Rollover is impending.

The application of fundamental physics principles illuminates the theoretical basis of the SSF. Because all of these issues can be investigated by our students, this topic represents a rich and relevant application of fundamental physics principles that illuminates a critical societal issue.

Development of the Static Stability Factor (SSF)

There are two types of rollovers: tripped and untripped. A tripped rollover occurs when the vehicle wheels hit an obstacle such as a curb or pothole. In this section, we wish to develop the conditions for an untripped rollover. Since an untripped rollover results solely from friction forces acting on the outside wheels, it is also called a "friction rollover."

Consider the free-body diagram of a car rounding a horizontal curve (see Fig. 1). We will assume that the car is a rigid body, inasmuch as we are not considering suspension or tire deformation effects. We will say more about these effects later, but they are of secondary importance in the following discussion. The view of the car is from the rear, as it rounds a curve that is into the paper and turns to the left. We assume that the car is just on the point of rollover, i.e., *rollover is impending.* Therefore, the inside wheels are just about to leave the ground and the forces on these wheels are zero.

In Fig. 1, m = mass of car, g = acceleration due to gravity, f = total frictional force on two outside wheels (not necessarily the maximum frictional force available), N = total normal force on two outside wheels, G is the center of gravity of the car, t = track width, and h = height of G above road. Applying Newton's second law in the radial direction r gives

$$f = \frac{mv^2}{r}. \tag{1}$$

Newton's second law in the vertical direction gives

$$N = mg. \tag{2}$$

Taking the sum of the moments about G gives

$$N\left(\frac{t}{2}\right) - fh = 0. \tag{3}$$

Substituting for f from Eq. (1) and N from Eq. (2) into Eq. (3) gives the "rollover condition" as

$$\frac{t}{2h} = \frac{v^2}{rg}. \tag{4}$$

The term $t/2h$ is referred to as the Static Stability Factor (SSF). Note that this term is totally determined by the vehicle geometry, whereas the term on the righthand side of Eq. (4) is determined by the motion of the vehicle.

In order to develop an understanding of the SSF, consider typical values for a passenger van,[2] t = 1.7 m and h = 0.8 m. These give a value of 1.06 for the SSF. If the driver of this car wishes to round a curve of radius 10 m, Eq. (4) gives the speed v as 10.2 m/s. This means that if the car rounds this curve at 10.2 m/s, then rollover is impending. Let us now increase the track width to t = 1.8 m. We now see that for this curve, the vehicle is just about to roll over at v = 10.5 m/s. Thus, when the track width t increases, the vehicle becomes more stable.

Similarly, we can show that as the center of gravity height h decreases, the vehicle becomes more stable. This completely agrees with our intuition: when the track width t increases or the center of gravity height h decreases, the overall stability of the car increases. It therefore follows that larger values of the SSF mean that the vehicle is more stable.

Car on a Slope

We now wish to develop the corresponding equations for a car cornering on a slope. Again, we consider rollover to be impending. Imagine that the car is on the outside surface of a vertical cone and is describing a horizontal circle around the cone. The paper is a vertical plane that passes through the apex of the cone. In Fig. 2 the view is from the rear of the car.

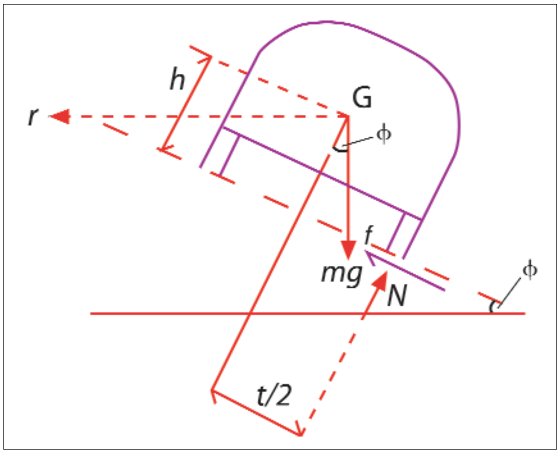

Fig. 2. Car rounding curve on a slope. Rollover is impending.

Applying Newton's second law in the radial direction r gives

$$f\cos(\phi) - N\sin(\phi) = \frac{mv^2}{r}. \tag{5}$$

Applying Newton's second law in the vertical direction gives

$$N\cos(\phi) + f\sin(\phi) - mg = 0. \tag{6}$$

Taking the sum of the moments about G gives

$$N\left(\frac{t}{2}\right) - fh = 0.$$

or (7)

$$f = N\left(\frac{t}{2h}\right).$$

Substituting for f from Eq. (7) into Eq. (5) and solving for N gives

$$N = \frac{mv^2}{r} \cdot \frac{1}{\left[\frac{t}{2h}\cos(\phi) - \sin(\phi)\right]}. \tag{8}$$

Substituting for f from Eq. (7) into Eq. (6) and solving for N gives

$$N = \frac{mg}{\left[\frac{t}{2h}\sin(\phi) + \cos(\phi)\right]}. \tag{9}$$

Equating the righthand sides of Eqs. (8) and (9) gives:

$$\frac{\frac{t}{2h} - \tan(\phi)}{\frac{t}{2h}\tan(\phi) + 1} = \frac{v^2}{rg}. \tag{10}$$

This is an interesting equation because it shows the dramatic effects of slope on rollover. This becomes most critical when a car veers off the side of the road onto a steep downslope. If the driver tries to correct too quickly, rollover can easily occur. For a vehicle whose SSF value is $t/(2h) = 0.9$, $r = 10$ m, and $\phi = 5°$, Eq. (10) gives the impending rollover speed as 8.59 m/s. This can be contrasted to the corresponding zero slope value of 9.39 m/s.

It is interesting to compare Eq. (10) with Eq. (9-4) on page 311 of Gillespie,[2] which appears to be in error. Gillespie's equation gives a result of 9.84 m/s for $t/(2h) = 0.9$, $r = 10$ m, and $\phi = 5°$, instead of the 8.59 m/s value of Eq. (10). This represents a difference of 14.5% that cannot be accounted for by the small-angle approximation assumed by Gillespie.

The validity of Eq. (10) can be partially verified by the following observations.

Equation (10) reduces to Eq. (4) when $\phi = 0$.

Equation (10) reduces to a very interesting result at $v = 0$:

$$\tan(\phi) = \frac{t}{2h}. \tag{11}$$

This gives the rollover condition for a vehicle parked sideways on a slope where sideways sliding is prevented. It gives us a method to measure the SSF, which is the method actually used in practice. This method is called the "tilt-table test" or "dolly rollover test."[2] The vehicle is parked sideways on a sloped dolly, and the downhill wheels are prevented from sliding. The angle of the slope is raised until the vehicle is on the verge of rollover. The SSF can then be calculated from Eq. (11).

Equation (11) can be independently (and more easily) derived by considering the angle that causes the center of gravity of the vehicle to be directly over the point of contact of the downhill wheels and the slope.

Effect of Friction

We now wish to discover how the SSF relates to the friction between the tires and the road surface. In the above discussion, we assumed that there was sufficient frictional force to pull the car around the circle. However, we know that this friction cannot exceed $f_{s,max}$ in the static case and f_k in the sliding case. In this discussion, we will assume that $f_{s,max} = f_k$.

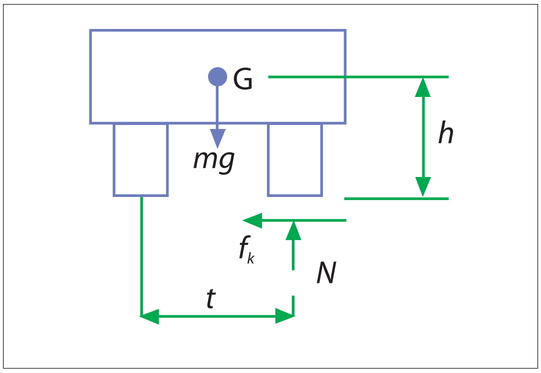

Fig. 3. Free-body diagram of car sliding sideways to the right. Rear view of car is shown. Rollover is impending.

Consider the car in a sideways slide. Figure 3 shows a free-body diagram of the car sliding sideways to the right. Again, the view of the car is from the rear. We are assuming that the frictional force f_k is such that rollover is impending.

Taking the sum of the moments about G gives

$$N\left(\frac{t}{2}\right) - f_k h = 0. \quad (12)$$

The friction equation gives

$$f_k = \mu_k N. \quad (13)$$

Substituting for f_k from Eq. (13) into Eq. (12) gives

$$\frac{t}{2h} = \mu_k. \quad (14)$$

Thus, for sideways sliding, the rollover condition is given by Eq. (14). If the SSF $> \mu_k$, then the vehicle will slide sideways instead of rolling over. If the SSF $< \mu_k$, the vehicle will roll over and will not slide sideways.

We can easily see that the greater the value of μ_k, the more prone the vehicle is to roll over. A top-heavy vehicle with a low SSF will spin out on an icy road, but will roll over easily on a dry road.

The conclusion from both sets of analyses above is:

If a vehicle with an SSF $< \mu_k$ rounds a horizontal curve of fixed radius at increasing speed, this vehicle will eventually roll over rather than slide sideways.

Suspension and Tire Effects

The above analyses consider the car as a rigid body. If we consider the effect of the suspension, we realize that during cornering, the center of gravity of the car shifts to the outside of the curve. This effectively reduces the lever arm, $t/2$, of the force N in Eq. (3). Thus, the track width t and the associated SSF are reduced when suspension effects are considered. Gillespie[2] reports that this reduction is about 5%. A similar mechanism arises from the lateral deflection of the outside tires. This deflection allows the point of application of the normal force N to move slightly inboard during cornering, again reducing the lever arm $t/2$. This effect may contribute another 5% reduction to the effective SSF.[2] The total of the above effects is a combined 10% reduction in the SSF. From Eq. (14) the rollover condition thus becomes

$$(0.9)\frac{t}{2h} = \mu_k$$

or (15)

$$\frac{t}{2h} = \frac{\mu_k}{0.9}.$$

For the rollover condition of a single-vehicle untripped rollover, a clean, dry pavement represents the most dangerous case. The value of μ_k for this situation is about 0.88.[3] Dividing this by 0.90 allows us to state the following:

If the SSF of a vehicle is less than about (0.88/0.9 = 0.98) 1.0, then this vehicle is prone to roll over rather than spinning out when cornering.

We note that the practical method discussed above [Eq. (11)] for measuring the SSF partially measures the reduction of the SSF due to the suspension and tire deformation factors. Thus, here we have a static test that partially measures dynamic effects!

The above analysis does not consider the effect of a tripped rollover, where the vehicle encounters a pothole or a curb. Neither does it consider the effect of road slope, where the vehicle drives off the road and attempts to regain the road while on a severe slope. Both of these effects argue that, for safety, the SSF should be greater than 1.0. How much greater will be revealed in the following section.

Rollover Accident Data

An investigation of single-vehicle-rollover accident rates was conducted by Robertson and Kelley.[4] Figure 4, taken from this study and replotted by Gillespie,[2] shows the actual accident rollover rate as a function of the SSF. (Gillespie used the term "Rollover Threshold" rather than the now accepted "Static Stability Factor.")

One striking aspect of this figure is the sensitivity of rollover to slight changes of SSF for vehicles with values of SSF below 1.2. In the Robertson and Kelley paper,[4] evidence is presented showing that lower-stability vehicles overturn proportionately more often on the road than after leaving the road. This suggests that tripping is less of a factor in crashes of lower-stability vehicles, compared to higher-stability vehicles, since one encounters more potential tripping adjacent to roads than on them.

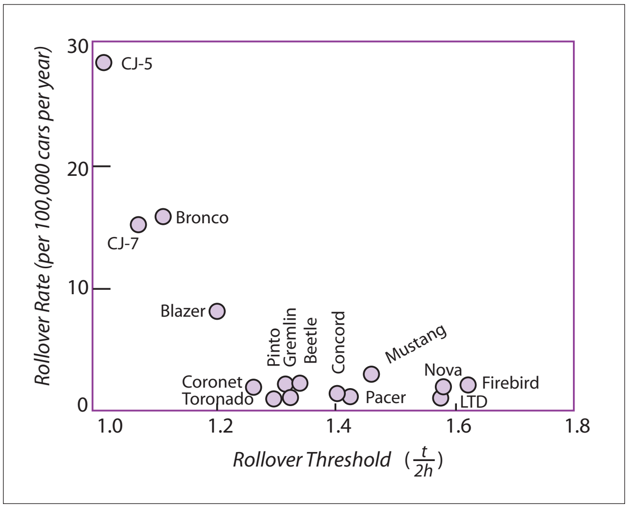

Fig. 4. Rollover rates of passenger cars and SUVs.[2]

The above indicates that the rollovers for SSF <1.2 are the untripped or friction-type rollovers discussed in this paper. In Fig. 4, the vehicles with SSF values less than 1.2 are the Jeep CJ-5 and CJ-7, Ford Bronco, and Chevy Blazer, which are the forerunners of the many SUVs now on the market. Currently, typical SSF values[2] of SUVs range from 0.8 to 1.2. It is reasonable to expect that the rollover rate should be inversely related to the SSF; however, the extreme sensitivity of this relationship is dramatic.

The second aspect of Fig. 4 is that for passenger vehicles with SSF values greater than 1.2, the rollover rate seems to be independent of the SSF. This is an artifact of the above graph. Gillespie[2] plots the rollover rate for SSF values greater than 1.2 and shows that for this range, there is a slight decrease of rollover rate for increasing SSF. This range of SSF values covers tripped rollovers.

These data have led Robertson[5] to propose that a minimum SSF of 1.2 be required for new vehicles sold in the United States for passenger use and that recall of the Jeep CJs be considered.

Recent Developments

Because of the large costs involved, until very recently car makers have strongly resisted redesigning SUVs with wider tracks. "Frontline" reports that in the new design, Ford has increased the track width of the Ford Explorer by 2 inches (5.08 cm). "Frontline" ends its report[1] by interviewing Jacques Nasser, former CEO of Ford, who maintained that this redesign was not made for safety reasons. In light of Fig. 4, it is clear why this seemingly small increase in track width could significantly lower the rollover accident rate. We will leave it to the reader to evaluate Nasser's statement.

In response to persistent safety concerns, the U.S. Department of Transportation has adopted the five-star rating system, based primarily on SSF values, that provides consumers with a measure of a vehicle's propensity to roll over. There seems to be general agreement that while this is a good first step, it is insufficient. Because the five-star rating system does not consider what could be critical differences in emergency handling caused by varying suspension designs, choice of tires, steering response, or the presence of an electronic stability-control system, consumer groups[6] have also called for a dynamic test for rollover. In response to these concerns, Congress has directed NHTSA to develop and implement a dynamic on-road handling test to gauge and score rollover propensity.

One irony of this whole safety issue is that SUVs continue to be marketed with a rugged image that implies great stability in emergency situations. On Dec. 20, 2002, it was widely reported that Ford Motor Company would pay $51,000,000 to settle claims about rollover dangers in SUVs. The money goes to all 50 states, D.C., Puerto Rico, and the Virgin Islands. In addition, Ford added disclaimers to television commercials that show aggressive driving in SUVs. The disclaimer reads, "Professional driver, closed course, do not attempt."

The automakers are clearly aware of the seriousness of the rollover issue. In the latest models, they go to extraordinary lengths to deal with the prevention and consequences of rollovers — using rollover-detection systems, stability control systems, and side and ceiling air bags. Until the fundamental issues of track width and center of gravity height are addressed, perhaps it would be wise to include another safety feature in SUVs — roll bars.

Class and Lab Uses

There are a number of very fruitful ways to use these concepts in the classroom and the lab. In the classroom, the ease with which the SSF can be derived from fundamental physics concepts is very appealing. The immediate application of the theory shows the strong relevance of physics to a critical safety concern of our society.

Extensions for homework or laboratory projects include:

1. Show that the SSF can be measured by placing the vehicle sideways on a slope, blocking the downside wheels from sliding, and then raising the slope until the vehicle is on the verge of tipping over. We leave it to the reader to show that, for this situation, the SSF = tan(ϕ), where ϕ = angle of plane.
2. What change in the SSF is caused by fully loading a particular SUV with passengers? This can be determined by estimating the increase in the height of the center of gravity caused by the passengers.
3. What is the effect of a roof-rack filled with camping gear on the SSF?
4. What effect will the 2-in (5.08-cm) increase in the track width of the Ford Explorer have on its SSF?
5. Using an old-fashioned record player and a simple rectangular wood block, determine the values of v and r that just cause rollover. Equation (4) can then be used to compare $v^2/(rg)$ with the SSF determined from project 1 above.

There are indications that vehicle manufacturers are resisting the publication of SSF values. It is likely that consumer pressure will force this to change. Track width values can be found easily on the Internet. Center-of-gravity heights are harder to locate, but should become more accessible in the near future.

References

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