ON-ROAD ROLLOVER TESTING: OUTRIGGER HEIGHT AND DATA FILTERING

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ABSTRACT

A single degree of freedom rollover model is used to suggest guidelines for outrigger installation and for data filtering.

INTRODUCTION

Dynamic testing for vehicle rollover characteristics requires knowledge regarding the effects of sideforce over time on roll energy, for filtering the test data. Height setting of the outriggers must be made with view of the data sought, but also with consideration of safety implications of the forces acting on the outriggers.

WHEN DOES ROLLOVER BEGIN?

Tip-up begins when the rollover moment—sideforce times CG height—exceeds the restoring moment—weight times the effective half-track (Figure 1). With "two wheel lift" the CG height increases and the effective T/2 decreases: therefore the tip-up angle will accelerate so long as "excess sideforce" remains. If the excess sideforce is of too-short duration the two wheel lift will be only momentary.

A fundamental question is "When does rollover begin?" In processing test data the roll angle and roll rate traces give a indication of the instability point. Under moderate sideforce the vehicle will tend to roll at a decreasing rate (as a damped second-order system) until the quasi-steady "roll angle per g" is reached. The roll consists of two motions: the sprung mass on the suspension and the total vehicle on its tires. Under moderate sideforce the two motions combine as one, but as the roll instability point is passed the *total vehicle* roll angle will begin to increase at an increasing rate until outrigger strikedown. The inflection point in the roll angle trace between decreasing and increasing roll rate is the "tip-up point" of unstable behavior. The inflection point usually appears after visible one-wheel lift and coincident with the beginning of two-wheel lift. However, it can also occur shortly after visible two-wheel lift.

EXAMPLES

This rollover behavior can be seen in results of tip-up threshold testing. These tests use ATI's outriggers (Figure 2), which have an air-cylinder force cushion in the slider/roof rail strut (Reference 1).

Figure 3 shows the threshold behavior with a well-damped roll motion, in two test runs under identical conditions of speed and reversed steer. One run, shown with dotted lines, produces a tip-up. The run shown with a solid line does not tip up. The point of instability at 10 degrees is clear, as is the outrigger's cushioned initial strike-down at 13 degrees. The roll angle is increasing at an increasing rate until the "glitch" at initial outrigger strikedown, due to outrigger force preload. The roll angle then increases at a slowing rate, resisted by increasing outrigger downforce, to the maximum roll angle.

Figure 4 shows a less-damped threshold behavior. Again the inflection point at 11 degrees and the outrigger's initial strikedown at 14 degrees are clear.

In Figures 3 and 4 the excess sideforce is small, since at the threshold the vehicle is like a card standing on end: it can roll or not roll. Nevertheless, it can be seen that the roll rate between the instability point and outrigger strikedown is increasing rapidly.

In Figure 5 the excess sideforce is very large. The inflection point at 11 degrees where the roll angle "takes off" is there, but not so obvious. The roll motion powers through the outrigger's initial cushioned strikedown, until the hard limit of 23 degrees is reached.

OUTRIGGER HEIGHT DICHOTOMY

For the inflection point to be reached, the outriggers must be set high enough to avoid interference. Outriggers take out energy and resist additional roll angle. Therefore, if they engage too early, the existence of tip-up cannot be verified, even if some minor "two wheel lift" is observed.

On the other hand, it will be shown in this report that the forces in the outrigger system, and especially the shock loads, increase rapidly as the roll allowed before touchdown is increased. The outriggers must counteract the moment due to excess side force, and they must absorb the momentum associated with roll velocity. A system set too high will be subjected to extreme loading.

ADDITIONAL QUESTIONS

A second fundamental question is "Will complete rollover occur in this maneuver if outriggers weren't there?" As noted above, the test data must show that excess sideforce exists for enough time to complete the rollover process in the absence of the outrigger system.

A third fundamental question is "What lateral acceleration was needed to cause rollover?" In processing data the lateral acceleration trace is always noisy and must be filtered. Filtering consists of averaging out those noise peaks and valleys which are too short to affect tip-up. A given average value must be present for sufficient time that complete rollover would have resulted in the absence of outriggers.

The simplified analysis in this report examines these questions, to provide objective guidelines for outrigger use and tip-up data processing.

ROLLOVER DYNAMICS

A sidepull or centrifuge test defines an "sidepull T/2h", which exists at quasi-steady state tip-up. As indicated in Figure 6, the effective T/2 is the horizontal distance from the vertical projection of the CG (as deflected by suspension elasticity and suspension roll angle) to the deflected tire. Effective h is the height of the vehicle CG under the steady state tip-up load.

Dynamic loading may exceed the sideforce which produces the steady state roll angle, suspension and tire deflections. However, of much greater importance are the deflections, principally roll angle, due to dynamic excess caused by stored energy in the rollover maneuver. For example, typical roll angles at steady state wheel lift are 6–8 degrees; while typical roll angles at the dynamic inflection point are usually 10–12 degrees. Sideforce is not capable of *causing* these extreme roll angles. The roll momentum caused by the maneuver powers the roll angle well past the steady state response point; and the sideforce, because of the reduced T/2h, is capable of holding or further increasing that excess roll angle. In other words, the sideforce is "excess" over the *reduced T/2h*. In fact, testing experience has demonstrated that the lateral acceleration at the tip-up threshold is usually less than the steady state sidepull figure.

CENTER OF TOTAL VEHICLE ROLL

A vehicle's total roll angle is composed of the sprung mass rolling about the suspension roll angle, plus the total vehicle rolling due to vertical and lateral deflection of the tires. A vehicle-mounted gyroscope measures this total angle, as does the sidepull test. While suspension roll centers are usually above ground, the "center of roll" of the total motion is always well below ground until the roll motion is entirely about the tire fulcrum.

In the computations, the CG height is held constant, while the total roll angle is increased to various excess values preceding tip-up. The distance to the total vehicle roll center takes into account both suspension roll angle and tire deflections.

METHOD OF ANALYSIS

For our analysis we use the undeflected values of T/2 and h along with the steady state tip-up values determined in a sidepull test. We then extrapolate the differences, assuming uniform gradients, to "excess total vehicle roll angle" of 80, 100, and 120 percent, which result in a decreased "effective T/2h". These values are used, along with the sidepull lateral acceleration, to calculate roll acceleration, velocity and angles, etc.

The computations do not include any direct contribution from initial roll momentum. In Figures 3 and 4, the roll velocity is negligible at the inflection point where our analysis begins: the momentum contribution consists of the excess roll angle (or its equivalent in excess sideforce) on which the analysis is based.

Roll acceleration is found for various magnitudes of excess roll angle, and the nonlinear equations are plotted vs time. Roll velocity and angle, and roll kinetic energy and required potential energy are found by numerical integration and plotted vs time. The length of time that the lateral acceleration must be applied is found from equality of kinetic and potential energies. The computed time to equality is used in filtering actual test data by the running-average method, to determine the average lateral acceleration required for tip-up.

Figure 6 shows a vehicle on its suspension at incipient tip-up. The sprung mass is rolled to the angle ϕ measured in the sidepull test. The fulcrum for tip-up is not the center of the tire tread, but the outer shoulder of the deformed tire. The CG moves toward the fulcrum due to roll angle and to tire and suspension deformation; and it may rise or fall somewhat due to suspension geometry. CG height becomes h_{eff} and the half-track becomes $(T/2)_{eff}$.

Figure 7 shows the vehicle during tip-up. Taking moments about the fulcrum, we have the weight (mg) of the vehicle times the lateral distance $(T/2)_{eff} = k \text{ cosine } (\theta+\theta_0)$ as restoring moment, acting to keep the vehicle down; and the inertial force (ma) times the height distance $h_{eff} = k \text{ sine } (\theta+\theta_0)$ as rollover moment acting to tip it up. The rollover acceleration is found from the difference between the restoring moment and the rollover moment, divided by the moment of inertia of the complete vehicle about the tire fulcrum. The *tip-up angle* is θ, so the angle between the horizontal and the line from the fulcrum to the CG becomes $\theta+\theta_0$.

HYPOTHETICAL VEHICLE

We assume a light SUV or pickup with a CG of 25 inches and a 55 inch track width. Geometric T/2h is therefore 1.10. We further assume a steady state sidepull or centrifuge liftoff at 0.9g. The roll gradient is 6 degrees/g, so roll angle at 0.9g is 5.4 degrees. We assume a CG rise of 0.5 inches for all liftoff conditions (no suspension travel after liftoff). Weight is 2550 pounds and roll moment of inertia is 310 lb-ft-sec^2.

At 0.9g, from the effective T/2h = 0.9, we find T/2 = 0.9 (h + 0.5) = 23 inches.

Reduction in T/2 is 27.5 – 23 = 4.5 inches.

Distance from CG to “roll center of total vehicle” is found from 4.5 = R sin(5.4 degrees). Then
R = 4.5 / sin(5.4 degrees) = 48 inches.

The moment of inertia about the CG is I_{xx}: but in tip-up the moment of inertia is that about the fulcrum, which is that about the CG plus the mass times the square of the distance from CG to fulcrum:

$$I_F = I_{xx} + mk^2 \qquad \text{where } k^2 = \left[(T/2)^2 + h^2 \right] \tag{1}$$

The angle θ_0 in Figure 7 is: $\theta_0 = \tan^{-1}\left[h/(T/2) \right]$

TABULAR DATA

EXCESS percent	**ANGLE** degrees	**48sinθ** inches	**$(T/2)_{eff}$** inches	**$(T/2h)_{eff}$** inches	**k**	**I_F**
0	5.4	4.5	23.0	0.90	34.3	957
80	9.7	8.1	19.4	0.76	32.0	873
100	10.8	9.0	18.5	0.73	31.5	856
120	11.9	9.9	17.6	0.69	31.0	838

COMPUTATIONS

Taking moments,

$$I_F\ddot{\theta} = -mgk\cos(\theta+\theta_0) + mak\sin(\theta+\theta_0) \tag{2}$$

$$\ddot{\theta} = (mgk/I_F)\left[-\cos(\theta+\theta_0) + (a/g)\sin(\theta+\theta_0)\right] \tag{3}$$

Note that:

at $\theta = 0$ and $\ddot{\theta} = 0$: a/g = T/(2h)

at $(\theta+\theta_0) = 90$ degrees : $\ddot{\theta}$ = m(a/g)k

The angular acceleration equation is plotted vs θ for several values of excess (Figure 8); then it is numerically integrated to plot angular velocity vs time (Figure 10); and integrated again to plot angle vs time Figure (11). Roll acceleration is then plotted against time (Figure 9).

During rollover, kinetic energy = $\frac{1}{2} I_F \dot{\theta}^2$ (4)

Remaining potential energy for rollover = $mg\left[k - k\sin(\theta+\theta_0)\right]$ (5)

Kinetic energy and required potential energy are plotted vs time on the same graph in Figure 12. Where kinetic energy equals or exceeds required potential energy the rollover can be completed without additional sideforce. The intersections show “crossover time” vs excess roll angle. Referring these points to Figure 11 yields 23, 25, and 27 degrees tip-up at the crossover times for 120, 100, and 80 percent excess.

OUTRIGGER LOADING

The outriggers must cancel the tip-up moment due to excess sideforce, and they must absorb the kinetic energy resulting from roll momentum. The excess sideforce moment is found from Figure 8 or from Figures 9 and 11. The kinetic energy is found from Figures 11 and 12. The energy is absorbed by force through a distance, so outrigger compliance reduces the required force. However, outrigger compliance also increases the allowable roll angle and therefore the maximum moment from excess sideforce; so it cannot be overdone. Too high an allowable roll angle also increases the shock that the driver experiences when the vehicle “free-falls” at the completion of the tip-up maneuver. These factors entered into the design of ATI’s force-cushioned outriggers.

FILTERING OF LATERAL ACCELERATION DATA

Lateral acceleration required to produce rollover is often used as a vehicle figure of merit. But from the analysis herein (and from simple engineering logic) a *combination of lateral acceleration and time* is required. A running-average filter is one in which each point is the average of preceding and following values. For example, with a 1 second running average filter each point is the average of values up to ½ second before and ½ second after that point. In test data, the *peak* value of a running-averaged lateral acceleration trace is the maximum acceleration *sustained* for a time equal to the filter time period.

SELECTION OF FILTER TIME

When the kinetic energy due to tip-up momentum exceeds the potential energy required to reach 90 degrees roll angle, the roll will be completed with no further application of sideforce. This point is shown in Figure 12. Up to this point an average lateral acceleration must be maintained, equal to the excess lateral acceleration on which Figure 12 is based. From this analysis, ATI has chosen a 0.5 second running-average filter for lateral acceleration data in its reversed steer test protocol. Significant sideforces exist before and after the actual filter time: for this reason ATI chose 0.5 seconds over the 0.6 indicated in Figure 12. Based on their own analyses of the problem, Ford (Reference 5) and NHTSA (Reference 6) have recently chosen 0.4 second running-average filters.

Figure 13 shows the 5 Hz filtered lateral acceleration trace from the tip-up in Figure 4, along with the result after a 0.5 second running-average filter.

LATERAL ACCELERATION AT ROLLOVER

If the suitably filtered lateral acceleration is found for a *minimum tip-up* run and a *maximum non-tip* run, their *average* can be called "the lateral acceleration at rollover". This definition, originated by Toyota, has been used in all ATI test reports since 1998 as the most suitable figure of merit for rollover resistance. The maximum lateral acceleration in a non-tip run must defined as that which occurs in the vicinity of maximum roll angle, since as a vehicle slides to a stop it sometimes exhibits high values of lateral acceleration which are meaningless without a simultaneous "excess roll angle"

BUMP STOPS

The effects of bump stops is not included in this analysis. When a vehicle rolls into its stops, any kinetic energy of suspension roll becomes tip-up energy. However, data from systematic testing indicates that roll angle increases at a decreasing rate before the unstable inflection point, so suspension-roll kinetic energy is small (unless excess lateral acceleration is very high, in which case bump stops don't matter). Since the tip-up moment of inertia is about 3 times that of suspension roll inertia, the bump stop effect should generally be negligible in testing for untripped rollover thresholds.

PREVENTING ROLLOVER

The analysis herein shows that the primary cause of rollover is a reduced T/2h. Measures that will increase rollover resistance by increasing effective T/2h are the following:

1. Increase geometric track width;
2. Increase suspension roll stiffness;
3. Increase suspension roll damping;
4. Decrease tire lateral elastic compliance (generally, lower section height tires);
5. Decrease suspension lateral compliance;
6. Decrease geometric CG height;
7. Increase plow tendency at high lateral accelerations (by roll couple distribution or tire load transfer sensitivity).

Note that these suggestions are made without consideration of possible effects on ride and handling, or of "the law of unintended consequences". In particular, increased roll stiffness and damping should be attained by nonlinear components that would come into play only at high values of roll angle and roll velocity.

REFERENCES

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2. ATI Test Report 102400: *Reversed Steer Testing – 1994 Mazda 2300 RWD Pickup,* at 8A-10:53 and 8A-12:33.
3. ATI Test Report 082001: *Reversed Steer Testing – 1993 Suzuki Sidekick 4-Door 4WD,* at 6-29:20 and 6-31:15.
4. ATI Data File 101001: *ISO Task Force Testing, NHTSA PRISM, 1993 Suzuki Sidekick* at 2-37:17.
5. Ford Motor Company Comments to *NHTSA Consumer Information Regulations, Rollover Resistance, Docket No. NHTSA-2001-9663*, page 8 of 9.
6. G.J. Forkenbrock, W.R. Garrott, M. Heitz and B.C. O'Hara, *A Comprehensive Experimental Evaluation of Test Maneuvers That May Induce On-Road, Untripped Rollover.* Phase IV of NHTSA's Light Vehicle Rollover Research Program, DOT HS 809-513, October 2002, Section 5.5.1.1.

ACKNOWLEDGMENT

Our thanks to Attorney Paul F. Hultin of Wheeler, Trigg & Kennedy, whose constructive criticism regarding "eyeball filtering" of lateral acceleration data prompted the research described in this report.

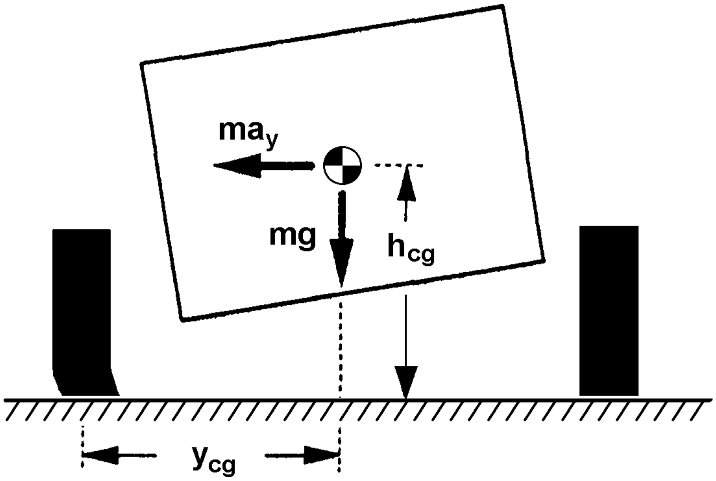

Figure 1

Tire Side Forces at Rollover

$$m a_y h_{cg} = m g y_{cg} \quad or \quad \frac{a_y}{g} = \frac{y_{cg}}{h_{cg}}$$

Figure 2

ATI’s Outriggers (Light version)

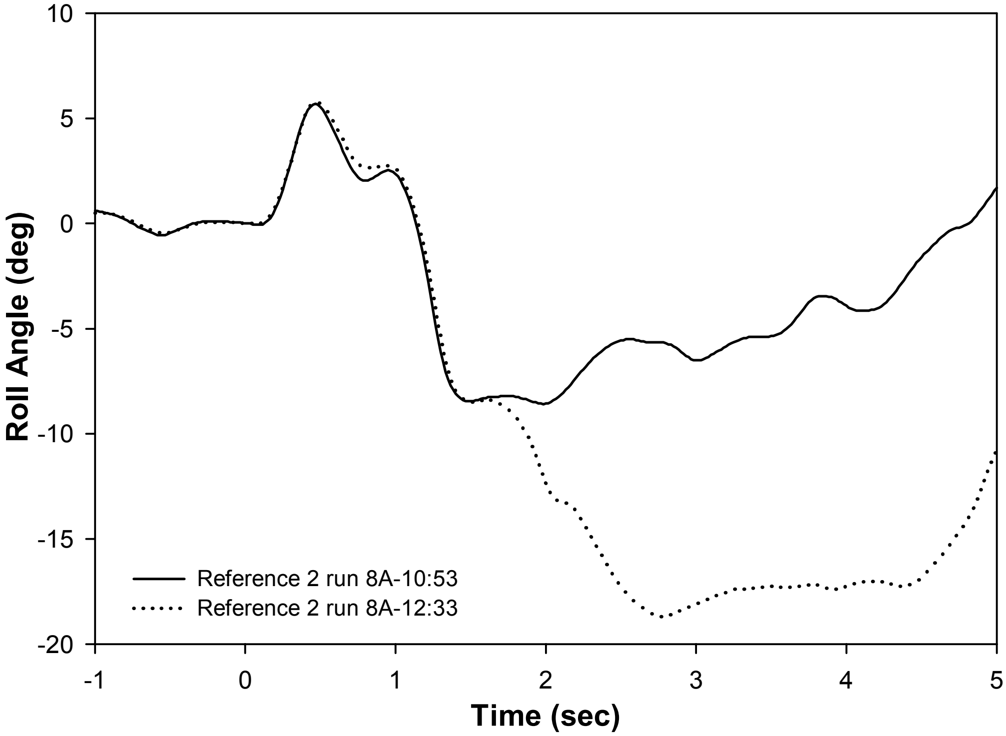

Figure 3

Rollover Threshold response with small excess sideforce

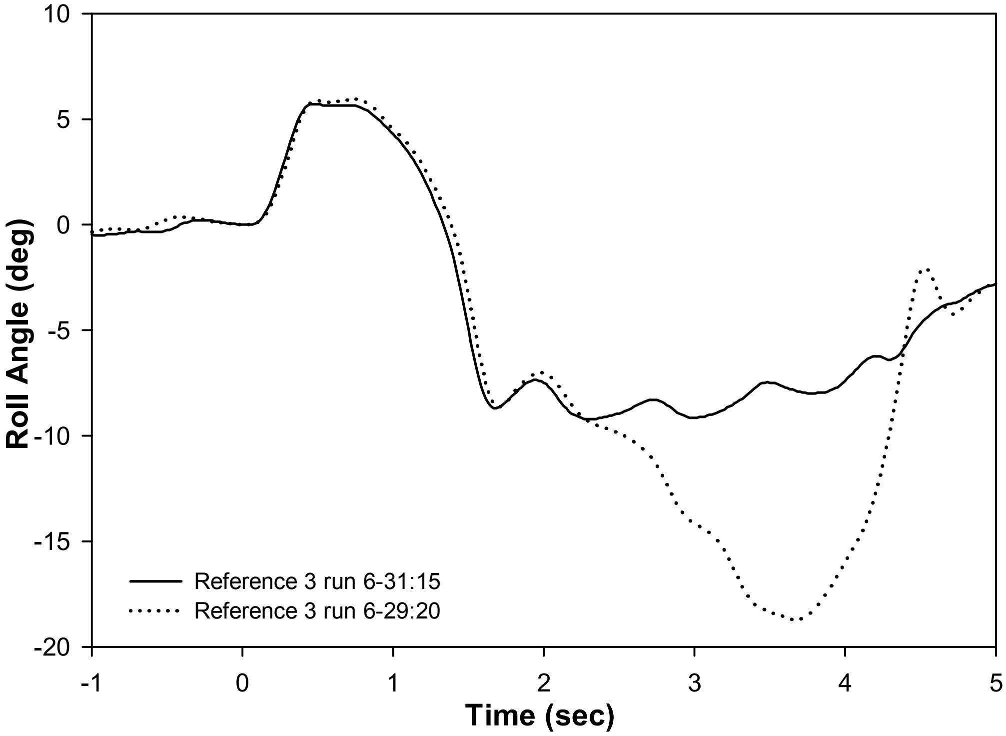

Figure 4

Rollover Threshold with oscillatory roll response

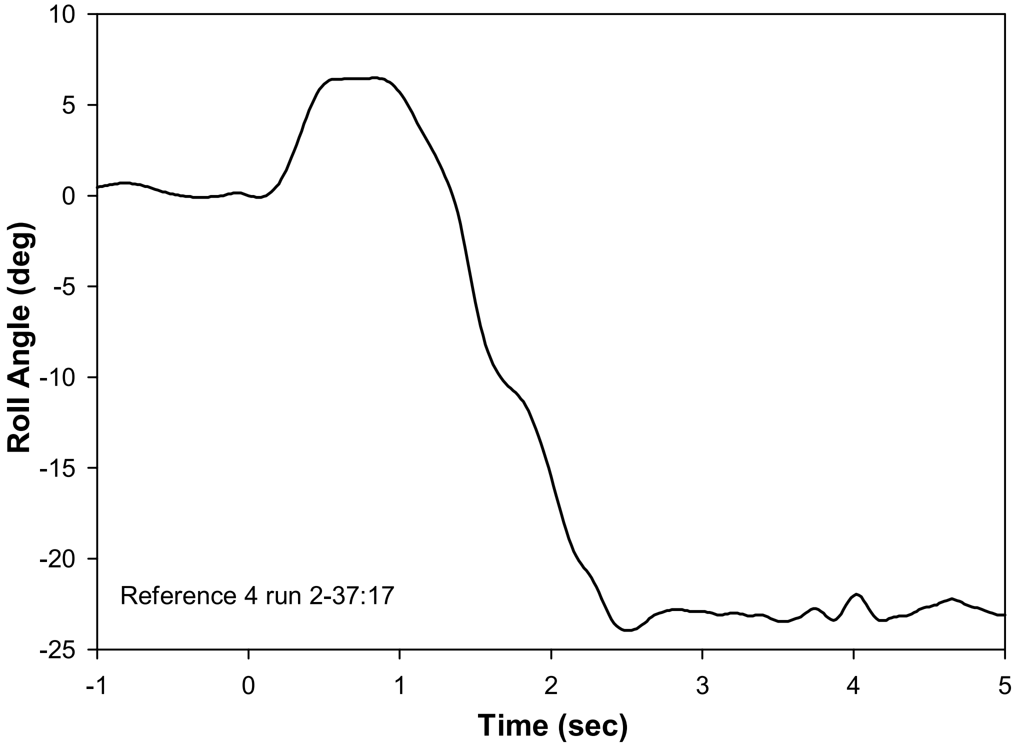

Figure 5

Rollover Response with large excess sideforce

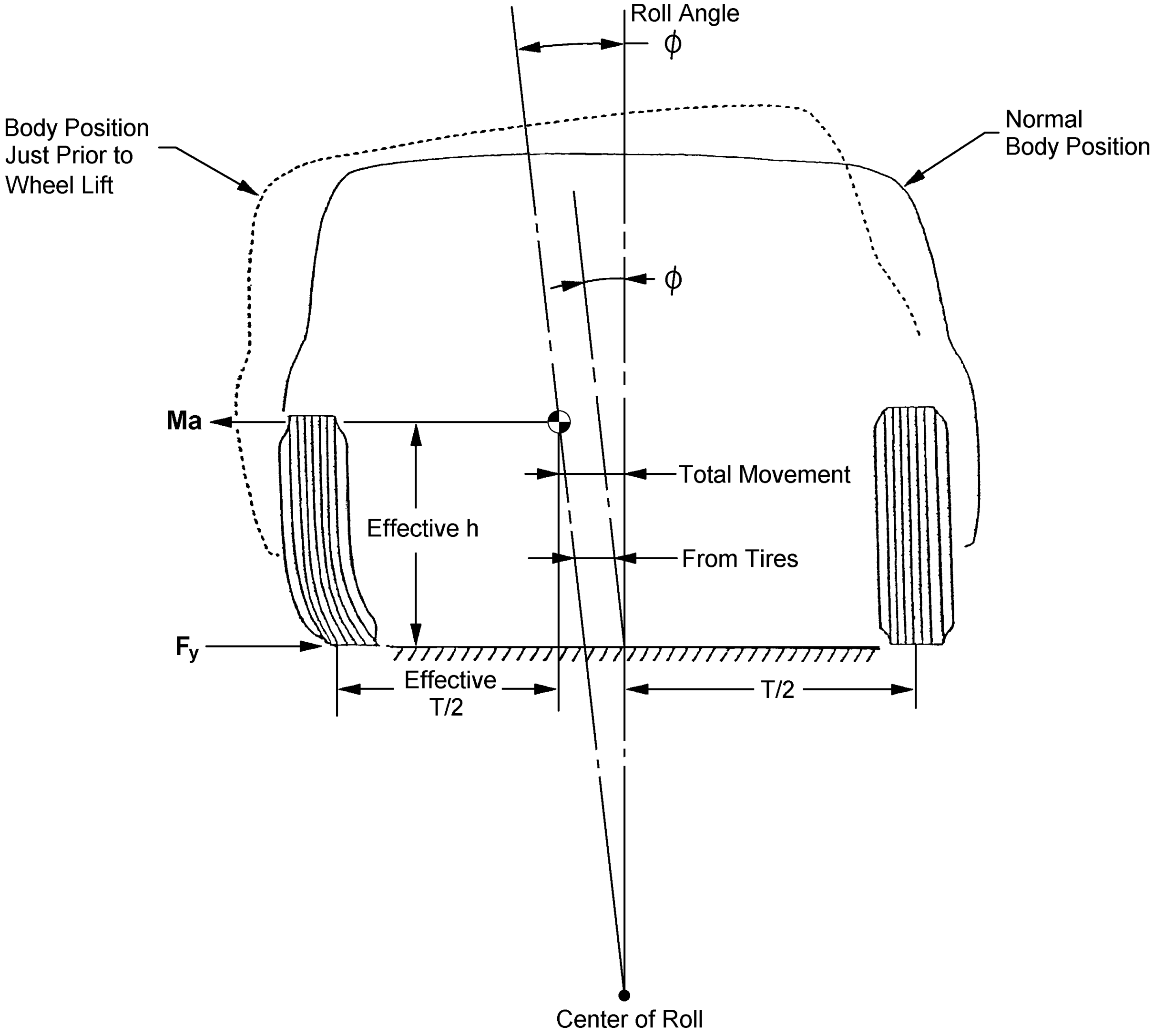

Figure 6: Vehicle at Incipient Tip-up

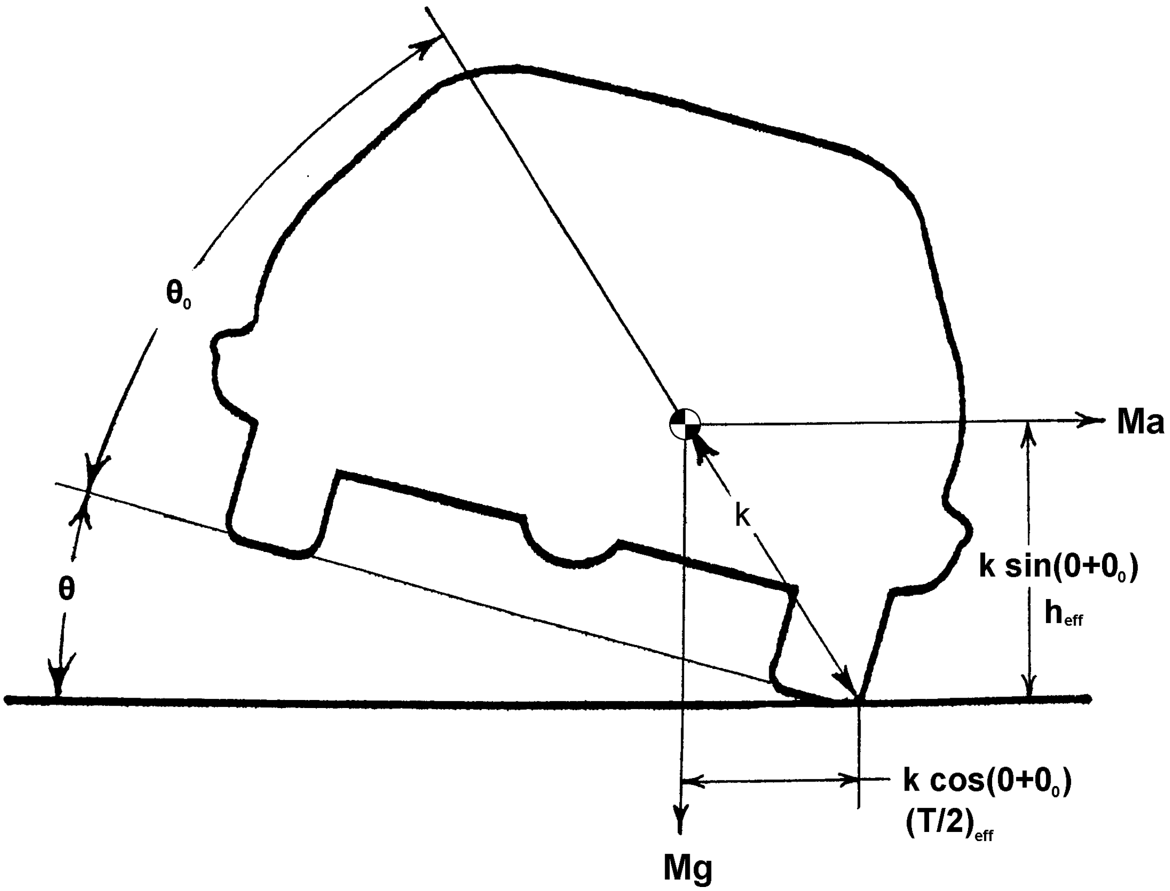

Figure 7

Geometry During Tip-Up

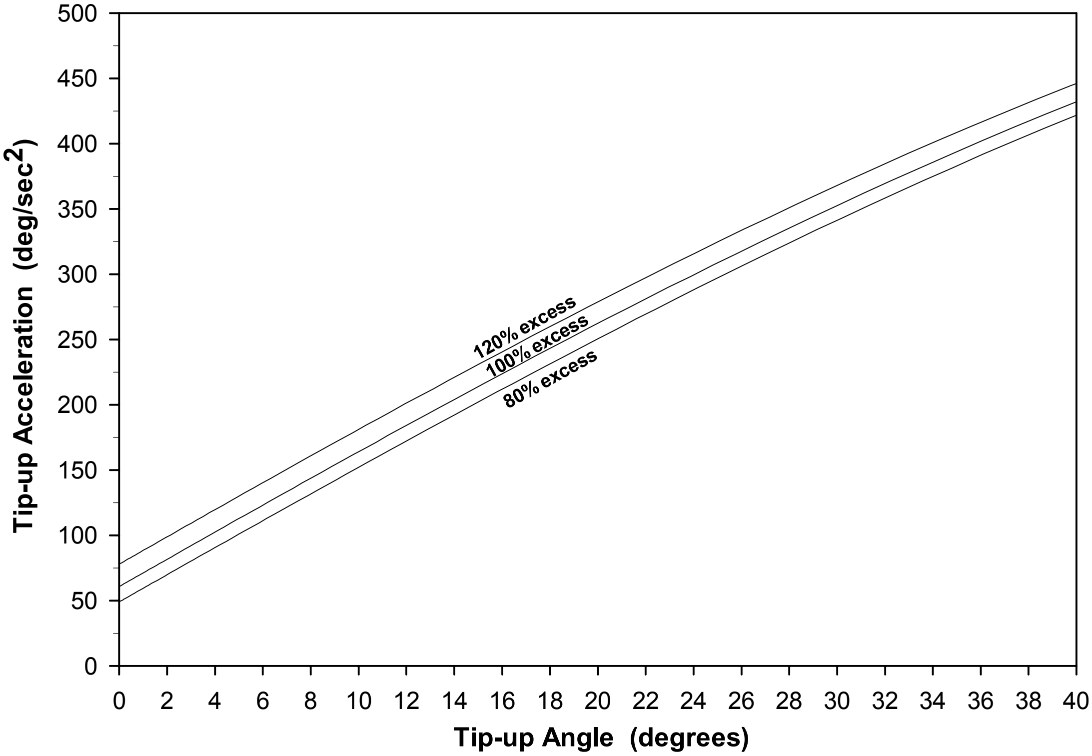

Figure 8: TIP-UP ACCELERATION vs TIP-UP ANGLE for Light SUV

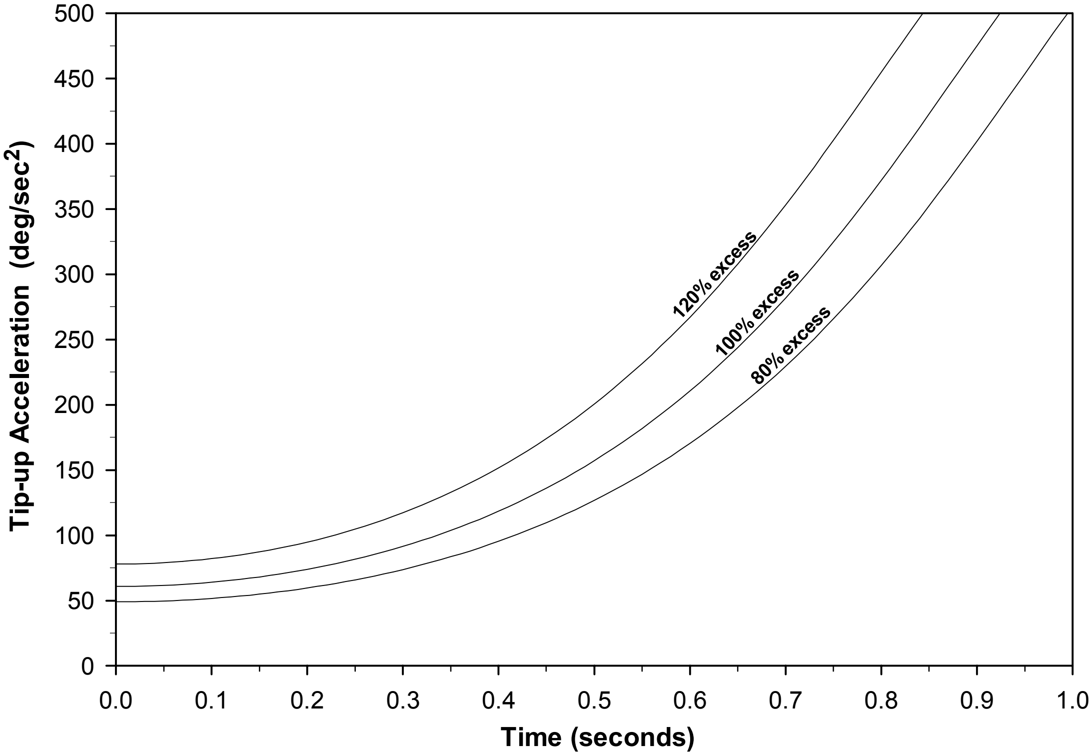

Figure 9: TIP-UP ACCELERATION vs TIME for Light SUV

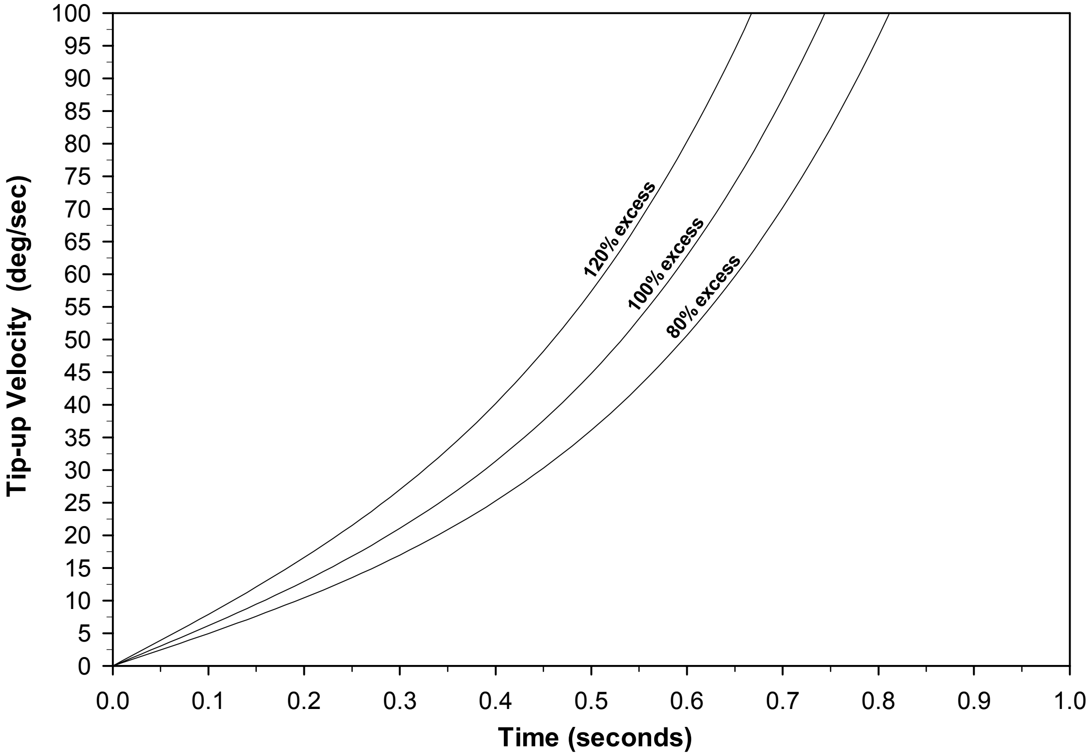

Figure 10: TIP-UP VELOCITY vs TIME for Light SUV

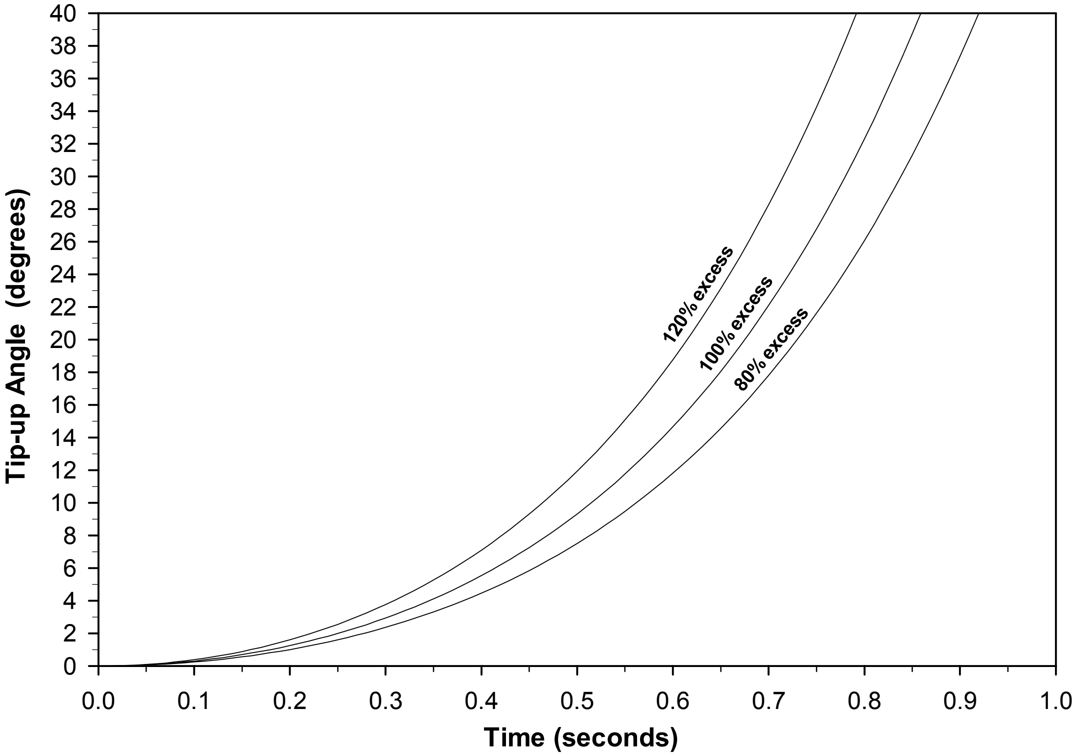

Figure 11: TIP-UP ANGLE vs TIME for Light SUV

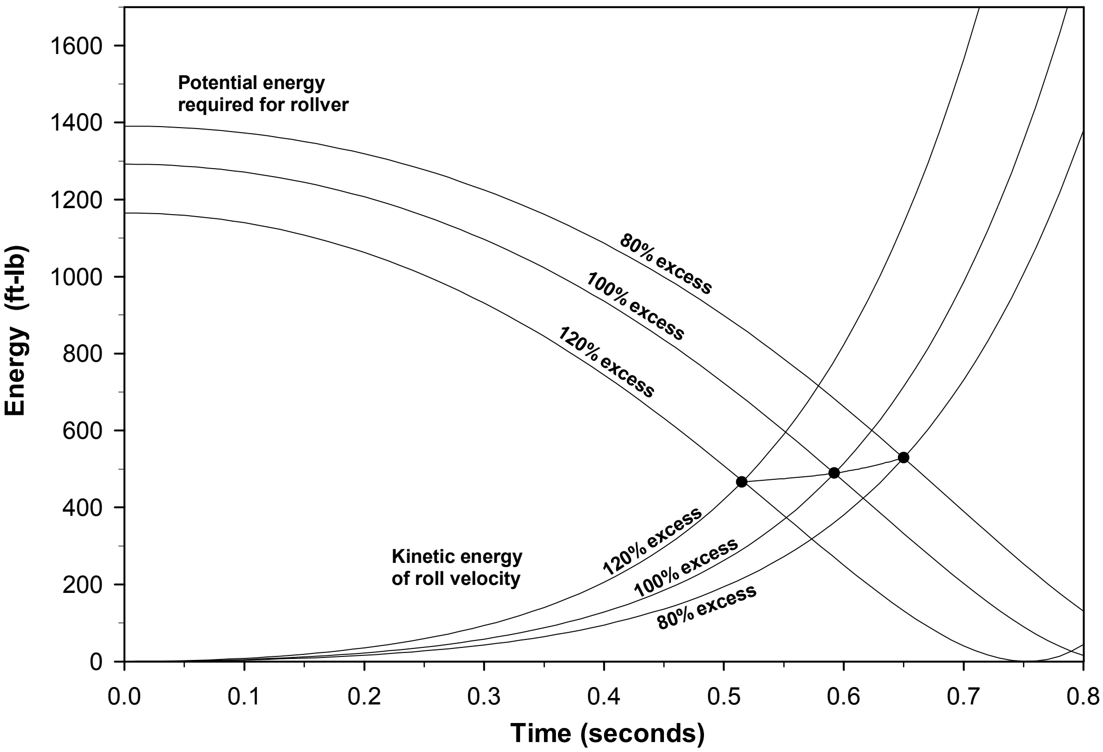

Figure 12: POTENTIAL and KINETIC ENERGY vs TIME for Light SUV

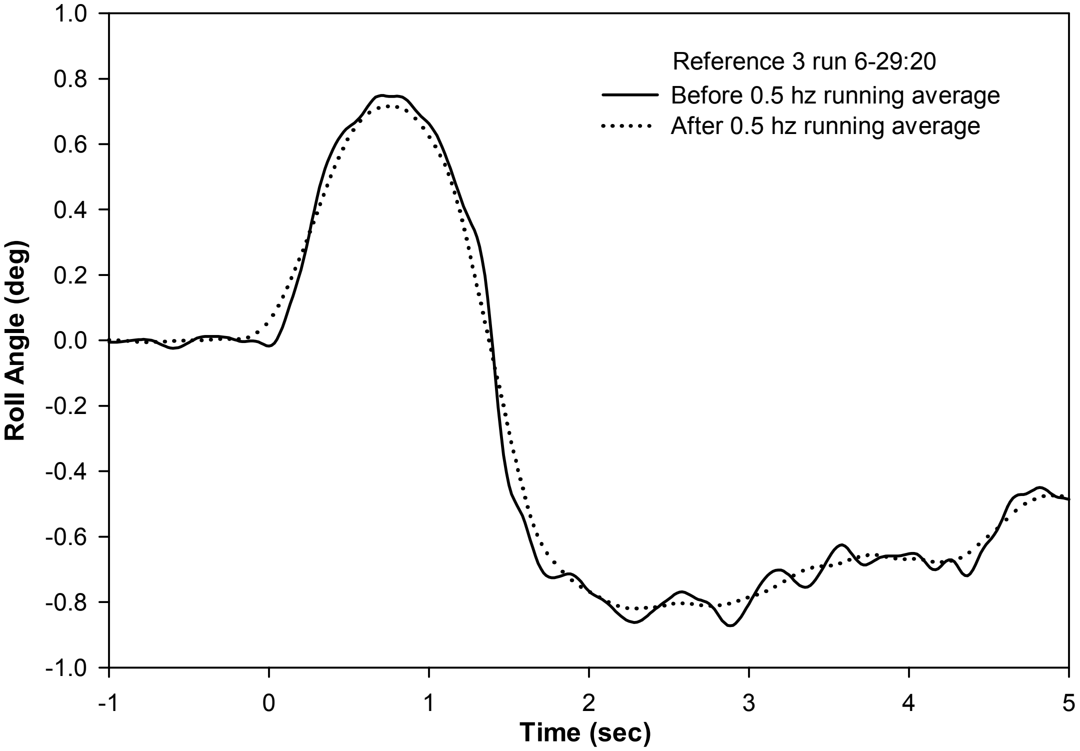

Figure 13: Effect of 0.5 second Running Average Filter