Tripped Rollover Crashes

MARC1 SOLUTIONS

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Short Paper PCB3 – 2014

www.pcbrakeinc.com

1.0. Introduction

The rollover of a motor vehicle can be caused by different mechanisms. It may simply be a vehicle running off the road on a steep embankment and tipping over. It may be a high-center-of-gravity vehicle rounding a curve too fast. It may be a vehicle responding to left-right steering inputs by the driver loading up the suspension sufficient to roll. It may be a vehicle sliding sideways against a curb or furrowing in soft off-road terrain. It may even be a vehicle "traveling" up a guy wire and falling on its roof. It may be an SUV bumped by another vehicle causing it to spin out of control into a freeway median and roll over as reconstructed in Figure 1.

Friction rollovers such as cars, trucks or tractor-semitrailers rolling over in a turn including the effects of suspension parameters are discussed in Chapter 27. MARC1–P applies.

Investigating rollover accidents requires careful and detailed accident scene inspection, vehicle examination and injury analysis. No two rollover crashes are alike. Each crash will exhibit a large number of unique crash events, and only a small number of common factors. Experts often limit their reconstruction of rollover crashes to calculating a pre-tripping speed from distance and drag factor after impact, followed by some extended animation. Frequently, no distinction between a high initial angular velocity and tipping-on-its-side rollover is made. However, since injuries are often severe, a detailed vehicle motion analysis and occupant kinematics study must be made to clearly identify causes of injury and defects claims, if any.

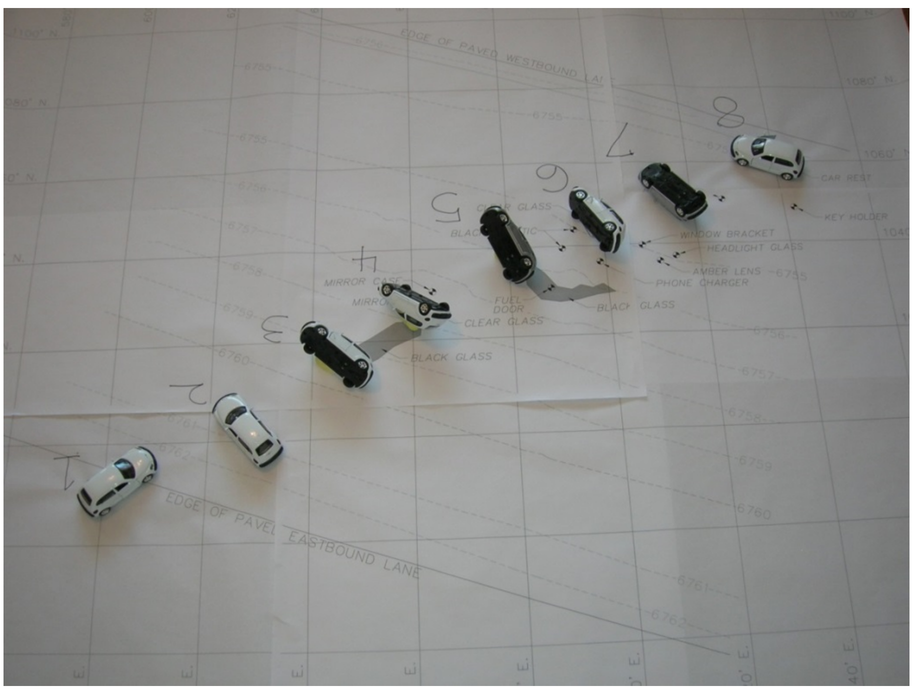

Figure 1. Sequenced Locations of SUV Rollover Accident Reconstruction.

The sequenced locations of the SUV rollover crash accident reconstruction are shown in Figure 1. The accident occurred in the median of I80 near the Utah-Wyoming border. The vehicle was not available for inspection. Detailed vehicle photographs were available. Accident scene evidence was reasonably well preserved by snow covering the median during the winter months until our site inspection in the following spring.

Inspection of Figure 1 shows detailed information concerning specific rollover events and vehicle components such as mirror, antenna or glass debris located during our accident site inspection six months later. We had measured the distances between different scene data points. Using a typical after-trip drag factor allowed us to calculate a probable speed at the trip point. Was this a high-angular velocity tripping? How high would the SUV rise off the ground? Were witness accounts consistent with physical evidence? Did the first vehicle/ground contact and crush deformation indicate a high angular velocity trip? Was crush intrusion due to severe roll dynamics or design defects issues?

When our medical experts quoted the Malibu rollover study as the basis for their opinions, we realized that most "simple" reconstructions do not address dynamic tripping details. How was the initial linear kinetic energy of the vehicle changed into rotational and linear energy after impact? How much energy was "lost" in form of suspension springs/shock absorber/tire displacements. What were the restitution effects, if any? In the Malibu study, the car was dropped off a inclined sled moving at 32 mph. In the study a significant rotational velocity of approximately 360 deg/sec was only achieved after the right front leading tire of the air-borne vehicle had made contact, that is, well after the rollover had begun (*see* Section 27.04[3] of 7th edition of Limpert Accident Reconstruction Book).

An example of another rollover analysis is shown in Section 27.04[4]. Only very simple reconstruction concepts in terms of speed, time and distance were applied to analyze certain aspects such as occupant throw distance, number of rolls or rest position.

2.0. "Roller Coaster" Rollover of International Scout II

2.1. Viewing the Video

The Scout II rollover is a tripped roll off a moving and stopping sled. The vehicle data are: Curb weight is 3609 lb, wheel base 100 in., track width 57.2 in., length 165.2 in., width 70 in., overall height 67.2 in., c.g.-height empty 24.6 in. (*see* table on page 26-18 for IH Scout), standard tire size F78-15 with tire diameter of 27 inches and tire width of 7.7 inches.

Study the video carefully as an expert reconstructionist "eye witness". Observe what the leading (left) tires do when stopped by the rail. Define the tripping point in terms of vehicle location relative to the track as well as dynamic parameters visible in the video. What are the different effects of rigid and real-life suspension geometry upon the tripping mechanism and subsequent rollover? Observe the deformation of the cab as it contacts the ground. What specific ground contact(s) produces the largest drag force?

Watching a rollover crash test on video versus watching the actual test brings with it certain significant differences. In a video concentrating on the moving vehicle, I can repeatedly watch and analyze details of the trip, crush deformations with the ground, center-of-gravity height, and others. However, distances travelled may be more difficult to determine. When at the scene of an actual rollover crash, distances and ground data are (usually) more easily identified and measured.

View rollover video of Scout

If visible in the video, answer the following questions:

a. Roll angle at moment of tripping
b. Maximum c.g.-height of airborne vehicle
c. Horizontal travel distance from tripping to rest
d. Horizontal distance on ground after first ground contact
e. First vehicle contact point/area of vehicle with ground
f. Approximate angular velocity while airborne
g. Speed before tripping
h. Linear speed when ground contact was made after being airborne

Figure 2. Scout at or just before Tripp Moment

The free-body diagram of the tripping vehicle is shown below. The impulse P_y is the force acting in the y-direction during a very short period of time that actually causes the center-of-gravity to rise. *See* Section 27.04[2] for the details of the tripping impulse analysis. No system compliance and suspension deflections are considered.

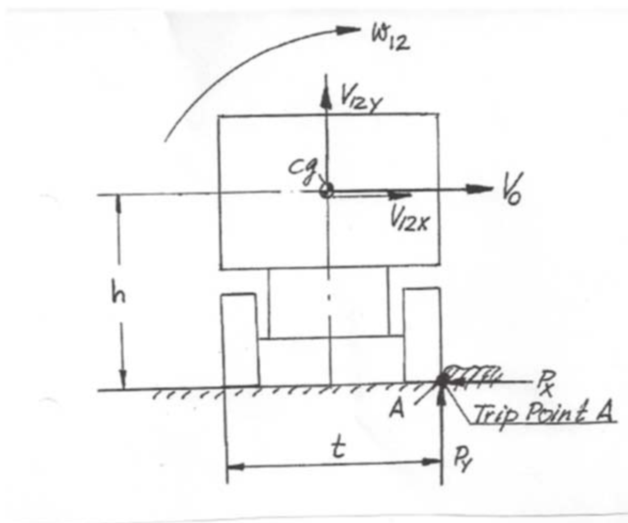

Figure 3. Vehicle at Moment of Tripping: Impulse Analysis

2.2. Roller Coaster Analysis

The minimum trip speed for the Scout II to simply fall on its side in a one-quarter roll is given by Eq. 27-10 and can by calculated by MARC1-O2 as shown. Inspection shows that the tripping speed must be at least 12.59 or approximately 13 mph. Eq. 27-10 assumes that the vehicle is a rigid body without any roll angle deflection, no rising of the center-of-gravity before tripping, as well as no "shortening" of the half-the-track width resulting in lowering of the stabilizing effect of the vehicle weight.

For the remaining three quarter rolls of the Scout II we have a theoretical distance of approximately (2)(70) + (1)67 = 207 in. or 17 ft. Using a post tripping drag factor of 0.8g yields a speed to complete the three quarter rolls of $V_{trip} = \{13^2 + (30)(17)(0.8)\}^{1/2} = 20$ mph. Combining speeds (*see* Section 20-07) yields the tripping speed as $[13^2 + 20^2]^{1/2} = 24$ mph. A speed of 24 mph will probably not raise the center-of-gravity above the ground as well as yield an angular velocity sufficiently high to rotate the Scout one-half turn before coming in ground contact with the driver side roof edge.

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Monday, October 20, 2014

MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
********** PROGRAM 'O-2' RUN FOR PCB 3 -2014 **********
VEHICLE ROLLOVER OR SIDE SLIDE

Information For Vehicle                     1974 IH  Scout II
=============================================================
INPUT DATA:

Vehicle Center of Gravity Height, IN:          ===>    25.60
Vehicle Track Width, IN:                       ===>    70.00
Vehicle Weight, LBS:                           ===>  4009.00
Roll Moment of Inertia, FT·LBS·SEC²:           ===>   400.90
Tire-Road Friction to Roll, D'LESS:            ===>     1.37
=============================================================
OUTPUT DATA:

Minimum Sliding Speed for Tripping, MPH:       ===>    12.59
=============================================================
```

An important issue involved in reconstructing rollover crashes is the real after-tripping deceleration or drag factor of the rolling/sliding vehicle before coming to rest. Many drag factors were determined in rollover tests from the known pre-trip speed and the after-tripping distance of the vehicles tested. Depending upon the velocity change experienced by the vehicle during the tripping process, such an analysis may be incorrect. The run-out dynamics is greatly affected by how the kinetic energy of the vehicle before tripping is changed into rotational and kinetic energies after tripping as well as the shape and deformation of the vehicle providing specific roll resistance versus sliding resistance which are all part of the drag factor after tripping.

Neil K. Cooperrider and co-authors address this issue in their SAE publications 900366 (Testing and Analysis of Vehicle Rollover Behavior) and 980022 (Characteristics of Soil-Tripped Rollovers.

The authors conclude in their SAE 980022 paper as follows:

"Post-trip decelerations as low as 0.4g's are often used in accident reconstruction calculations. When such values are used, one should be careful to ensure that enough deceleration is attributed to the trip phase where decelerations of 1.2 g's or higher are encountered".

2.3. Important Dynamic Tripping and Rollover Parameters Obtained from the Video.

The following are my ***estimates*** based upon viewing the Scout rollover video many times:

a. Roll angle at moment of tripping: 20 to 30 degrees
b. Maximum c.g.-height of airborne vehicle: 1.5 to 2 feet
c. Horizontal travel distance from tripping to rest: 27 feet
d. Horizontal distance on ground after first ground contact: 15 feet
e. Horizontal distance while airborne: 12 feet
f. Airborne time: 0.5 to 0.6 sec
g. First vehicle contact point/area of vehicle with ground: Roof edge driver side
h. Approximate angular velocity while airborne: 180 deg/0.6 sec = 300 deg/sec
i. Speed before tripping: 30 to 35 mph?
j. Total post-tripping time: 2.3 to 2.5 seconds
k. Time to rest after ground contact has been made: 1.7 to 2.0 seconds, average 1.85 sec
l. Linear speed when ground contact was made after finishing airborne: (2)(15) ft/(1.85 sec) = 16.2 ft/sec or 11mph

The MARC1-O3 printout is shown. The distances calculated by MARC1-O3 are the theoretical free-flight distances (Section 20.03) of the center-of-gravity of the vehicle ignoring any height and width dimensions of the Scout. Consider them only as guide lines.

Figure 4. First Clear Indication of Driver Side Roof/Ground Contact

Inspection of the Roller Coaster video does not indicate a constant angular deceleration during the entire 360-degree roll motion as one would expect with a square-box cross-sectional roll area. It appears that the air-borne angular roll velocity decreased after ground contact with the roof had been made after approximately 180 degree of rolling.

Energy balance across the tripping process indicates that energy before tripping minus energies after tripping equals 88,864 lbft. These energies are due to suspension roll stiffness, shock absorbers, viscous tire damping, elastic component deflections, and others.

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                    Tuesday, October 28, 2014

   MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
   ********** PROGRAM 'O-3' RUN FOR PCB 3 -2014 **********
                   VEHICLE MULTIPLE ROLL TRIP

Information For Vehicle                        1974 IH  Scout II
=================================================================
INPUT DATA:

Vehicle Center of Gravity Height, IN:             ===>     28.00
Vehicle Track Width, IN:                          ===>     70.00
Vehicle Weight, LBS:                              ===>   4000.00
Coefficient of Restitution, D'Less:               ===>      0.00
Velocity Before Tripping, MPH:                    ===>     30.00
Mass Moment of Inertia About
     C of G of Vehicle, FT·LBS·SEC²:              ===>    400.90
=================================================================
OUTPUT DATA:

Mass Moment of Inertia
      About Trip Point, FT·LBS·SEC²:              ===>    864.89
Angular Velocity After Tripping, DEG/SEC:         ===>    281.16
Velocity After Tripping in X-direction, MPH:      ===>      7.81
Velocity After Tripping in Y-direction, MPH:      ===>      9.76
Impulse in X-direction, LB*SEC:                   ===>      4041
Impulse in Y-direction, LB*SEC:                   ===>      1778
Take-off Angle at C of G, DEG:                    ===>     51.34
Resultant Velocity After Tripping, MPH:           ===>     12.50
Energy Loss During Tripping, LB*FT:               ===>     88864
Maximum Vertical C of G Height, FT:               ===>      3.19
Maximum Horizontal C of G Distance, FT:           ===>     10.18
=================================================================
```

Parameter	Observed in Video	MARC1-O3	Units
Tripp Velocity	30 to 35?	30 (35)	mph
C.G. Height	1 -1.5	3.19 (4.35)	ft
Air-Borne Distance	12	10.18 (13.85)	ft
Air-Borne Time	1.8		sec
Air-Borne Roll Angle	180		deg
Max. Ang. Velocity	180/0.6 = 300	281.16 (328)	deg/sec
C.G .- Take-Off Angle	35 - 45	51.34 (51.34)	degree
Post-Trip Velocity x-direction	11.4	7.81 (9.11)	mph
Post-Trip Velocity y-direction		9.76 (11.39)	mph
Resultant Velocity after Tripp	15 to 20 mph?	12.5 (14.59)	mph

Table 1. Comparison of Observed with Calculated Data

A trip speed of (35) mph instead of 30 mph yields an angular velocity of (328) deg/sec. Inspection shows the departure angle not be a function of trip velocity. The underlying assumption is that the rigid vehicle body rotates about the trip point A. In Section 27.04[2] it is called the “hooking” assumption given by expression 5. The departure angle α is a function of the of one-half track width divided by center-of-gravity height. For the Scout II $\tan\alpha = (70/2)/28 = 1.25$ and $\alpha = 51.34$ degrees.

3.0. High Angular Velocity Toyota Rollover Accident.

3.1. Observing the Rollover – Being an Eye Witness

The rollover of a real rollover accident is shown in the video attached. Click on the link to view video. Study it carefully as an expert reconstructionist eye witness. The car travels fast in a right-hand curve, rotates counterclockwise off the road, striking a trip point such as a raised berm, etc. If possible, answer the following questions:

a. Number of rolls
b. Maximum height of airborne vehicle
c. Horizontal travel distance
d. Horizontal distance on ground after first ground contact
e. First contact point/area of vehicle with ground
f. Approximate angular velocity while airborne
g. Speed before tripping
h. Linear speed when ground contact was made after being airborne

View rollover video of Toyota

My viewing of the video tape resulted in the following observation estimates:

1. Total number of rolls: 4
2. Total post-trip time (air-borne plus ground contact): 5.25 seconds
3. Number of air-borne rolls: 2-1/2 plus or 900 to 930 degrees
4. Air-borne time: 1.8 seconds
5. Horizontal air-borne distance: 30 to 35 feet (difficult to estimate)
6. Maximum air-borne center-of-gravity height: 11 feet
7. Maximum horizontal ground contact distance: 25 to 30 feet
8. Number of rolls on ground: 1-1/2 = 540 degrees
9. Speed estimate just before tripping: 55 to 60 mph
10. Speed estimate after ground contact: Less than 10 mph

Vehicle information: Toyota weight: 2800 lb; height: 60 in.; width: 68 in.; track width: 60 in.; roll mass-moment of inertia: 300 lbft sec^2; center-of-gravity height: 20 in.; wheel base 102 in.

Figure 5. Toyota at Tripp Moment

Fig. 6. App. Take-Off Angle Along upper Dirt Edge to Car: Greater than 45 Degrees

Figure 7. Toyota at Maximum C.G. Height off Ground

The center-of-gravity height may be estimated from knowing that the c.g location is approximately three to four feet behind the front axle. Knowing the length of the car provides a scale from the front bumper to the ground (white fog line). Eye witness accounts relative to how high in the air the vehicle actually was may be inaccurate.

Figure 8. Toyota First Ground Contact after Being Airborne

3.2. MARC1 – O3 Application

The MARC1-O3 printout for the high angular velocity trip is shown. For a specified trip speed of 60 (50) mph, the calculated and observed data are shown in the comparison table shown.

Parameter	Observed in Video	MARC1-O3	Units
Tripp Velocity	50 to 60?	60 (50)	mph
C.G. Height	11	8.73 (6.06)	ft
Air-Borne Distance	20	23.20 (16.11)	ft
Air-Borne Time	1.8		sec
Air-Borne Roll Angle	930		deg
Max. Ang. Velocity	930/1.8 = 517	542 (452)	deg/sec
Ang. Vel. After Ground Contct	510/[5.25 – 1.8] = 148		deg/sec
Post-Trip Velocity x-direction		10.76 (8.97)	mph
Post-Trip Velocity y-direction		16.15 (13.46)	mph
Resultant Velocity after Tripp	15 to 20 mph?	19.41 (16.17)	mph
Take-Off Angle after Tripp	45 to 55	56.31 (56.31)	degree

Table 2. Comparison of Observed and Calculated Dynamic Data

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                    Friday, October 24, 2014

   MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******* PROGRAM 'O-3' RUN FOR Shortpaper PCB3 - 2014 *******
                  VEHICLE MULTIPLE ROLL TRIP

Information For Vehicle                           0 TOYOTA 1
============================================================
INPUT DATA:

Vehicle Center of Gravity Height, IN:        ===>    20.00
Vehicle Track Width, IN:                     ===>    60.00
Vehicle Weight, LBS:                         ===>  2800.00
Coefficient of Restitution, D'Less:          ===>     0.00
Velocity Before Tripping, MPH:               ===>    60.00
Mass Moment of Inertia About
     C of G of Vehicle, FT·LBS·SEC²:         ===>   300.00
============================================================
OUTPUT DATA:

Mass Moment of Inertia
      About Trip Point, FT·LBS·SEC²:         ===>   561.27
Angular Velocity After Tripping, DEG/SEC:    ===>   542.56
Velocity After Tripping in X-direction, MPH: ===>    10.76
Velocity After Tripping in Y-direction, MPH: ===>    16.15
Impulse in X-direction, LB*SEC:              ===>     6276
Impulse in Y-direction, LB*SEC:              ===>     2058
Take-off Angle at C of G, DEG:               ===>    56.31
Resultant Velocity After Tripping, MPH:      ===>    19.41
Energy Loss During Tripping, LB*FT:          ===>   276036
Maximum Vertical C of G Height, FT:          ===>     8.73
Maximum Horizontal C of G Distance, FT:      ===>    23.20
============================================================
```

For the 50 mph tripping velocity, increasing the center-of-gravity height from 20 in. to 24 in. yields an angular velocity of 497 deg/sec. We can conlude that the travel speed at the moment of tripping was between 50 and 60 mph. The maximum angular velocity was between 450 and 550 deg/second.

4.0 The Effective Vehicle/Ground Friction Coefficietn after Tripping

The vehicle does not decelerate while airborne after triping. After ground contact the linear and angular decelerations are a complicated function of how the vehicle contacts the ground in terms of momentary lever arm and impulse at the specific vehicle area/ground contact. After first ground contact the vehicle may bounce back into the air to repeat a number of additional airborne events.

Regardless of the complicated issues, energy balance applies. *See* Eq.(21-6) for details.

Energy balance: $E_e = E_b + E_{in} - E_{out}$

With the vehicle at rest on level ground relative to the trip point, energy E_e at the end of the process $E_e = 0$. Energy taken out E_{out} is the crush energy E_c associated with the deformation of the vehicle body, and the rolling/sliding energy E_{drag} of the car it makes its way to the rest position. Energy at the beginning E_b are the linear and rotational energies of the vehicle immediately after tripping as the vehicle just has begun becoming airborne.

The energy balance equation is:

$$0 = (m/2)(V_{11})^2 + (I/2)(\omega_{11})^2 – E_c – [(W)(f_{12})(S_{12})];\ lbft$$

Where: W = vehicle weight, lb; S_{12} = distance after impact while in contact with the ground, ft; f_{12}= vehicle/ground friction coefficient

Solving for vehicle/ground friction coefficient f_{12} yields:

$$f_{12} = \{(m/2)(V_{11}{}^2) + (I/2)\ (\omega_{11})^2 – E_c\}/[(W)(S_{12})]$$

Substitution of the data for the 60 mph Toyota tripp speed MARC1-O3 run and the ground distance of 24 feet observed in the video result in the following quation with crush enegy assumed as E_c = 20,000 lbft:

$$f_{12} = \{(86.9/2)(28.45)^2 +(300/2)(9.46)^2 – 20{,}000\ \}/[(2800)(25)] = 0.408$$

The vehicle/ground friction coefficient is 0.408g. Consequently, an average friction coefficient of 0.408 existed throughout the after-tripping ground contact motion between the vehicle and the ground.

If the vehicle had no crush deformation with E_c = 0, then f_{12} = 0.69. When rollover drag factors are published, they usually do not separate out the crush enery of the damaged vehicle.

However, from observing the video, we know that the actual friction coefficient is not constant and varies between a minimum and maximum value. If we conducted a drag test pulling the vehicle across the ground and measuring the drag force with a load cell and computing a friction coefficient, it probabaly will be greater than 0.408. The measured drag force would depend how the body surfaces/shapes interact with the ground and which vehicle surface engages more with the ground. Finally, if we constructed a pulling device allowing the vehicle to rotated freely about its longitudinal axis as it is pulled, the actual rolling resistance would be more closely duplicated.

It appears that the Toyota rollover crash and in particular center-of-gravity height achieved after tripping (Figure 7) are not the rollover crash test typically conducted by researchers.

5.0. Conclusions.

The two rollover crashes discussed are significantly different in several respects. The Scout II appears to roll over as if it were travelling horizontally while airborne. The Total car with a much higher angular velocity after impact rises higher into the air. Consequently, as the Total makes ground contact its impact speed with the ground will be greater. The Toyota seems to sustain very little occupant space intrusion, suggesting excellent roof strength or a roll bar inside the vehicle. The Scout "molded" its roof design and A- and B-pillars to fit the flat ground while the Toyota rolled over the ground in a barrel fashion with some bouncing. The ground contact drag factor of the Scout II is greater than that of the Toyota.

Viewing of the rollover videos only once as an eye witness normally does clearly shows that some rollover parameters are not easily observed and recalled correctly at a later time. The main reasons are that witnesses do not practice watching dynamic events, and the accident may be very dramatic causing the witness to focus only on one particular element. Later he "concludes" what must have happened than rather what he actually observed.

"Static" rollover when a vehicle turns a given curve at increasing speeds can easily be analyzed when basic vehicle dimensions and weight distributions are available. However, when the sideways motion of a vehicle is suddenly stopped, either by a curb or ditch, by furrowing dirt or increased tire-road friction (locked tire to rolling tire), "tripped" rollover may result.

The purpose of using MARC1 software in the reconstruction of tripped rollovers is to help the reconstructionist analyze specific elements of the crash such as initial angular velocity, speed after tripping, center-of-gravity height or flight distance to evaluate physical evidence and witness statements. Effects of suspension compliance and initial roll angle prior to tripping can be evaluated. Crush damage and intrusions must be carefully analyzed to accurately account for high vaulting ground crashes versus high tripping speeds. The angular velocity immediately after tripping appears to be an important indicator of pre-trip velocity. The theoretical departure angle is only a function of center-of-gravity height and track width (T/2h), while the actual angle is a function of suspension tug-under, sideways tire deflection, and rise of c.g.-height.

When reconstructing a rollover crash we usually have distance measurements, however are lacking flight height and initial angular velocity. Combining MARC1-O3 with the scene data available provides a good basis for an accurate rollover crash reconstruction. Simply picking a questionable after-tripping drag factor out of a book and calculating the speed before tripping impact while ignoring the tripping-delta-V is not enough.

Note: Sections referenced throughout this paper are from: *Motor Vehicle Accident Reconstruction and Cause Analysis* by Rudolf Limpert, 7th edition 2012, published by LexisNexis, www.bookstore.lexis.com