Crash Test Overview – Rollover Crashes

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Introduction

- Why Testing?
  - As crash investigators and reconstructionists, we seldom see a crash happen.

- Seeing the Crash Test:
  - What do the vehicle(s) do during the crash sequence
    - High Speed video
    - Evidence on the road or ground
    - Evidence from the vehicle(s)

- Interpret the Evidence
  - How did the vehicle(s) interact with each other or the ground?
  - Evidence analysis for speed
Many crashes involve situations where the vehicle overturns, or rolls over. When this happens, the analysis may become more complex. There are many factors an investigator must consider in a rollover analysis. Often, there is more than one occupant in the rolled vehicle, and one or both may be ejected. The analysis of the crash depends on the evidence you can gather.
Introduction (cont.)

- In potential criminal cases, the identity of the driver becomes important if some occupants are killed and others survive.
- In civil cases, the identity of the driver may be important for determining responsibility, regardless of the occupants’ survival.
- It is up to the reconstructionist to determine who was driving when the rollover event occurred.
- However, identifying the driver or determining occupant seating becomes difficult in cases where one or more people are ejected in the rollover.
- In these situations, close attention must be given to both occupant kinematics and vehicle dynamics.
In addition to driver identity, the reconstructionist often needs to calculate the speed of the vehicle.

Also, it is important to know what kind of rollover event this actually was, so the proper analysis may be performed.

We will break our presentation into four sections:
- Taxonomy of Rollover Events
- The Crash Tests
- Evidence Gathering
- Instrumental Results / Speed
Section 1

Taxonomy of Roll Events
Types of Rollover Events

- Rollover Crashes may be broken into three broad categories:
  - Side to Side Roll
  - Barrel Roll
  - Flip-Over ("Endo")

- In addition, each may be sub-categorized by the relative violence of the event:
  - Tip-Over – Less than one full revolution
  - Rollover – One or more revolutions
Side to Side Roll

- This overturn is what many investigators think of when the word “rollover” is spoken.
- In essence, the velocity vector of the vehicle is nearly at right angles to its heading. It is sliding sideways.
- It may have obtained this orientation as a result of an impact or inappropriate steering, which causes the vehicle to spin.
- The roll event may be precipitated by a curb strike, furrowing in soft material, or by dynamic instability.
Side to Side Roll

- This SUV is in an orientation to roll over.
- Note the pavement being dug up by the leading wheel rims.
- Both leading tires are unbeaded from the wheels and are flat.
- Surprisingly, this vehicle did not overturn. (IATAI Conference 2004)
Barrel Roll

- A barrel roll overturn may be defined when the velocity vector of the vehicle is more in line with its heading.
- A force acts to rotate the vehicle about its longitudinal axis, which precipitates the overturn.
- A vehicle running off the road onto a steep shoulder may roll onto its side or top, whereupon it will skid to a stop or to an impact.
- An example of the barrel roll is the “movie” collision where a vehicle vaults over another upon collision. It’s not real life, but is entertaining…
Barrel Roll

- Often the overturn of a tractor-trailer is a barrel roll.
- The TT is traveling down the road at highway speed and drops into the ditch.
- The trailer tips onto its side, often taking the tractor with it.
- The unit then slides to a stop or to impact.
Flip-Over (“Endo”)

- A flip-over is an overturning event characterized by rotation about an axis lateral to the vehicle.
- A vehicle with a high center of mass in a frontal collision with a frame-high barrier may undergo a flip-over. This would of necessity be a violent collision.
- Vehicles going airborne off of mountainous roads or bridges may also undergo a flip-over upon landing.
Flip-Over ("Endo")

- This pickup went off a steep mountain pass after a CSY.
- Its overturning was a combination of all three basic rollover types.
- Note how the frame is bent.
Rollover or Tip-over?

- By our definitions, a tip-over is not as energetic event as a rollover.
- A tip-over may be characterized by less than one revolution.
- A rollover consists of one or more revolutions.
- The dynamic loads on the occupants *from the tip-over itself* are usually less than the dynamic loads experienced during a rollover.
- However, a tip-over may be fatal to occupants even though the dynamic forces are not as high.
Rollover or Tip-over?

- Both vehicles were involved in fatal crashes.
- The pickup in the upper photo tipped over onto its top in a side to side roll, overturning ½ revolution.
- The car in the bottom photo overturned as the result of a high speed rollover.
- In both cases, the passengers were killed.
- Note the relative damage.
Section 2

The Crash Tests
Vehicles: Pre-Crash

Honda

Explorer

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The VC4000 is used for data acquisition

Tri-Axial Accelerometer
Roll Rate Sensor

Air operated, R/C brake system. There is also a GPS receiver on the dash
Delivery System and Ramp

Yoke & Breakaway

Tow Cable, Ramp & Sheave
Delivery System and Ramp

Building the Ramp

The final ramp design approximates a parabola

Sheave & Mounting
Crash Test 1 - Honda
Crash Test 2 - Explorer
Section 3

The Aftermath – Gathering the Evidence
Scene Evidence

- Scene evidence may include tire marks leading up to the point of overturn.
- Once the overturn has happened, there may be gouges in the pavement or soil indicating where the vehicle may have come into contact with the ground.
- Debris of many kinds, including occupants, may be left in the path of the overturning vehicle.
- All of this evidence should be measured and mapped.
Scene Evidence

Path from Launch

Path to Final Rest
Scene Evidence

Debris Field

Tempered glass debris from side window
Scene Evidence

Gouges

Mapping the Scene
Scene Evidence
Scene Evidence

Prepared by:
Sgt. Andrew Mallory
Missouri State Highway Patrol

September 17, 2010
Scene Evidence

TEST 2

tire mark on ramp
bolt start of fiberglass tape
gouges
hole from stabilizer
DV3 camera
tire marks leading to ramp
cement edge
DVIII camera
tire mark on ramp
spare tire
tail light glass
total station
reference prism

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Scene Evidence

- Examine the scene carefully, and look for disturbances in the pavement or soil.
- When debris is noted, ask yourself how it got there.
  - Was it jammed into the soil or pavement by impact?
  - Was it thrown off or out of the vehicle?
  - Where did it come from? Glass, plastic, occupant, etc.?
- Ask “What can this evidence tell me about the orientation and path of the vehicle at this point”.

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Evidence from the outside of the overturned vehicle can tell us much about how the crash happened.

All of the scratches, dings, dents and missing parts will help us to determine the vehicle motion in the rollover event. Some questions:

- What was the leading side?
- Where was the first ground contact on the vehicle?
- Subsequent ground contacts?
- How many times did it roll?
- Did it hit anything along the way?
Driver’s side has damage showing ground contact. The broken out driver’s door window is a potential ejection portal
Note the broken front passenger door window. The right front tire has been unseated from the bead. The damage on the front fender was from the first ground contact. The passenger side rear view mirror has been torn off.
Exterior Vehicle Evidence

• Number of Rolls
  ○ It is convenient to determine the number of quarter-rolls the vehicle undergoes.
  ○ Evidence of ground contact will show as scratching on the contacting surface, as it is sliding with respect to the ground.
  ○ We may examine the scratching to see if multiple patterns exist.
  ○ Scratches on top of scratches indicate multiple ground contacts for that surface.
Exterior Vehicle Evidence

- Document the scratching on the vehicle, both photographically and with a sketch.
- The number of scratches overlapping on a given side may tell us the number of times that side came into contact with the ground.
- We may then figure the number of rolls based upon ground contacts (4 sides per roll) and final position.
- If the vehicle is on its wheels, then there was at least one full roll.
  - A vehicle on its top would have rolled “x” & ½ times.
Number of Rolls v Distance or Speed

From *Fundamentals of Traffic Crash Reconstruction*, IPTM, Pg 712
Both photos show multiple direction scratching
As the vehicle tips in a side to side roll, the following may happen:

- The center of mass lifts off the ground, and the vehicle may have enough roll velocity to allow the leading side roof edge to clear the ground.
- Higher vehicles, such as pickups and vans, may contact the ground with the leading roof edge.
- The first ground contact for passenger cars is then with the trailing roof edge at some angle with respect to the ground.
- Often times, this first ground impact is the most severe impact in the roll sequence.
Exterior Vehicle Evidence

This hard side impact caused a collapse of the structure
Interior Vehicle Evidence

- Evidence from inside the vehicle may assist us to determine occupant position in the vehicle at the moment of trip.
- People inside the vehicle tend to move toward the periphery of the vehicle when the vehicle is in the air. (SAE 851757, Orlowski, et al)
- When a hard ground contact is made, then the occupants may tend to move toward that impact force.
Interior Vehicle Evidence

- Note the bulge in this passenger door.
- The vehicle rolled with the driver’s side leading.
- The first hard impact was on the passenger side roof edge.
- The impact direction was probably about 10:30 (clock).
- The passenger’s body pushed out the door.
Interior Vehicle Evidence

- Blood, hair, and fiber evidence from the interior of the vehicle.
- Document the position inside the passenger compartment and recover the evidence for forensic examination.
A shoe print on the brake pedal may be important.
If the driver and passengers are of different stature and size, the position of the seat may be important in determining who was driving.

Seat positions do not usually change in a rollover event.

The seat adjustments may be measured with a tape measure, either to the seat back or to the front of the seat cushion.

The seat position may be determined by exemplar people, IF all other forensic work has been accomplished.
Interior Vehicle Evidence
Interior Vehicle Evidence

- Note structures or controls inside the passenger compartment that may leave distinctive marks on the occupants.
- Ask yourself when and where in the roll sequence the occupant could have come into contact with the structure or control.
- *Pattern Injuries* are often the result, and marks on the occupant may be matched.
Ejection Portals are those openings in the passenger compartment that will allow occupants to move out of the passenger compartment and outside the vehicle.

- A partial list includes door windows, doors opened during the roll, broken out windshields & back glass, and sunroofs.

It takes *time* for a person to traverse the ejection portal.

- Because of the combination of rotation and translation of both the passenger and the vehicle, it is likely the occupant will leave forensic evidence behind around the portal.
- The edges of the ejection portals should be examined forensically for trace evidence.
- Clothing, hair, and blood samples should be taken from occupants to match up to the evidence gathered from both inside the passenger compartment and the ejection portals.
Ejection Portal Examples

Several!

Sunroof and Driver’s Door

Popped out Windshield
Section 4

Speed Calculations
Instrumental Results
Overturning Vehicle Speed

- We will examine two kinds of analysis in this section
  - The first analysis will examine the lateral acceleration required to cause the vehicle to overturn.
    - Within this analysis, we will consider this lateral force acts for enough time to precipitate the overturn.
  - Secondly, we will see how to determine vehicle speed at the moment of the overturn.
    - This speed may then be used in a combined speed equation to determine speeds at other points in the trajectory.
Consider the Diagram on the right.

This vehicle has a lateral force being applied at ground level.

Because the center of mass is higher than the force application plane, there will be a moment (torque) placed on this vehicle. This moment is about point “O”.

If the torque produced by this side force is greater than the resisting torque caused by the vehicle weight, then the vehicle will overturn.
For a level surface, the equation on the right defines the lateral acceleration required to *trip*, or overturn.

This is sometimes called the “*tip-over stability ratio*”, or the “*propensity to roll*”.

In this equation:
- $f =$ lateral acceleration
- $T_w =$ Track Width
- $h =$ CM height

\[ f = \frac{T_w}{2h} \]
In the equation just presented, the vehicle is considered to be a **rigid body**.

- This means we do not consider any suspension deformations in the propensity to roll for the vehicle.
- Dealing with suspension deflections is beyond the scope of this presentation.
- A straightforward inclusion of suspension deflections may be found in SAE 2002-01-0965, “Rollover Stability Index Including Effects of Suspension Design” Aleksander Hac, Delphi Automotive Systems.
Lateral Acceleration to Overturn

- Consider a vehicle going around a turn...
  - A lateral force (acceleration) is required to change the direction of the vehicle.
  - Assume the vehicle is in a maximum performance turn:
    - If the lateral acceleration factor, $f$, required to cause the vehicle to overturn is *less than* the friction available on the road surface, then the vehicle will tip over rather than begin to slide.
    - On the other hand, if the propensity to roll is higher than the available friction, the vehicle will enter a CSY or slide out rather than overturn.
Examples: Car Left, Truck Right

\[ f = \frac{T_w}{2h} \]

\[ T_w = 5.5 \]

\[ h = 1.7 \]

\[ f = \frac{5.5}{3.4} \]

\[ f = 1.61 \]

\[ f = \frac{T_w}{2h} \]

\[ T_w = 7.5 \]

\[ h = 7.0 \]

\[ f = \frac{7.5}{14} \]

\[ f = 0.53 \]
Lateral Acceleration to Overturn

- In the example just presented, let $\mu = 0.80$.
- The car would either slide out or enter a CSY before it was able to overturn as it would require $1.61g$ from the road to overturn.
- The truck would tip over before it was able to slide because it needed only $0.53g$ to overturn and the road was able to give $0.80g$. 
Truck Tip-Over Speed

- Consider this tractor-trailer rounding a level curve with a 250 foot radius.
- At what speed will it overturn?
- The result is the tip-over speed for this tractor-trailer.

\[ S = 3.86 \sqrt{rf} \]
\[ r = 250 \]
\[ f = 0.53 \]

\[ S = 3.86 \sqrt{250(0.53)} \]
\[ S = 3.86 \sqrt{132.5} \]
\[ S = 44.43 \text{ mph} \]
Lateral Acceleration to Overturn

- As we have seen, it usually takes more lateral acceleration to overturn a passenger car than is provided by tire – surface friction.
- This is because cars generally have lower centers of mass in relation to track width than do pickups, SUVs and commercial vehicles.
  - The average lateral f for soil furrowing was 1.62g.
  - The average lateral f for a curb strike was 12.4g.
  - In this testing, investigators reported it was not uncommon for the suspension to be knocked out from under the vehicle in a curb strike.
  - In these test cases, the vehicle did not overturn, but slid to a stop upright. Crash vehicles may still overturn.
Speed at Overturn

Once a passenger car, light truck, van, or SUV begins to roll, it will start decelerating.

If it hits nothing except unencumbered ground (or pavement) until it stops, we may apply a drag factor to this motion and treat it as a skid.

- If the vehicle does undergo an impact, we may deal with the impact in the same way as if the vehicle skidded to the impact.
- The impact speed becomes part of the combined speed equation.
Drag Factors of Vehicles During the Rollover:

- SAE 720966, Hight: \( f = 0.4 \text{ – } 0.65 \)
- SAE 890857, Orlowski: \( f = 0.36 \text{ – } 0.61 \)
- SAE 2002-01-0942, Altman: \( f = 0.48 \) (average)
- SAE 890859, Bratten: \( f = 0.5 \) (average)

These references are for differing surfaces that are level and not covered with brush or other impeding objects.

For soft soil or sand situations, then the drag factor will tend to increase.

Any brush, large rocks, or other things the vehicle may interact with will clearly increase these values!
Drag Factors of Vehicles Sliding on the Top or Sides (SAE 830612, Warner):

- Sliding on Concrete: $f = 0.3 - 0.4$
- Rough Asphalt: $f = 0.4$
- Gravel: $f = 0.5 - 0.7$
- Dry Grass: $f = 0.5$

These values are for level surfaces…

- In general, the softer the surface, the higher the drag factor.
In the first crash test, the center of mass of the Honda traveled approximately 87.13 feet from the edge of the ramp to final position.

The speed of the Honda at take off was measured at 38.2 mph.

From this information the average deceleration factor for the Honda during the rollover event was calculated.
Thus, the average deceleration factor for the Honda was 0.55 as it traveled through the rollover event.

\[ f = \frac{S^2}{30d} \]

\[ = \frac{38.2^2}{30(87.13)} \]

\[ = \frac{1459.24}{2613.90} \]

\[ = 0.55 \]
In the second crash test, the center of mass of the Explorer traveled approximately 99.39 feet from the edge of the ramp to final position.

The speed of the Explorer at take off was measured at 37.1 mph.

From this information the average deceleration factor for the Explorer during the rollover event was calculated.
Thus, the average deceleration factor for the Explorer was 0.46 as it traveled through the rollover event.

\[ f = \frac{S^2}{30d} \]

\[ = \frac{37.1^2}{30(99.39)} \]

\[ = \frac{1376.41}{2981.70} \]

\[ = 0.46 \]
In looking at both deceleration factors from both tests, 0.55 for the Honda and 0.46 for the Explorer, it can be seen that they both correlate nicely with the published values previously discussed.
VC4000 Results
VC4000 Results
Although, as we have seen, rollover events are violent and complex. However this doesn’t mean they can’t be analyzed. As with any event, analyzing in segments simplifies the problem and allows overall conclusions to be reached. In rollover events where occupant positioning is one of the issues to be determined, accurate and detailed evidence gathering is imperative. It’s not sufficient to merely say the vehicle rolled x feet to a stop. It must be determined how the vehicle rolled and the orientation of the vehicle as it struck the ground or other major objects. Without this information a proper dynamics analysis cannot be performed and in turn a proper kinematics analysis cannot be completed. Thus, no seating determination can be obtained. Thus, careful attention to detail will allow us to properly analyze the rollover event.
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