Investigating and Reconstructing 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 are 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.
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.
- What drag factors are appropriate?

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 five sections:
- Taxonomy of Rollover Events
- The Crash Tests
- Evidence Gathering / Interpretation
- Instrumental Results / Speed / Drag Factors
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
Types of Rollover Events
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.
This Honda is in a side to side roll over.
The travel (bearing) is from left to right with the long axis of the vehicle (heading) almost perpendicular to the travel (bearing).
Barrel Roll

- A barrel roll overturn may be defined when the velocity vector (bearing) 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.
- It may also quickly transition into a side to side roll.
- An example of the barrel roll is the “movie” collision where a vehicle vaults over another upon collision. It’s unusual but can happen in sideswipe collisions…
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.
Barrel Roll

- The Honda begins its rollover trajectory off of a ramp...a barrel roll.
- It transitions quickly to a side to side roll.
- This is common with many vehicles.
Barrel Roll – Case Example

- The vehicle VW/Gol begins its rollover trajectory after a collision with an official vehicle...a barrel roll.
Barrel Roll – Case Example

- The vehicle displacement after the collision was around 14 m.

- Vehicle speed: 40-50 km/h
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.
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 $\frac{1}{2}$ 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
Crash Test 3 - Venture
Crash Test 4 - Caprice
Section 3

The Aftermath – Gathering the Evidence - Discussion
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

Chops in the pavement can show where hard or sharp parts of the vehicle were forced into the surface.

Scrapes and gouges show surface contact and path.
Scene Evidence - Honda

TEST 1

tire marks leading to ramp
ramp
bolt start of fiberglass tape
tire mark
glass
Debris
gouges
cement edge
DVIII camera
cell phone antenna

Prepared by:
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Missouri State Highway Patrol

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Chevrolet Ventura van rollover test

- Chev van final position
- Gouges
- Window glass
- Tire marks
- Landing area
- Airborne distance
- Scrape
- Ramp

Chev van approaching ramp

Scale: 0 10 20 30 40 50 ft

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Scene Evidence - Caprice

| Rollover Crash #2 | IPTM Special Problems 2011 | Chevrolet Caprice | DATE: 5/3/11 |

- Ramp
- Scratches
- Final Rest
- Airborne
- Gouges

Map showing the direction and location of the crash with relevant evidence markers.
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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Exterior Vehicle Evidence

- 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?
Note the soil and grass impacted into the leading edge of the passenger door and A-Pillar.
Exterior Vehicle Evidence - Honda

Hard impact on the back passenger side, with significant inward intrusion into the passenger space
The Honda passenger side shows a more significant impact toward the rear of the passenger compartment than is shown on the front fender and door area.
The Honda Driver’s side shows ground contact only on the front fender.
Exterior Vehicle Evidence - Honda

Overlapping scratching on the Honda passenger door near the top by the B-pillar. Scratching shows two ground contacts.

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Driver’s side has damage showing ground contact. The broken out driver’s door window is a potential ejection portal.
Exterior Vehicle Evidence: Explorer

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: Venture

Note the broken windows on the passenger side. The damage on the front fender was from the first ground contact. The passenger side rear view mirror has been torn off. The windshield is broken but in place.
Exterior Vehicle Evidence: Venture

More of the multiple direction scratching around the window frame.
Exterior Vehicle Evidence: Venture

Hood scratches on the Venture are in a single direction.
Exterior Vehicle Evidence: Caprice

Skippy should have been wearing his seatbelt! Note the final position is still on the driver’s side.
Exterior Vehicle Evidence: Caprice

Heavy grinding on passenger side and A-pillar indicates sustained slide. Look for such evidence on the pavement.
Heavy grinding on hood and top indicates sustained slide. The driver’s side roof has crushed in.
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.
Figure 20.16: These graphs were created using data from Ref. [40]. These data confirm our intuition that more rolls result from higher amounts of mechanical energy at the beginning of the rollover event.

From Fundamentals of Traffic Crash Reconstruction, IPTM, Pg 712
Ref. 40 is by Altman and others, SAE 2002-01-0942.
Exterior Vehicle Evidence

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
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.
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.
Interior Vehicle Evidence

- 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.
Some Pattern Injuries are Definitive

Seat belt abrasions are very strong evidence. This abrasion was on a subject who denied being the driver in a fatal DUI crash. Once confronted with this evidence, he pled guilty and was sentenced to prison.
Interior Vehicle Evidence

- 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

- Popped out Windshield
- Sunroof and Driver’s Door
- Several!

Popped out Windshield
Rollover Kinematics: Case Study

• Scenario:
  – Broad side slide down a slope
  – A tip-over event with ¼ roll
  – Two unbuckled occupants
  – Fatal injuries sustained when the passenger door frame crushed the victim

• Claim: The dead guy was driving.

• Approach:
  – Model the positions, velocities and accelerations of the occupants.
  – Accelerations indicate direction of applied force.

• Assumptions:
  – Rigid body motion
  – Occupants remain fixed to vehicle for kinematic analysis.
Draw a Picture

- Initial velocity is heading down the slope
- Define the origin at the center of gravity. Follow SAE conventions.
Simulation Output

t = 0.000 sec, \( Y = 0.000 \text{ ft} \), \( v_Y = 14.855 \text{ ft/sec} \), \( Z = 0.000 \text{ ft} \), \( v_Z = 2.080 \text{ ft/sec} \), \( \phi = 0.573^\circ \), \( \omega = 0.000^\circ/\text{sec} \), slope = 14 percent,
\[ a_{\text{driver}} = 1.552g, \ a_{\text{passenger}} = 1.441g, \]
Simulation Output

$t = 0.050 \text{ sec}, Y = 0.706 \text{ ft}, v_Y = 13.377 \text{ ft/sec}, Z = 0.080 \text{ ft}, v_Z = 1.090 \text{ ft/sec}, \phi = 0.978^\circ, \omega = 16.386^\circ/\text{sec}, \text{slope} = 14 \text{ percent},$

$a_{\text{driver}} = 1.592g, a_{\text{passenger}} = 1.481g,$
Simulation Output

$t = 0.100 \text{ sec}, Y = 1.340 \text{ ft}, v_Y = 12.017 \text{ ft/sec}, Z = 0.109 \text{ ft}, v_Z = 0.079 \text{ ft/sec}, \phi = 2.233^\circ, \omega = 34.116^\circ/\text{sec}, \text{slope} = 14 \text{ percent},$

$a_{\text{driver}} = 1.633g, a_{\text{passenger}} = 1.529g,$
Simulation Output

\[
t = 0.150 \text{ sec}, \ Y = 1.912 \text{ ft}, \ v_Y = 10.921 \text{ ft/sec}, \ Z = 0.088 \text{ ft}, \ v_Z = -0.904 \text{ ft/sec}, \ \phi = 4.421^\circ, \ \omega = 53.859^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent}, \\
\quad a_{\text{driver}} = 1.775g, \ a_{\text{passenger}} = 1.672g, 
\]
Simulation Output

\[ t = 0.200 \text{ sec}, \ Y = 2.438 \text{ ft}, \ v_Y = 10.211 \text{ ft/sec}, \ Z = 0.020 \text{ ft}, \ v_Z = -1.778 \text{ ft/sec}, \ \phi = 7.648^\circ, \ \omega = 75.423^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent}, \ a_{\text{driver}} = 0.845g, \ a_{\text{passenger}} = 0.761g, \]
Simulation Output

t = 0.250 sec, Y = 2.941 ft, \( v_Y = 9.985 \) ft/sec, \( Z = -0.084 \) ft, \( v_Z = -2.324 \) ft/sec, \( \phi = 11.950^\circ \), \( \omega = 96.002^\circ/\)sec, slope = 14 percent,
\( a_{driver} = 0.812g \), \( a_{passenger} = 0.608g \).
Simulation Output

$t = 0.300$ sec, $Y = 3.445$ ft, $v_Y = 10.223$ ft/sec, $Z = -0.204$ ft, $v_Z = -2.367$ ft/sec, $\phi = 17.176^\circ$, $\omega = 111.520^\circ$/sec, slope = 14 percent

$a_{\text{driver}} = 0.844g$, $a_{\text{passenger}} = 0.488g$
Simulation Output

- t = 0.350 sec, Y = 3.969 ft, v_Y = 10.795 ft/sec, Z = -0.312 ft, v_Z = -1.886 ft/sec, \( \phi = 22.969^\circ \), \( \omega = 119.110^\circ/\text{sec} \), slope = 14 percent
- \( a_{\text{driver}} = 0.897g \), \( a_{\text{passenger}} = 0.457g \)
Simulation Output

\[t = 0.400 \text{ sec}, Y = 4.527 \text{ ft}, v_Y = 11.542 \text{ ft/sec}, Z = -0.387 \text{ ft}, v_Z = -1.078 \text{ ft/sec}, \phi = 28.954^\circ, \omega = 119.985^\circ/\text{sec}, \text{slope} = 14 \text{ percent}, a_{\text{driver}} = 0.922 g, a_{\text{passenger}} = 0.473 g,\]
Simulation Output

\[ t = 0.450 \text{ sec}, \ Y = 5.124 \text{ ft}, \ v_Y = 12.324 \text{ ft/sec}, \ Z = -0.420 \text{ ft}, \ v_Z = -0.250 \text{ ft/sec}, \ \phi = 34.953^\circ, \ \omega = 119.985^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent}, \]
\[ a_{\text{driver}} = 0.938g, \ a_{\text{passenger}} = 0.495g, \]
Simulation Output

\[ t = 0.500 \text{ sec}, \ Y = 5.760 \text{ ft}, \ v_Y = 13.115 \text{ ft/sec}, \ Z = -0.412 \text{ ft}, \ v_Z = 0.569 \text{ ft/sec}, \ \phi = 40.953^\circ, \ \omega = 119.985^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent} \]

\[ a_{\text{driver}} = 0.951g, \ a_{\text{passenger}} = 0.519g, \]
Simulation Output

\[ t = 0.550 \text{ sec}, Y = 6.435 \text{ ft}, v_Y = 13.907 \text{ ft/sec}, Z = -0.363 \text{ ft}, v_Z = 1.387 \text{ ft/sec}, \phi = 46.952^\circ, \omega = 119.985^\circ/\text{sec}, \text{slope} = 14 \text{ percent} \]

\[ a_{\text{driver}} = 0.961g, a_{\text{passenger}} = 0.543g, \]
Simulation Output

\[ t = 0.600 \text{ sec}, \ Y = 7.150 \text{ ft}, \ v_Y = 14.691 \text{ ft/sec}, \ Z = -0.273 \text{ ft}, \ v_Z = 2.213 \text{ ft/sec}, \ \phi = 52.951^\circ, \ \omega = 119.985^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent} \]

\[ a_{\text{driver}} = 0.968g, \ a_{\text{passenger}} = 0.566g, \]
Simulation Output

$t = 0.650 \text{ sec}, Y = 7.904 \text{ ft}, v_Y = 15.459 \text{ ft/sec}, \ Z = -0.141 \text{ ft}, v_Z = -3.055 \text{ ft/sec}, \ \phi = 58.950^\circ, \ \omega = 119.985^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent}$

$a_{\text{driver}} = 0.974g, \ a_{\text{passenger}} = 0.588g$
Simulation Output

\[ t = 0.700 \text{ sec}, \ Y = 8.696 \text{ ft}, \ v_Y = 16.202 \text{ ft/sec}, \ Z = 0.033 \text{ ft}, \ v_Z = 3.922 \text{ ft/sec}, \ \phi = 64.950^\circ, \ \omega = 119.985^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent}, \]
\[ a_{\text{driver}} = 0.980g, \ a_{\text{passenger}} = 0.608g, \]
Simulation Output

$t = 0.750$ sec, $Y = 9.524$ ft, $v_Y = 16.912$ ft/sec, $Z = 0.251$ ft, $v_Z = 4.822$ ft/sec, $\phi = 70.949^\circ$, $\omega = 119.985^\circ$/sec, slope = 14 percent, $a_{\text{driver}} = 0.986g$, $a_{\text{passenger}} = 0.627g$. 
Simulation Output

\[ t = 0.800 \text{ sec}, \ Y = 10.386 \text{ ft}, \ v_Y = 17.581 \text{ ft/sec}, \ Z = 0.516 \text{ ft}, \ v_Z = 5.763 \text{ ft/sec}, \ \phi = 76.948^\circ, \ \omega = 119.985^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent} \]

\[ a_{\text{driver}} = 0.994g, \ a_{\text{passenger}} = 0.647g, \]
Simulation Output

$t = 0.850 \text{ sec}, Y = 11.281 \text{ ft}, v_Y = 18.202 \text{ ft/sec}, Z = 0.829 \text{ ft}, v_Z = 6.752 \text{ ft/sec}, \phi = 82.948^\circ, \omega = 119.985^\circ/\text{sec}, \text{slope = 14 percent}$

$a_{\text{driver}} = 1.004g, a_{\text{passenger}} = 0.669g$
Simulation Output

\[ t = 0.900 \text{ sec}, \ Y = 12.206 \text{ ft}, \ v_Y = 18.768 \text{ ft/sec}, \ Z = 1.192 \text{ ft}, \ v_Z = 7.796 \text{ ft/sec}, \ \phi = 88.947^\circ, \ \omega = 119.985^\circ/\text{sec}, \ \text{slope} = 14 \text{ percent} \]

\[ a_{\text{driver}} = 1.019g, \ a_{\text{passenger}} = 0.693g, \]
Simulation Output

\[ t = 0.909 \text{ sec}, Y = 12.375 \text{ ft}, v_Y = 18.864 \text{ ft/sec}, Z = 1.263 \text{ ft}, v_Z = 7.990 \text{ ft/sec}, \phi = 90.027^\circ, \omega = 119.985^\circ/\text{sec}, \text{slope} = 14 \text{ percent} \]

\[ a_{\text{driver}} = 1.022g, \quad a_{\text{passenger}} = 0.698g, \]
Kinematics of Skippy in the Caprice – 30 frames per second
Kinematics of Skippy in the Caprice – 240 frames per second
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.
Lateral Acceleration to Overturn

- 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.

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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:
- $f = \text{lateral acceleration factor}$
- $T_w = \text{Track Width}$
- $h = \text{CM height}$

$$f = \frac{T_w}{2h}$$
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.
- 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 is required to change the direction of the vehicle, which results in an acceleration.
  - Assume the vehicle is in a maximum performance turn:
    - If the lateral acceleration factor, f, required to cause the vehicle to overturn is \textit{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 \textit{higher} than the available friction, the vehicle will enter a CSY or slide out rather than overturn.
Example

### Passenger Car

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

\[T_w = 5.5 \text{ ft}\]

\[h = 1.7 \text{ ft}\]

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

\[f = 1.61\]

### Commercial Vehicle

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

\[T_w = 7.5 \text{ ft}\]

\[h = 7.0 \text{ ft}\]

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

\[f = 0.53\]
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 $0.80g$. 
Consider this tractor-trailer rounding a level curve with a 250 foot radius.

At what speed will it overturn?

The result is the \textit{tip-over speed} for this tractor-trailer.

\begin{align*}
S &= 3.86 \sqrt{rf} \\
rf &= 250 \text{ ft} \\
f &= 0.53 \\
S &= 3.86 \sqrt{250(0.53)} \\
S &= 3.86 \sqrt{132.5} \\
S &= 44.43 \text{ mph}
\end{align*}
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.
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.
Measuring Protocol:
- Measure the distance moved by the vehicle CM from the point of trip until final rest…or an impact.
  - Follow the path of the CM
- Measure the slope(s) along the rollover trajectory

Calculate effective drag factor(s):
\[ f = \mu \pm m \]

Remember \( \mu \) is the level road/surface drag factor. The percentage of braking associated with a rollover is 100%.
Drag Factors of Overturns

Drag Factors of Vehicles During the Rollover:

- SAE 720966, Hight: \( f = 0.4 \) – \( 0.65 \)
- SAE 890857, Orlowski: \( f = 0.36 \) – \( 0.61 \)
- 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 Overturns

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 if the vehicle can dig in.
Drag Factor Testing: 03/17/11

Van on Rough Asphalt. Smooth asphalt to right in photo.

Load cell between pickup and tow strap. The pull is slow (quasistatic) so inertial loads do not affect the results. Rough asphalt.
Drag Factor Testing: 03/17/11

Top drag on sandy loam soil next to the test track.
Drag Factor Testing: 03/17/11

- We hooked the Chrysler van (4019 lb) to the pickup with a load cell.
  - The van was dragged multiple times over the smooth asphalt, the rougher asphalt, and the grassy soft soil next to the test track.
  - The van was dragged both on the side and top.
  - There was no significant difference between the two.

<table>
<thead>
<tr>
<th></th>
<th>Smooth</th>
<th>Rough</th>
<th>Grass/Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.521</td>
<td>0.494</td>
<td>0.707</td>
</tr>
</tbody>
</table>

95% Confidence Interval on Means

<table>
<thead>
<tr>
<th></th>
<th>Smooth</th>
<th>Rough</th>
<th>Grass/Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>0.436</td>
<td>To</td>
<td>0.605</td>
</tr>
<tr>
<td>Rough</td>
<td>0.397</td>
<td>To</td>
<td>0.533</td>
</tr>
<tr>
<td>Grass/Soil</td>
<td>0.674</td>
<td>To</td>
<td>0.741</td>
</tr>
</tbody>
</table>
Drag Factor Testing: 05/03/11

We hooked the Caprice sedan (4050 lb) to the pickup with a load cell.

- The Caprice was dragged on its top once over the smooth asphalt and once over the rougher asphalt,

<table>
<thead>
<tr>
<th></th>
<th>Smooth</th>
<th>Rough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.62</td>
<td>0.54</td>
</tr>
<tr>
<td>Peak</td>
<td>0.75</td>
<td>0.61</td>
</tr>
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</table>
Drag Factor of Overturn: Honda

- 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.
Drag Factor of Overturn: Honda

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

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

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

\[ = 0.55 \]

Thus, the average deceleration factor for the Honda was 0.55 as it traveled through the rollover event.
Drag Factor of Overturn: Explorer

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.
Drag Factor of Overturn: Explorer

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

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

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

\[ = 0.46 \]

Thus, the average deceleration factor for the Explorer was 0.46 as it traveled through the rollover event.
Drag Factor of Overturn: Venture

- In the third crash test, the center of mass of the Venture traveled approximately 166.25 feet from the edge of the ramp to final position.
- The speed of the Venture at take off was measured at 47 mph.
- From this information the average deceleration factor for the Venture during the rollover event was calculated.
Drag Factor of Overturn: Venture

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

\[ f = \frac{47^2}{30(166.25)} \]

\[ = \frac{2209}{4987.5} \]

\[ = 0.44 \]

Thus, the average deceleration factor for the Venture was 0.44 as it traveled through the rollover event from the edge of the ramp to final rest.
Drag Factor of Overturn: Caprice

- In the fourth crash test, the center of mass of the Venture traveled approximately 198 feet from the edge of the ramp to final position.
- The speed of the Venture at take off was measured at 50 mph.
- From this information the average deceleration factor for the Caprice during the tip-over event was calculated.
Thus, the average deceleration factor for the Caprice was 0.42 as it traveled through the tip-over event from the edge of the ramp to final rest.
Drag Factor of Overturn

- We have obtained four drag factors from these four tests: 0.55, 0.46, 0.44 and 0.42.
- The average for these four tests was 0.47.
  - This fits well within the previously published and discussed data.
- Recall the Drag Factors:
  - SAE 720966, Hight: \( f = 0.4 - 0.65 \)
  - SAE 890857, Orlowski: \( f = 0.36 - 0.61 \)
  - SAE 2002-01-0942, Altman: \( f = 0.48 \) (average)
  - SAE 890859, Bratten: \( f = 0.5 \) (average)
The standard protocol for measuring rollover distance is from trip to final rest.

- In these tests, the “trip” would be the edge of the ramp.
- Both the Honda and Explorer never went “airborne” when leaving the ramp.
- The Venture was airborne for 54.5 feet.
- The distance from first touch to final rest was 111.75 feet.
- How might this effect the drag factor if measured from first touch to final rest?
Thus, the average deceleration factor for the Venture was 0.66 as it traveled through the rollover event from first touch to final rest.

This is higher than the sliding drag factors measured.

As the vehicle falls to the ground, the effective frictional force increases because of the ground impulse.
The Caprice entered a barrel roll maneuver, tipping over a half roll and then sliding to a stop on its side and top.

- The total distance from trip to stop was 198 feet
- The Caprice was in the air for 34 feet
- Thus, the slide was 164 feet

Thus, by using the distance equation, the drag factor for the slide portion is 0.51.

- This is similar to the pull test done with the load cell on that surface.
- Unlike the Venture, the Caprice dissipated most of its energy by sliding along the surface.
Number of Rolls v Distance or Speed

From Fundamentals of Traffic Crash Reconstruction, IPTM, Pg 712

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A Barrel Roll Case: SUV Hyundai/Tucson

Video from a private câmera.
A Barrel Roll Case: Crash Sequence #1

- 1st collision area between Hyundai/Tucson and Fiat/Palio, (tire marks) and Hyundai/Tucson point of overturn
- 2nd collision area Fiat/Palio into the wall
- 3rd collision area between Hyundai/Tucson and motorcycle Honda, gouges

Displacements are in meters
A Barrel Roll Case: Scene Evidence

1st collision area between Hyundai/Tucson and Fiat/Palio, (tire marks) and Hyundai/Tucson point of overturn

tire marks (Hyundai/Tucson is overturning)

tire and surface marks (Fiat/Palio)
A Barrel Roll Case: Scene Evidence

- Tire marks (Hyundai/Tucson is overturning)
- Debris from vehicles
- 2nd collision area: Fiat/Palio into the wall
- Fiat/Palio final rest
- Tire and surface marks (Fiat/Palio)
A Barrel Roll Case: Scene Evidence

debri from vehicles

tire marks
(Hyundai/Tucson is overturning)
tire and surface marks (Fiat/Palio)
Fiat / Palio
final rest
A Barrel Roll Case: Vehicle Evidence

Damage on the vehicle Fiat/Palio due to 1\textsuperscript{st} and 2\textsuperscript{nd} collisions.
A Barrel Roll Case: Scene Evidence

3rd collision area between Hyundai/Tucson and motorcycle Honda: gouges

Path of the overturning Hyundai/Tucson: scrapes
A Barrel Roll Case: Crash Sequence #2
A Barrel Roll Case: Scene Evidence

3rd collision area between Hyundai/Tucson and motorcycle Honda: gouges

Path of the overturning Hyundai/Tucson: scrapes

debris field (motorcycle parts)
A Barrel Roll Case: Scene Evidence

Path of the overturning Hyundai/Tucson: scrapes

motorcycle Honda CG 125 final rest
A Barrel Roll Case: Vehicle Evidence

Motorcycle/Honda damage.
A Barrel Roll Case: Scene Evidence

4th collision area: Hyundai/Tucson into the pole and metallic fence

Path of the overturning Hyundai/Tucson: scrapes
A Barrel Roll Case: Scene Evidence

Path of the overturning Hyundai/Tucson: scrapes

4th collision area: Hyundai/Tucson into the pole and metallic fence
A Barrel Roll Case: Scene Evidence

Path of the overturning Hyundai / Tucson moving overturned

4th collision area: Hyundai / Tucson into the pole and metallic fence

Hyundai / Tucson final rest

debris from vehicles

Path of the overturning Hyundai/Tucson: scrapes
A Barrel Roll Case: Scene Evidence

Path of the Hyundai/Tucson moving overturned

Hyundai/Tucson final rest

debris from vehicles
A Barrel Roll Case: Vehicle Evidence

SUV Hyundai/Tucson damage.

Scratching on the Hyundai/Tucson left side, on the roof and on the hood. Scratching shows ground contact.
A Barrel Roll Case: Vehicle Evidence

SUV Hyundai/Tucson damage.

Hard impact on the roof, with significant inward intrusion into the passenger space.
Hyundai/Tucson Speed at Overturn

It will be considered that the vehicle hits nothing except the ground. The MC and fence collisions were low energy and offset.

The Hyundai/Tucson entered a barrel roll maneuver, tipping over a half roll and then sliding to a stop on its side and top.

The distance traveled by the vehicle CM from the point of trip until final rest was approximately 77 m (252.5 ft.).

The average drag factor from IPTM testing on 03/17/11 (rough asphalt and level surface) ranges from 0.397 to 0.533. (95% Confidence)
Once the vehicle begins to roll, it will start decelerating.

As we considered the vehicle hits nothing, we may apply a drag factor to this motion and treat it as a skid: The two minor impacts are essentially included in the stochastic range of the drag factor.

\[ v = \sqrt{30df} \] (MPH)

\[ f = (0.465 \pm 0.068) \]
\[ d = (252.5 \pm 0.12) \text{ ft.} \]

The speed of the Hyundai at trip was calculated (Method of Monte Carlo with Excel) at 54.9 MPH to 63.6 MPH. (95% Confidence)

A video analysis calculated the speed of the Hyundai at: 52 MPH to 62 MPH.
In Section 1, we looked at a taxonomy of rollover events.

- **Side to Side Roll** – velocity vector near or perpendicular to the heading vector.
- **Barrel Roll** – velocity vector and heading vector parallel or nearly so.
- **Flip-over or “Endo”** – velocity vector initially parallel to the vehicle heading, rotation about the vehicle “y” axis or parallel axis after an impact.

Sub-Categories
- Tip-Over – less than one full revolution
- Rollover – one or more revolutions
Generally, the rollover is a more violent event than a tip-over.

In real-world crashes, it is possible or even likely the vehicle will transition from one type of roll to another.

- In three of our tests, the vehicles started out in a barrel roll configuration and transitioned quickly to a side to side roll.
- In the fourth test (Caprice), the vehicle barrel rolled and then slid to a rest on its top.
- The Caprice sedan is not as tall as the two SUVs or the Van.
Section 2 discussed the set-up and conduction of the crash tests.

- Vehicles identified
- Set-up of the vehicles
  - Delivery system
  - Braking system
  - Ramp

Crash Test Video

- Able to see the vehicle motion – various angles
  - Number of rolls
    - Honda – two
    - Explorer – two
    - Venture – 1 ¾
    - Caprice – 1/2
  - Transition from Barrel Roll to side to side roll
Section 3 is where evidence was gathered and discussed

- Scene evidence
  - Includes everything from point of trip to rest (or another impact) that was left behind because of the roll event
    - Debris, scratches, chops, gouges in the surface
    - “Where did it come from and how did it get there?”

- Vehicle Evidence – Tie in with Scene Evidence
  - Exterior vehicle evidence may show how many times a side of the vehicle came in contact with the surface
    - Overlapping scratches
    - Broken off parts
    - “How many quarter rolls”
Vehicle Evidence

- Interior vehicle evidence may help show who was sitting where
  - Tie in with pattern injuries
  - Where and when was the most severe ground impact?
    - Occupant motion
  - What trace evidence was found where?
    - Hair, fibers, blood, other body fluids, skin
  - Trace evidence around ejection portals
  - Seat adjustments
  - Shoe (or other) impressions from the brake / accelerator pedal

Case Study of Occupant Kinetics

- Kinetics is the study of kinematics and dynamics combined.
- Interior video of Caprice shows Skippy’s motion similar to the predicted motion.
Section 4 is a discussion and analysis of the crash tests

- Lateral acceleration to overturn
  - Rigid Body Model

- Speed at Overturn
  - High CM Vehicle rounding a turn
  - Speed from distance and drag factor
    - Distance measured from point of trip to rest (or impact)

- Analysis
  - Effective drag factors from rollover tests
    - Measuring from trip to final rest most consistent
  - Drag factors for vehicle sliding on top or side – three different surfaces
    - Reasonably consistent with published data
Summary: Section Four

○ Analysis
  ● Plot number of rolls v speed
  ● Plot number of rolls v distance
    • Consistent with published data
  ● Roll Rates
    • First two tests saturated the rate gyro at 90°/sec.
    • Venture test roll rate 86.3°/sec initially
  ● Speed
    • For the first two tests, the GPS data agreed well with the Stalker radar
    • No GPS data for the third test…speed from Stalker
    • Fourth test speed obtained from Stalker Radar, GPS, and integration of the load cell pull data.

Consider this presentation to be a tool to be used and studied…to assist with your investigations.
Questions?
Crash Tests by:

**University of Tulsa’s Crash Reconstruction Research Consortium (TU-CRRC)**

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  - Nate Shigemura, BSEE, Retired Illinois State Police
  - Andy Rich, BSME, Detective, Bergen County NJ
  - Michelle Fish-Rich, Ohio State Patrol, M.E. Student
  - John Daily, MSME, Retired Teton County Sheriff’s Office, WY
  - Lt. Barry Walker, MPA, West Chester, Ohio P.D.
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