IPTM Special Problems 2013
Crash Test Data

Crash Reconstruction Research Consortium
Introduction and Overview

- Jeremy Daily, Ph.D., P.E.
  - Associate Professor of Mechanical Engineering
  - Director of the Crash Reconstruction Research Consortium

- Jose Corcega
  - Graduate Student of Mechanical Engineering
  - Data acquisition with eDAQ system

- Andrew Kongs
  - Engineering Research Technician
  - All things electrical (Power Distribution, Brake Signals, and Wireless distribution system).
James Johnson
- Ph.D. Student in Computer Science
- VBox Data and Heavy Truck Digital Forensics

Amila Perera
- Graduate Student in Engineering Physics
- Steering measurements and HVE

Richard Ruth,
- IPTM Lead EDR Trainer
- Crash data from factory and ride along EDRs
- Alison Maskus, Electrical Engineering Graduate Student
- Skippy (and Paco)
- Olly, the dog (named after a computer program)
James Johnson on
Research and Projects at

THE UNIVERSITY OF TULSA
Andrew Kongs on
Systems used for

CRASH TEST SETUP
José Córcega  
Description of the  
DATA ACQUISITION SYSTEMS
VC4000DAQ

- 10Hz GPS
- Brake pedal sensor
- Tri-axial accelerometer
  - Used to determine drag coefficient
Racelogic VBox 3i

- 100Hz GPS system
- Serial communication
- Compact flash logging
- Brake trigger
- IMU
  - Tri-axial accelerometer
  - Tri-axial gyroscope
Racelogic Video VBox

- 10Hz GPS system
- 4 Cameras
- Microphone
- Compact flash logging
eDAQ Data Acquisition

- Rugged system designed for use in harsh environments
- Enables simultaneous and synchronous recording of multiple channels with different types of instruments
- Convenient data recording modes
- Simple interface
- 4 Layers
  - DIO
    - Digital I/O
  - HLS
    - High level analog
  - ECOM
    - Vehicle network communications
4 Layers

- ELBRG
  - Bridge
- HLS
  - High level analog
- ECOM
  - Vehicle network communications
Instruments

- **Accelerometer**
  - Tri-axial measurements
  - ±70gs
  - 10,000 Hz bandwidth

- **Gyroscope**
  - Tri-axial measurements
  - ±600 deg/s rates
  - 400 Hz bandwidth
Example Data

Accelerometer Y-axis in the White Impala
Delta V in the Y direction for the White Impala

DeltaV [MPH]

Time (secs)

Special Problems 2013 http://tucrrc.utulsa.edu
Instruments

- **eGPS-200Plus**
  - Combines data from 2 GPS antennas an IMU, and RTK units to provide several measurements at a rate of up to 200Hz

- **Measurements**
  - Acceleration (All 3 axis)
  - Angular velocity (All 3 Axis)
  - Speed
  - Heading, altitude, longitude
  - Slip angle*
Example Data from eGPS

- Yaw Rate and Heading for White Impala

![Graphs showing Yaw Rate and Heading for White Impala]
Yaw Angle from White Impala

<table>
<thead>
<tr>
<th>Time (secs)</th>
<th>Rotation [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>123.5</td>
<td>-60</td>
</tr>
<tr>
<td>124.0</td>
<td>-50</td>
</tr>
<tr>
<td>124.5</td>
<td>-40</td>
</tr>
<tr>
<td>125.0</td>
<td>-30</td>
</tr>
<tr>
<td>125.5</td>
<td>-20</td>
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<td>126.0</td>
<td>-10</td>
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<td>126.5</td>
<td>0</td>
</tr>
<tr>
<td>127.0</td>
<td>0</td>
</tr>
<tr>
<td>127.5</td>
<td>0</td>
</tr>
</tbody>
</table>

x:126.925  y:-57.304  n:614
Speed comparison for eGPS and VBOX 3i

Data Verification

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Data Verification

- No redundant measurement instrument
Data Verification

- No redundant measurement instrument

Car displacement starts
Data Verification

- No redundant measurement instrument

![Graph showing car displacement and heading over time](image)

- Car displacement starts
- Constant heading
eDAQ Data Recording Modes

- **Time history**
  - Records continuously

- **Burst history**
  - Buffer data
  - Records data in a predefined interval
  - Simplifies data processing
Interface (TCE)

- Test Control Environment
  - Create test setup files
  - Perform calibrations
  - Manage tests or data gathering
  - Monitor data
  - Remotely control testing instruments
Interface (Web)

- Limited access
- Manage networked cameras
- Quick test startup
Future Work

- Vehicle Buss Modules
  - J1939
  - J1708
  - Single wire CAN
  - J1850

- Comparison among Vehicle’s Network information and physical data recorded by instruments
White Cavalier into Blue Buick Park Avenue

CRASH TEST 1
Vehicle Descriptions

1998 Chevrolet Cavalier
- Bullet Vehicle
- 1G1JC5243W7315828

1995 Buick Park Avenue
- Target Vehicle
- 1G4CW52K2SH640024
VEHICLE WEIGHT SUMMARY

CRASH 1

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1998 Chevrolet Caviler</th>
<th>1995 Buick Park Avenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Front [lb]</td>
<td>841</td>
<td>1139</td>
</tr>
<tr>
<td>Left Front [lb]</td>
<td>882</td>
<td>1121</td>
</tr>
<tr>
<td>Right Rear [lb]</td>
<td>566</td>
<td>560</td>
</tr>
<tr>
<td>Left Rear [lb]</td>
<td>477</td>
<td>548</td>
</tr>
<tr>
<td>Total [lb]</td>
<td>2766</td>
<td>3368</td>
</tr>
<tr>
<td>Track width [in]</td>
<td>58</td>
<td>60</td>
</tr>
<tr>
<td>Wheel base [in]</td>
<td>104</td>
<td>111</td>
</tr>
<tr>
<td>Center of mass (X,Y) [inch] from left rear wheel</td>
<td>(67.1,31.7)</td>
<td>(72.3,30.3)</td>
</tr>
</tbody>
</table>
## CRASH 1 SUMMARY

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1998 Chevrolet Caviler</th>
<th>1995 Buick Park Avenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Speed [mph]</td>
<td>41.5</td>
<td>20</td>
</tr>
<tr>
<td>Impact Angle [deg (N)]</td>
<td>1.83</td>
<td>270</td>
</tr>
<tr>
<td>Delta V in X [mph]</td>
<td>-3</td>
<td>-</td>
</tr>
<tr>
<td>Delta V in Y [mph]</td>
<td>-17.5</td>
<td>22</td>
</tr>
<tr>
<td>Crash Pulse Time [ms]</td>
<td>150</td>
<td>151</td>
</tr>
<tr>
<td>Peak Angular Velocity [deg/sec]</td>
<td>-128</td>
<td>-289</td>
</tr>
<tr>
<td>Post impact Speed [mph]</td>
<td>15.2</td>
<td>-</td>
</tr>
</tbody>
</table>
CRASH TEST 1 VIDEOS
Consider the acceleration of a sensor

Earth fixed reference that does not rotate

Angular velocity of the vehicle

Angular velocity of the vehicle
Accelerometer Measurements

- Accelerometers measure accelerations with respect to the object they are mounted.
- Motion equations are Earth Fixed.
- Transform coordinates

\[
a_X = a_x \cos \Psi - a_y \sin \Psi \\
\]
\[
a_Y = a_x \sin \Psi + a_y \cos \Psi \\
\]

\( \Psi \) ... Heading Angle
Heading change during a collision

- Look at crash pulse and rate gyro data
  - Use the crash pulse (accelerometer data) to see where collision starts.
  - Integrate both curves to see how the delta-V and yaw angle develops
Yaw Rate

- Angular Velocity is the same for all parts of the car.
- Use two rate gyro sensors at different locations to get the same result.
- Center of rotation around right front for Buick during post impact.
Peak Yaw Rate at end of interaction

Buick Data (Target Car)

- Yaw Rate (deg/sec)
  - -300 to 0
- Accel in Y (g)
  - -20 to 70

Time (secs) 159 160 161 162

x:158.74  y:-2.05102  n:586636
x:158.74  y:-288.899  n:4693
Lateral Accel and Yaw Rate
(140 ms)
Angle Change During Impact

- Obtain angle data by integrating yaw rate

![Graph showing Yaw Angle vs. Time](Buick-Crash1_IPTM_2013)
Affecting the Accelerometer

- If angles change during impact, then acceleration components change.

\[
\begin{align*}
a_x &= a_x \cos \Psi - a_y \sin \Psi \\
a_y &= a_x \sin \Psi + a_y \cos \Psi
\end{align*}
\]

- \(\Psi\) is the heading angle that changes during rotation.

- Square and add together components to get the same magnitude.
Only one Acceleration Component

- Adjusting Acceleration according to angle does not affect delta-V for this case (27 deg maximum angle)

Curves fall on top of each other.
Rotation Rate Effects

- Even if the vehicle twist during a crash, it will likely not rotate enough to alter the delta-V readings just from rotation.

- Post impact trajectories do require addressing heading angles.

- What about angular velocity effects?
  - Centripetal acceleration
  - Tangential acceleration
  - Define a rotating position vector (lever arm)
Dynamics Equations

- Velocity of a point on a rotating and translating body in a plane

\[ \vec{v}_a = \vec{v}_{cg} + \vec{\omega} \times \vec{r}_{sens/cg} \]

Green and Black vectors are the same (used for addition)
Cross Product

- Calculate cross products by determinates

\[
\begin{vmatrix}
i & j & k \\
0 & 0 & \omega \\
r_x & r_y & 0
\end{vmatrix} = -\omega r_y i + \omega r_x j
\]

- Components of a vector are determined as

\[
\begin{align*}
r_x &= r \cos \theta_{sens} \\
r_y &= r \cos \theta_{sens}
\end{align*}
\]

where \( \theta_{sens} \) is the angle of the \( r \) vector from the \( x \)-axis
We can measure the position of a sensor.

Need to determine Center of Mass.
Acceleration Equations

- Velocity changes with time, so acceleration exists.
- Both the magnitude and direction of velocity change.
- In Earth Fixed Coordinates:
  \[ \vec{a}_{sens} = \vec{a}_{cg} + \vec{\alpha} \times \vec{r}_{sens/cg} - \omega^2 \vec{r}_{sens/cg} \]
  which gives the acceleration of the sensor. The angular acceleration is \( \alpha \) in radians/sec/sec. The angular velocity is \( \omega \) in radians/sec.
Determining Angular Acceleration

- Use a filtered finite difference to estimate angular acceleration.

Peak width about 30 ms
Sensing Acceleration

- Sensing acceleration of a rotating car requires knowledge of the heading angle change.
- At one instance, there is only one acceleration vector, but many ways to describe it.
- We pick coordinate systems to describe the vectors.
  - The dynamics equations use a non-rotating reference
  - Accelerometers are mounted to a rotating frame.
Acceleration Measurement

- Write in components with sensed accelerations

\[ a_{cg,x} = a_x \cos \Psi - a_y \sin \Psi + \alpha y_{sens} + \omega^2 x_{sens} \]
\[ a_{cg,y} = a_x \sin \Psi + a_y \cos \Psi - \alpha x_{sens} + \omega^2 y_{sens} \]

where \( a_x \) and \( a_y \) are sensed accelerations, \( \Psi, \omega, \) and \( \alpha \) are rotational components.

- If the sensor is located near the COM and the car has not rotated much, then the sensors measure the COM motion.
A Kinematic Model for Rotation

- Assumptions
  - Starts at a known yaw rate
  - Obtains a peak yaw rate at the end of the collision
  - Yaw rate remains constant while tires are unloaded
  - Comes to a stop from the torque due to friction
  - Area under curve gives total yaw angle
Yaw Model

- Collision
- Spinning and Skidding
- Peak Yaw Rate
Computing Values for the Rotation Model

- Total Angle Rotated = Area Under Curve

\[ \Psi_{total} = \frac{1}{2} t_{crash} \Delta \omega + t_{air} \Delta \omega + \frac{1}{2} t_{skid} \Delta \omega \]
Obtaining Values for the Rotation Model

- Peak angular velocity from angular momentum

\[ \Delta \omega = \frac{h}{k^2} \Delta v \]

Where \( h \) is the lever arm from the PDOF, \( k \) is the radius of gyration, and \( \Delta v \) is the change in velocity. (Beware of units!)
Example of Computing $\Delta \omega$

- Buick crash test data
  - Yaw moment of inertia = 2433 lb-ft-sec$^2$ (AutoStats)
  - Weight = 3533 lb (Measured)
  - $k^2 = \frac{l_{cg} g}{W} = \frac{2433(32.2)}{3533} = 22.17$ ft$^2$
  - $h = 5.1$ ft (Measured distance from damage centroid to EDR)
  - $\Delta v = 12.9$ mph or 18.9 ft/s

- Peak Angular Velocity

$$\Delta \omega = \frac{h}{k^2} \Delta v = \frac{5.1}{22.17} (18.9) = 4.348 \text{ rad/s} = 249 \text{ deg/s}$$
Computing $t_{skid}$

- Compute speeds at the beginning and end of the spin.

$$t_{skid} = \frac{0.0455(S_o - S_f)}{f}$$

(Eqn 12.40 in FTCR)

- Accounts for rollout

- Example: $f=0.45$, $S_f = 5$ mph, $S_o = 20$ mph

$$t_{skid} = \frac{0.0455(20-5)}{0.45} = 1.52 \text{ sec}$$
Develop the Model

- Solve for $t_{air}$

$$t_{air} = \frac{\Psi_{total} - t_{crash} - t_{skid}}{-265} - \frac{2}{0.080} - \frac{1.52}{2}$$

$$t_{air} = \frac{-249}{2} - \frac{2}{2} = 0.264 \text{ seconds}$$

- Average Angular Acceleration during the Crash

$$\alpha = \frac{\Delta \omega}{t_{crash}} = \frac{-249}{0.080} \times \frac{\pi}{180} = -54.3 \text{ rad/s/s}$$
Model for Rotation

![Graph showing measured yaw rate, angular acceleration, and time relationship.]

- Measured Yaw Rate (deg/s)
- Omega (deg/s)
- Alpha (rad/s)
Using the Model to Understand Measurements

\[ a_{cg,x} = a_x \cos \Psi - a_y \sin \Psi + \alpha y_{sens} + \omega^2 x_{sens} \]
\[ a_{cg,y} = a_x \sin \Psi + a_y \cos \Psi - \alpha x_{sens} + \omega^2 y_{sens} \]

- The crash phase model uses a constant angular acceleration, \( \alpha \).
  - \( \Psi = \frac{1}{2} \alpha t^2 \) and \( \omega = \alpha t \)
  - For our case, \( \Psi = 0.5(-54.3)(0.08)^2 = 0.1737 \) rad or 6 degrees.
  - \( \cos(6) = 0.994 \) and \( \sin(6) = 0.104 \)
Lever Arms for Sensors

- $y_{sens} = -1.29$ ft, $x_{sens} = -2.5$ ft
Computing Delta Vs

- Use computer to determine the area
Does the Adjustment make sense?

- The collision was closer to the Sensor than the Center of Mass
  - Sensor read Delta V of 22 mph in Y
  - The EDR located near the COM read 12.9 mph for Delta V in Y
  - The adjustment using the rotation model came up with 13.5 mph for predicted Delta V in Y for the COM based on reference data.

- Events farther away from the damage centroid have lower delta-V’s if there is rotation.
Photo showing Damage and Sensors

COM and EDR

eDAQ Accelerometer
Takeaways from Crash 1

- Evidence
- Sensor (EDR) Locations
  - Sensor rotations do not matter a lot during collisions because the angle change is small.
  - Sensor rotations do matter during post impact spins.
- Torque applied to reduce rotation is nearly constant once all tires are on the ground.
White Impala into White Cadillac

CRASH TEST 2
Vehicle Descriptions

2006 Chevrolet Impala
- Bullet Vehicle
- 2G1WS551269435709

1995 Cadillac Eldorado
- Target Vehicle
- 1G6EL12Y05U601252
## VEHICLE WEIGHT SUMMARY

### CRASH 2

<table>
<thead>
<tr>
<th>Measurement</th>
<th>2006 Chevrolet Impala</th>
<th>Cadillac El Dorado</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Front [lb]</td>
<td>1250</td>
<td>1203</td>
</tr>
<tr>
<td>Left Front [lb]</td>
<td>1132</td>
<td>1268</td>
</tr>
<tr>
<td>Right Rear [lb]</td>
<td>683</td>
<td>745</td>
</tr>
<tr>
<td>Left Rear [lb]</td>
<td>699</td>
<td>675</td>
</tr>
<tr>
<td>Total [lb]</td>
<td>3764</td>
<td>3891</td>
</tr>
<tr>
<td>Track width [in]</td>
<td>61</td>
<td>61</td>
</tr>
<tr>
<td>Wheel base [in]</td>
<td>111</td>
<td>108</td>
</tr>
<tr>
<td>Center of mass (X,Y) [inch]</td>
<td>(70.7,20.5)</td>
<td>(77.3,37.3)</td>
</tr>
</tbody>
</table>
## CRASH 2 SUMMARY

<table>
<thead>
<tr>
<th>Measurement</th>
<th>2006 Chevrolet Impala</th>
<th>Cadillac El Dorado</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Speed [mph]</td>
<td>40.9</td>
<td>19.49</td>
</tr>
<tr>
<td>Impact Angle [deg (N)]</td>
<td>359.6</td>
<td>268.6</td>
</tr>
<tr>
<td>Delta V in X [mph]</td>
<td>-22.26</td>
<td>-</td>
</tr>
<tr>
<td>Delta V in Y [mph]</td>
<td>-9.67</td>
<td>-</td>
</tr>
<tr>
<td>Crash Pulse Time [ms]</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Peak Angular Velocity [deg/sec]</td>
<td>-147</td>
<td>-</td>
</tr>
<tr>
<td>Post impact Speed [mph]</td>
<td>28.5</td>
<td>23.23</td>
</tr>
</tbody>
</table>
VBox Speeds from White Impala v Cadillac - IPTM 2013

Impala Impact Speed = 44.72 mph
Cadillac Impact Speed = 20.53 mph
Impala Post Impact Speed = 22.07 mph
Cadillac Post Impact Speed = 22.07 mph
Post Impact Drag Factor = 0.40

$y = -8.8393x + 111.84$
$R^2 = 0.9912$
Computing Drag Factor

- Given a time history of speed in mph
  - Determine the slope of the graph using the Trendline feature in Excel
  - The units of the slope are mph/s
  - Convert mph to ft/s by multiplying by 1.466
  - Divide by 32.2 to get g’s
- Example:

\[-8.8393 \times \frac{1.466}{32.2} = 0.4026\]
Maroon Impala into a Stationary Maroon Saturn

CRASH TEST 3
Vehicle Descriptions

2000 Chevrolet Impala
- Bullet Vehicle
- 2G1WF55K3Y9287419

1994 Saturn SC1
- Stationary Target
- 1G8ZE1592RZ162012
## VEHICLE WEIGHT SUMMARY

**CRASH 3**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Chevrolet Impala [lb]</th>
<th>Saturn [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Front</td>
<td></td>
<td></td>
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<tr>
<td>Left Front</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Rear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Rear</td>
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<td></td>
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<tr>
<td>Total</td>
<td>3389</td>
<td>2305</td>
</tr>
<tr>
<td>Track width [in]</td>
<td>62</td>
<td>56</td>
</tr>
<tr>
<td>Wheel base [in]</td>
<td>111</td>
<td>99</td>
</tr>
<tr>
<td>Center of mass (X,Y) [inch]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Speed of Maroon Impala into the Saturn - IPTM 2013

Impact Speed = 50.91 mph
Post Impact Speed = 31.11 mph
$\Delta v = 19.8$ mph
Post impact Drag Factor 1 = 0.083
Post impact Drag Factor 2 = 0.455

$y = -1.8296x + 53.935$
$R^2 = 0.935$
$y = -10.005x + 185.92$
$R^2 = 0.9955$
Consortium Website

All data from crash testing and this presentation will be available at

http://tucrrc.utulsa.edu

Credentials

User: TUCRRCmember
Password: TUCRRCpassword
Richard Ruth and Bill Wright
Present on

EVENT DATA RECORDER ANALYSIS
Safe Travels and Stay Safe!

THANK YOU