SHRP 2 S08: Analysis of the SHRP 2 Naturalistic Driving Study Data — Relationship between Driver Behavior and Safety on Rural 2-Lane Curves

Ninth Annual SHRP 2 Safety Symposium

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Background

- Crash rate 3 times higher on horizontal curves than tangent roadway sections
- Minnesota: 25 to 50% of road departure crashes on curves although curves account for only 10% of system mileage
- Iowa: 12% of fatal and 15% of major injury crashes occur on curves
- 56% of fatal run-off-road curves are speed related
Objective

- Define relationship between driver distraction, other driver, roadway, and environmental characteristics and risk of lane departure
  - Impact of countermeasures
  - Impact of specific roadway features (i.e., radius)
  - Impact of distraction/driver characteristics
  - Focus on curves on rural 2-lane paved roadways (lane tracker algorithm does not function on unpaved roadways)
Research Questions

• Data offered opportunity to explore curve relationships in several ways
• 4 fundamental research questions
• Each had different variables/method

1) What defines the curve area of influence?
2) What defines normal behavior on curves?
3) What is the relationship between driver distraction, other driver characteristics, roadway characteristics, environmental characteristics and risk of lane departure?
4) Can lane position at a particular state be predicted as a function of position in a prior state?
• “We the willing, led by the unknowing, are doing the impossible. We have done so much, with so little, for so long, we are now qualified to do anything, with nothing.”

  • Quote attributed to Mother Teresa
Data Needs

• Conducted literature review to identify factors of interest
• Reviewed available data from NDS and RID
  – Revised with updated data for Phase II
• Obtained IRB from ISU & UI for Phases I and II
• Completed data sharing agreement with VTTI for Phase II
Sampling Plan for Phase II

- Balanced:
  - Need for statistically representative sample based on potential number of covariates
  - Cost to procure data
  - Time to reduce and analyze data based on Phase I and new information as project progressed in Phase II
  - Time constraints for Phase II
Curve Identification

- NDS and RID not yet linked
- Overlaid with weighted trip maps to identify segments where trips were likely to have occurred
- Queried RID for rural 2-lane curves of interest
  - radius, presence of RS, etc.
- When mobile mapping not available
  - Reviewed other RID data, Google Earth
- Overlaid with weighted trip maps
- Identified potential curves
Curve Identification

- Identified curves of interest and reviewed for suitability
- Evaluation criteria
  - No turning or passing lanes in curve
  - No stop controlled intersection on the major approach in curves and tangents
  - No signal controlled intersections in curves or tangents
  - No railroad crossings within curve or tangents
  - No sites within 0.5 miles of town
  - No construction (need to check against forward view)
Curve Characteristics

- Identified additional roadway characteristics with Google
- Extracted other characteristics necessary for sample selection for roadways where mobile mapping not available
- Roadway Data
  - Distance between curves
  - Curve type (isolated, S-curve)
  - Radius
  - Lane width
  - Etc.
  - Presence of countermeasures:
    - Chevrons
    - Edge lines
    - Paved shoulders
    - rumble strips
    - Other curve signing
    - RPMs

Data sources: ESRI, Florida DOT
Data Request

- Identified 217 segments with 739 curves (FL, NC, NY, IN, PA)

<table>
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<tr>
<th>Study State</th>
<th>Miles Collected for RID</th>
<th>Rural/Rural Split</th>
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Data Request

• External request
  – data file with output from the in-vehicle data acquisition system (DAS) which provides vehicle network data such as speed, acceleration, position, etc.;
  – video with a forward and rear view of the roadway; and
  – information about each driver/vehicle such as age, gender, vehicle type, track width, etc.

• Internal request
  – UI to visit secure data enclave to view driver face, steering wheel, still cabin videos after traces have been verified
Data Request – Phase II

• VTTI provided forward view for each available buffer
  – Confirm roadway condition and identify sites with construction/other issues
  – Buffers with construction/other unidentified issues – removed
• Set filter to exclude traces
  – Lane tracker variables missing
  – Poor video quality (if known)
  – No forward/side acceleration
  – Need sufficient samples with steering wheel and pedal position
Reduced in-house

- RID
  - roadway characteristics
- times series from NDS
  - GPS
  - vehicle kinematics

Reduced at secure data enclave

- driver face
  - glance location
  - distraction
  - state (i.e. drowsy)
- over-shoulder
  - distraction
- cabin
  - # of passengers

Image sources: ESRI, VTTI, does not show unconsented driver
### SHRP 2 S08d – Data

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### Driver
- Driver age
- Gender
- Education level
- Annual miles driven
- Years of driving
- Number of moving violations
- Number of crashes

### Vehicle
- Vehicle year
- Vehicle model
- Vehicle make
- Vehicle track width

- ABS activation
- Acceleration, z-axis
- Cruise control
  - Time into trip
  - Elevation, GPS
  - Head position y
  - Ambient light
- Lane marking, probability, right
- Lane markings, probability, left
- Wiper setting
- Pitch rate, y-axis
- Roll rate, x-axis
- Seatbelt, driver
- Acceleration, x-axis
- Airbag, driver
- De-identified date
- Driver button flag
- Head confidence
- Head position z
- Lane marking, distance, left
- Lane marking, type, left
- Lane position offset
- Lane width
- Accelerator position
- Speed, vehicle network
- Accelerator position
- Radar range rate forward x
- Seatbelt, driver
- Acceleration, y-axis
- Alcohol
- Dilution of precision, position
- Electronic stability control
- Head position x
- Headlight setting
- Lane marking, distance, right
- Lane marking, type, right
- Timestamp
- Spatial position (Lat/Long)
- Steering wheel position
- Yaw rate, z-axis
- Pedal, brake
- Radar range rate forward y
Data Challenges

• Only 1/3 of full database available
  – Only 1 crash and 3 near-crash available
• Inability to set filters resulted in significant additional amount of data manipulation
  – But provided opportunity to best select traces of interest
Received 4,102 raw traces – evaluated key variables

Removed traces when key variables not functioning
Developed comparison matrix by driver age/gender and curve characteristics

Identified traces of interest (123 total)
  * acceleration >= 0.3 g
  * speed >= 100 kph

Requested forward view for traces of interest (123) and an additional 864 traces selected to balance driver/roadway characteristics

Driver/glance location reduced for 515 traces
Due to reliability of data, not all traces were used for all research questions
Reduction of Roadway Factors

- Most variables reduced for all curves (used RID when available)
- forward view
  - Sight distance
  - Quality of lane markings
- Added estimate of road furniture
  - rating system of 1 – 3 (ranges from little to no road furniture to significant roadway furniture)

<table>
<thead>
<tr>
<th>Feature</th>
<th>ArcGIS</th>
<th>SHRP2 RID</th>
<th>Google Earth</th>
<th>SHRP 2 NDS Forward Video</th>
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<td>presence of chevrons</td>
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<td>presence of w1-6 signs</td>
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Reduction of Vehicle Factors

- Spatially correlated vehicle trace to curve
  - Location of vehicle upstream, within, downstream of curve
- Calculated lane position from lane tracking variables
  - Lane position offset and vehicle track width
Smoothing

• Some amount of noise present in variables
  – False lane departure
• Evaluated several smoothing methodologies
  – Kalman (overly complicated for purpose)
  – Weighted moving average
• Moving average method
  – Reduces random noise while preserving step function
  – \( y[i] = \frac{1}{M} \sum x [i + j] \)
  – Offset
  – Acceleration (x, y)
  – Steering
  – Pedal position
Reduction of Kinematic Driver Factors

• Steering wheel position: intended to use as indicator of driver fatigue to select traces with potentially drowsy drivers
  – (present in << vehicles than expected)
  – Not able to preselect drowsy drivers in data request

• Driver response – DAS variables
  – Speed
  – Average speed
  – Amount over posted or advisory speed
  – Standard deviation of speed
  – Forward/side acceleration
  – braking
  – gas pedal input
Reduction of Kinematic Driver Factors

- Head position available but not quality ensured sufficient for current use
- glance location
  - forward and steering wheel
  - Head position
  - Eye movement (if visible)
- distractions
  - in conjunction with glances away from forward roadway
- Amount of time looking at forward roadway, roadway related tasks, and non-roadway related tasks
## Driver Characteristics

### Percentage of Drivers Exceeding the Advisory or Posted Speed Limit

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<th>Over Speed Limit</th>
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<th>30 to 40 mph advisory speed</th>
<th>45 to 50 mph advisory speed</th>
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<td>73.2%</td>
<td>45.6%</td>
<td>49.1%</td>
<td>11.6%</td>
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<td>28.1%</td>
<td>30.2%</td>
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## Selected Curve Characteristics

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Not present
Crash Surrogates

- Not sufficient crashes (1 crashes/3 near crashes)
- Need lane departure crash surrogates
- Surveyed literature and considered against available data
  - Time to collision (spatial location of vehicle and objects not sufficiently accurate; forward radar not processed)
  - Lane deviation (common measure for lane departure and data are available)
    - Offset from lane center
    - Lane tracker accuracy unknown
    - Frequent gaps in offset
      - Gaps in lane lines, sensor malfunction
    - Only reliable for subset of data
Crash Surrogates

- Lane offset/lane position when sufficiently reliable available
  - Research question 2 and 4
- Encroachment (lane crossing)
  - occurred when two of the following criteria were present:
    - vehicle edge is 0.2 meter beyond lane line
    - 0.2 g lateral acceleration is present
    - lane crossing is visually confirmed using the forward view
  - Research question 3
Research Question 1

- Defines curve area of influence
  - Identifies where driver begins reacting to curve
  - Applications for design, signing, countermeasure placement, setting speed limits
- Build on models of theoretical curve driving behavior
- Data sampling: time series (continuous) data at level provided in DAS
  - One row = 0.1 sec
  - 400 meters upstream of PC
- Evaluated kinematic variables that indicate change in attention and response
Research Question 1

• Change point model identifies point at which speed or pedal point change from upstream driving (164 to 180 m)
• Inferred driver reaction point
• 127 traces over 43 curves (IN, NY, NC)
• Developed models by curve by direction (inside vs outside)
• Also developed Bayesian Model for curves with multiple samples of drivers across curve (11 curves)
  – Average reaction point is 105 m (64 to 136 m)
  – Drivers react sooner when radius increases
  – Driver react 2 meters sooner when traveling on outside of curve

Average Change Point

<table>
<thead>
<tr>
<th>Radius</th>
<th>average change point (m) for pedal position models</th>
<th>average change point (m) for speed models</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 500</td>
<td>-113.5</td>
<td>-96.8</td>
</tr>
<tr>
<td>500 to &lt; 1000</td>
<td>-156.0</td>
<td>-178.8</td>
</tr>
<tr>
<td>1000 to &lt; 1500</td>
<td>-163.9</td>
<td>-146.1</td>
</tr>
<tr>
<td>1500 to &lt; 2000</td>
<td>-198.1</td>
<td>-194.4</td>
</tr>
<tr>
<td>2000 to &lt; 2500</td>
<td>-205.6</td>
<td>-191.1</td>
</tr>
<tr>
<td>2500 to &lt; 3000</td>
<td>-219.7</td>
<td>-164.5</td>
</tr>
<tr>
<td>&gt;= 3000</td>
<td>-166.5</td>
<td>-141.2</td>
</tr>
</tbody>
</table>
Research Question 1

Key Findings
- Drivers react 164 to 180 meters upstream of PC
- Drivers react sooner when radius is greater

Implications
- MUTCD warning sign placement visible, around 107 to 175 feet
- Decreased reaction time for smaller radius may suggest need for curve delineation countermeasures (chevrons, edge line, etc.)

Limitations
- Driver glance location could not be used to identify reaction point, relied on change in speed/pedal position
- Noise in pedal and speed made it difficult to isolate reaction point
- Reaction point may be more pronounced for larger radius curves
Research Question 2

• Research Question 2: How do drivers normally negotiate curves
  – Comparison of lane offset and speed
    • six key points along the curve (PC, PT and 4 equally spaced points between)
    • upstream (50, 100, 150, 200, 250, 300 meter)
  – Compares change in speed and lane offset upstream versus within curve
  – Used panel data model with random effects and ordinary least squares
Lane Position Right-side

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-0.22185</td>
<td>0.0005</td>
</tr>
<tr>
<td>Offset at 100 feet upstream of curve</td>
<td>0.36714</td>
<td>0.0000</td>
</tr>
<tr>
<td>Distracted at the previous point in the curve or upstream indicator (0: not distracted, 1:distracted)</td>
<td>0.13592</td>
<td>0.0500</td>
</tr>
<tr>
<td>Drivers age (years)</td>
<td>0.00345</td>
<td>0.0001</td>
</tr>
<tr>
<td>C1 position indicator (0:not C1, 1:C1)</td>
<td>0.16931</td>
<td>0.0001</td>
</tr>
<tr>
<td>C2 position indicator (0:not C2, 1:C2)</td>
<td>0.18865</td>
<td>0.0012</td>
</tr>
<tr>
<td>C3 position indicator (0:not C3, 1:C3)</td>
<td>0.39609</td>
<td>0.0000</td>
</tr>
<tr>
<td>C4 position indicator (0:not C4, 1:C4)</td>
<td>0.26790</td>
<td>0.0000</td>
</tr>
<tr>
<td>PT position indicator (0: not PT, 1:PT)</td>
<td>0.17682</td>
<td>0.0020</td>
</tr>
<tr>
<td>First order auto regression disturbance parameter (phi 1)</td>
<td>0.57808</td>
<td></td>
</tr>
<tr>
<td>2nd order auto regression disturbance parameter (phi 2)</td>
<td>-0.28316</td>
<td></td>
</tr>
</tbody>
</table>

Number of Observations: 216

- GLS model with AR(2) correlation structure
  - Distraction shifts drivers towards right
  - Offset in upstream has effect on offset in curve
  - Offset varies by position in curve
Lane Position Left-side

- GLS model with AR(2) correlation structure
- Non-roadway glances shifts driver towards centerline
- Offset in upstream has effect on offset in curve
- Presence of larger paved shoulder shifts driver away from centerline towards shoulder
- Offset varies by position in curve

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.00067</td>
<td>0.9904</td>
</tr>
<tr>
<td>Offset at 100 feet upstream of curve</td>
<td>0.44811</td>
<td>0.0002</td>
</tr>
<tr>
<td>Non-roadway (NR) glance at point in curve indicator (0: roadway glance, 1:NR glance)</td>
<td>-0.13466</td>
<td>0.0193</td>
</tr>
<tr>
<td>Night indicator (0:daytime, 1:night)</td>
<td>-0.12283</td>
<td>0.0155</td>
</tr>
<tr>
<td>Paved shoulder greater than 4' indicator (0: paved shoulder less than 4', 1: paved shoulder &gt;=4')</td>
<td>0.21273</td>
<td>0.0006</td>
</tr>
<tr>
<td>C1 position indicator (0:not C1, 1:C1)</td>
<td>-0.17691</td>
<td>0.0014</td>
</tr>
<tr>
<td>C2 position indicator (0:not C2, 1:C2)</td>
<td>-0.20758</td>
<td>0.0044</td>
</tr>
<tr>
<td>C3 position indicator (0:not C3, 1:C3)</td>
<td>-0.16169</td>
<td>0.0304</td>
</tr>
<tr>
<td>C4 position indicator (0:not C4, 1:C4)</td>
<td>-0.02272</td>
<td>0.7495</td>
</tr>
<tr>
<td>PT position indicator (0: not PT, 1:PT)</td>
<td>0.05718</td>
<td>0.4071</td>
</tr>
<tr>
<td>First order auto regression disturbance parameter (phi 1)</td>
<td>0.49063</td>
<td></td>
</tr>
<tr>
<td>2nd order auto regression disturbance parameter (phi 2)</td>
<td>-0.26283</td>
<td></td>
</tr>
<tr>
<td>Number of Observations</td>
<td>156</td>
<td></td>
</tr>
</tbody>
</table>
Speed

• OLS model with amount over the speed limit (mph) at C2 as dependent
  – Upstream speed effects speed in curve
  – Younger drivers and those who drive SUVs and trucks are expected to have higher speeds
  – Lower at night
  – Lower when engaged in a non-roadway related glance

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>3.70299</td>
<td>0.0006</td>
</tr>
<tr>
<td>Amount over the speed limit at 100 m upstream of curve</td>
<td>0.70772</td>
<td>0.0000</td>
</tr>
<tr>
<td>Drivers age (years)</td>
<td>-0.05340</td>
<td>0.0003</td>
</tr>
<tr>
<td>Night indicator (0: daytime or dusk, 1: nighttime)</td>
<td>-1.73462</td>
<td>0.0282</td>
</tr>
<tr>
<td>Large Vehicle Indicator (0: car, 1: truck or SUV)</td>
<td>1.30152</td>
<td>0.0289</td>
</tr>
<tr>
<td>Non-Roadway related glance at current point indicator (0: roadway related glance, 1: Non roadway related glance)</td>
<td>-3.32218</td>
<td>0.0372</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.741</td>
<td></td>
</tr>
</tbody>
</table>
Research Question 2

**Key Findings**
- Lane position: position within curve, distraction, age, time day
  - * drivers more vulnerable to lane departures at certain points in the curve
- Speed: upstream speed, distraction, time of day, age

**Implications**
- Countermeasures which target variation in lane (i.e. rumble strips, high friction treatments, paved shoulders, edge lines)
- Countermeasures targeting speed upstream and within curve:

**Limitations**
- Required reliable offset which reduced sample size
- Could not draw correlation between curve features/countermeasures
- Does not draw relationship between lane position, speed, and risk of roadway departure
Research Question 3

• What is the relationship between driver & roadway characteristics and roadway departure risk?
  – Response variables:
    • probability of left or right side lane encroachment
    • probability >= 5 or 10 mph over advisory/tangent speed limit
  – Event based analysis (one driver trip through curve or tangent section = 1 observation)
    • Reduced data 200 m upstream (upstream characteristics) and through curve (within curve)
    • Multiple driver, roadway, traffic, environmental variables
• Logistic regression model (n = 583 observations)
  – 57 right side lane departures and 40 left
  – Included random effects to account for repeated measures (curve and driver)
Right-side Encroachment

\[
\log\left(\frac{p_t}{1-p_t}\right) = \beta_0 + B_1x_1 + \beta_2x_2 + \beta_3x_3 + \beta_4x_4 + \beta_5x_5 + \beta_6x_6 + \alpha_i
\]

\[
\alpha_i \sim \text{Normal}(0, \sigma^2)
\]

where

- \(x_1\) = dummy variable for the presence of rumble strips,
- \(x_2\) = dummy variable for the presence of a W1-6 sign,
- \(x_3\) = fraction of time driver glance is away from the roadway and not engaged in driving tasks for 200m upstream of the curve,
- \(x_4\) = dummy variable for the direction of the curve (0 is outside, 1 is inside),
- \(x_5\) = dummy variable for the presence of a guardrail,
- \(x_6\) = radius of the curve, and
- \(\alpha_i\) = random effect for subject, which allows us to generalize these results for all drivers on these curves.

### Confidence Intervals for Right-side Encroachments

<table>
<thead>
<tr>
<th>Variable</th>
<th>Odds Ratio Est.</th>
<th>5%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rumble Strips</td>
<td>11.875</td>
<td>2.1883</td>
<td>64.4396</td>
</tr>
<tr>
<td>W1-6</td>
<td>3.1186</td>
<td>1.2125</td>
<td>8.0212</td>
</tr>
<tr>
<td>Up. NR</td>
<td>7.3516</td>
<td>1.4144</td>
<td>38.2115</td>
</tr>
<tr>
<td>Direction</td>
<td>6.5430</td>
<td>3.2967</td>
<td>12.9861</td>
</tr>
<tr>
<td>Guardrail</td>
<td>0.3486</td>
<td>0.1230</td>
<td>0.9884</td>
</tr>
<tr>
<td>Radius</td>
<td>0.9996</td>
<td>0.9993</td>
<td>0.9999</td>
</tr>
</tbody>
</table>
Right-side encroachment

- Presence of rumble strips increases odds by 11.8 (2.1 to 64.4)
- Presence of W1-6 increases odds by 3.1 (1.2 to 8.0)
  - (may be correlated to curve radius)
- Non-roadway related glances upstream of curve increases odds by 7.4 (1.4 to 38.2)
- Inside versus outside 6.5 (3.3 to 13.0)
- Presence of guardrail =0.4 (0.1 to 1.0)
- Radius (small correlation)
Left-side encroachment

- Male vs. female 3.8 times more likely (1.3 to 11.3)
- Inside versus outside 0.1 (0.05 to 0.27)
- Radius, minor impact
Entering Curve >= 5 mph

- Increase in age ⇒ less likely to speed, 0.97 (0.95 to 0.99)
- Fraction of time driver is following, 0.35 (0.18 to 0.70)
- Fraction of time driver glances at roadway related tasks within curve, 0.02 (0.0002 to 1.1)
- Highly visible markings versus just visible or obscured (2.4 and 57.3)
- Visibility (0 to 1), 0.12 (0.02 to 0.65)
- Speed limit (less likely with increased speed/advisory)
- Presence of curve advisory sign, 6.5 (3.2 to 12.8)
- Isolated curve versus S or compound curve (1.9 and 24.9)
Entering Curve $\geq 10$ mph

- Gender – Males 10.1 times more likely (2.9 to 35.9)
- Age $\Rightarrow$ less likely to speed, 0.97 (0.94 to 1.0)
- Upstream speed increases likelihood
- Fraction of time driver is following decreases
- Longer average glances at roadway-related locations $\Rightarrow$ less likely to speed
- Highly visible markings versus just visible or obscured (3.4 and 16.6)
- Presence of curve advisory sign, 10.9 (4.9 to 23.9)
- Isolated curve versus S or compound curve (4.9 and 24.7)
- Decreases as speed or advisory speed increases
# Right side Encroachment

<table>
<thead>
<tr>
<th><strong>Key Findings</strong></th>
<th>Presence of RS and W1-6 sign increase probability of right side encroachment and presence of guardrail decreases (may be correlated to type of curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-roadway related glances increase probability</td>
</tr>
<tr>
<td><strong>Implications</strong></td>
<td>Assuming type of curve is correlated – countermeasures which provide better delineation may reduce encroachments (just signing not effective)</td>
</tr>
<tr>
<td></td>
<td>Encroachments were common, may suggest effectiveness of RS (although counter-intuition), paved shoulders</td>
</tr>
<tr>
<td><strong>Limitations</strong></td>
<td>Could not establish correlation between encroachments and crash risk</td>
</tr>
<tr>
<td></td>
<td>Narrow range of countermeasures</td>
</tr>
</tbody>
</table>
Speed

Key Findings
Male, upstream speed, curve type, highly visible markings increase speeds
Following, glances away from roadway decrease

Implications
Speeding was common, 42% entered curve 5 + mph over, 21% entered curve 10+ mph over
Suggests need for speed management upstream

Limitations
Could not establish correlation between speed and crash risk
Narrow range of countermeasures
Research Question 4

- Research Question 4: *How does different factors (driver distraction/oncoming vehicle/curve geometry) influence lane keeping behavior?*

- Data sampling approach
  - time series data (continuous) data at level provided in DAS (10 Hz)

- Response variable: deviation within lane

- Covariates: similar to research question 2
  - Roadway (with focus on countermeasures)
  - Driver
  - Environmental
Research Question 4

- Dynamic linear model (DLM)
- Identifies driver response to roadways and traffic cues
- Findings:
  - oncoming vehicle and curve geometry had significant impact on lane deviation

Implications: model has potential for lane departure collision warning systems
Key Findings

Lane position can successfully be modeled as a function of vehicle state in a prior state and as a function of other characteristics, such as position within the curve or presence of oncoming vehicles.

Implications

Shows potential for use in developing collision warning systems.

Limitations

Only 1 sample.
Questions??