EVALUATING LANE DEPARTURE CRASHES USING NATURALISTIC DRIVING STUDY DATA

Strategic Highway Research Program 2

Transportation Research Board

Fourth Safety Research Symposium SHRP 2

July 23-24, 2009

Research Team: The Center for Transportation Research and Education (CTRE) at Iowa State University and the University of Iowa

Shauna Hallmark, , Alicia Carriquiry, , Yu-Yi Hsu, Linda Boyle, Reginald Souleyrette, Neal Hawkins, Tom McDonald, Omar Smadi Abhisek Mugdal

ctre Center for Transportation Research and Education

IOWA STATE UNIVERSITY

THE UNIVERSITY OF IOWA

Project Objectives

- Analyze lane departure crashes using data from existing naturalistic driving studies and other sources
- Develop analytical tools for use in full scale in-vehicle driving study to answer research questions related to road departure
- Provide feedback to improve full scale naturalistic driving study data collection and analysis and mobile mapping data collection so that lane departures can be fully addressed

Research Questions

- 12 initial questions combined to 3
- Significant overlap between questions
- Followed SO2's global approach
  - Address as many factors as possible that might be used in SO8
  - S08 researches will narrow questions

Research Questions

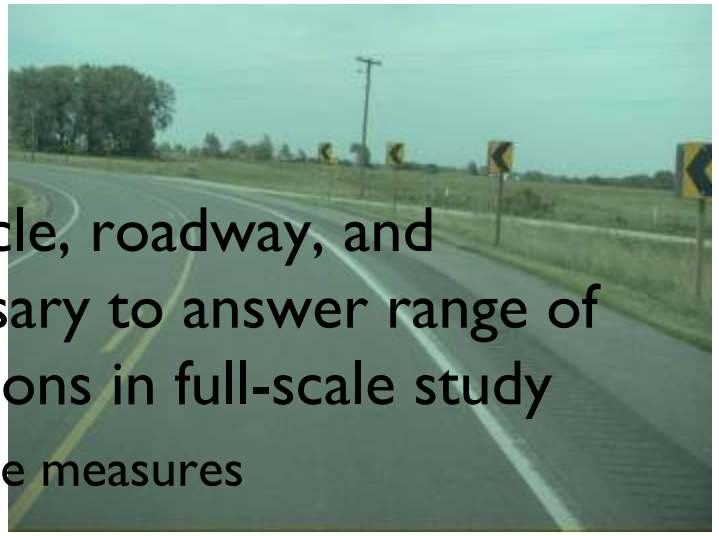
Research Question 1	What kinematic variables can be used to identify lane departure incidents (lateral drift, lane departure, near-crash, etc)? For instance, a side acceleration of X feet or a roll rate of Y might define a lane departure.
Research Question 2	What environmental, roadway, driver, or vehicle factors influence whether a vehicle departs its lane and which factors influence outcome (i.e. safe recovery and return to roadway, minor conflict with safe return, near miss with safe return, property damage accident, injury accident, etc)? For instance: ▪ How likely are drivers to over-correct or counter steer away from edge line rumble strips resulting in a potential encroachment into an adjacent lane rather than a road departure? ▪Does roadway lighting have any impact on driver response and outcome?
Research Question 3	What is the relationship between lane departure crash surrogates and crashes?

Datasets

- VTTI 100-Car Naturalistic Driving Study
  - 33 crashes or near crashes for open country or interstate
  - Continuous and reduced event data for crashes and near-crashes
    - Events already selected
  - Forward imagery for events (non-driver)
  - Additional 8 events from data sharing web site (continuous and reduced data but not imagery)
- UMTRI RDCW Field Operational Tests
  - First week of data before system was turned on
  - Continuous vehicle data for rural roadways (10 Hz)
  - Forward imagery at 2 Hz (no driver face imagery)
  - Data for 44 drivers on rural roadways
  - Reduced for rural 2-lane paved
    - Event
    - Continuous
  - Michigan road database
  - Michigan crash database
  - Aerial imagery

IDENTIFYING DATA NEEDS TO ANSWER LANE DEPARTURE QUESTIONS

Data Needs



- Identified relevant driver, vehicle, roadway, and environmental variables necessary to answer range of lane departure research questions in full-scale study
  - Selection of incidents for surrogate measures
  - Explanatory variables
- Reviewed existing datasets
  - Determined feasibility of extracting data
  - Identified limitations
  - Made recommendations for full-scale
- Determined frequency, accuracy, and resolution necessary
  - Depends on application
  - i.e. Shoulder width ± 0.5 feet
  - Spatial position for TTC

Data Needs for Full-Scale Study

- Summarized roadway, driver, environmental, and vehicle data needs to answer range of lane departure questions
  - Not comprehensive but attempted to anticipate common range of likely questions
- Reviewed proposed data elements and collection protocol to determine if adequate for lane departure RQs
  - SO3 and SO5 (most currently available information)
  - Accuracy, frequency, and resolution of data elements collected

Data element: presence/type of edge and centerline rumble strips
Need: independent variable in the statistical analysis; also needed to establish outcome of lane departure
Potential source for data element: roadway databases, mobile mapping, or forward video
Desired accuracy: placement ± 0.5 feet
Frequency: once per mile or when rumble strip starts or ends
Comments on extracting data from existing datasets: Would be best from mobile mapping but can be determined from the forward video as shown left particularly with color. However, characteristics, such as width, depth, or skip distance, would be difficult or impossible to extract from images.

Roadway Data Elements

Roadway Factors

Data Element	Data Stream	Accuracy	Frequency	Priority
Lane width	Mobile mapping, forward video	± 0.328 ft (0.1 m)	10 Hz	high
roadway and shoulder surface type	Roadway datasets, mobile mapping, forward video	N/A	N/A	high
shoulder and median width	Roadway datasets, mobile mapping, forward video	± 0.5 ft (0.15 m)	10 Hz	high
number of lanes, access control, presence and type of median	mobile mapping, aerial imagery	N/A	once per mile or when characteristics change	medium
curve length and radius	mobile mapping or aerial imagery	± 25 feet (7.62 m)	once per curve	high
super-elevation, lane cross-slope	Mobile mapping van	± 0.5%, 0.1%	Several times per mile	medium
Curve direction	Forward imagery, aerial imagery	N/A	Collected for each curve	High
Distance between successive curve	Mobile mapping data, aerial imagery	± 25 feet (7.62 m)	once per curve	medium
type and characteristics of curve spirals	Roadway datasets, mobile mapping, forward imagery	± 25 feet (7.62 m)	once per curve	medium
amount of grade (%), length of grade (ft) and location and characteristics of the crown and crest vertical curve	Roadway datasets, mobile mapping	0.5% for grade and ± 25 feet (7.62 m)	Begin and end points of grade change	Medium
Signing	Existing sign inventories, mobile mapping, forward imager	± 6.6 ft (2.0 m)	Once per sign	High
number of driveway or other access points	mobile mapping, aerial imagery, forward imagery	N/A	as needed	Medium
presence and type of edge and centerline rumble strips	Roadway datasets, mobile mapping, forward imagery	N/A	Start and end of rumble strip	High
roadway delineation	Forward imagery	N/A	once per mile or as situation changes	Medium
location and type of roadside objects	Mobile mapping data, aerial imagery	± 3.0 feet (0.914m)	As they occur	medium

Needs:

1) Evaluate event outcomes (time to collision, distance to collision, distance to roadway edge, rollover potential)

Positional accuracy of ± 3.0 feet (fixed object)

V = 60mph (80.67 ft/sec)

Error = 3.0 feet ÷ 80.67 ft/sec
= ± 0.058 seconds

Would affect TTC ± 0.06 sec

2) Explanatory variables

Table 3-3: Environmental Factors

Data Element	Data Stream	Accuracy	Frequency	Priority
roadway surface condition	Archived RWIS data, forward or other outward facing imagery, status and frequency of wiper blades, outside temperature	will be qualitative measure	10 min intervals or if conditions change	high
Ambient condition	Archived weather information, forward imagery	will be qualitative measure	10 min intervals or if conditions change	Low, if surface condition is collected
ambient lighting including street lighting	sun angle, dawn, dusk, day, night indicator can be obtained from time stamp data and us naval observatory astronomical data, subjective measure from forward imagery	will be qualitative measure	Once per mile or as conditions change	medium
Visibility	forward or other outward facing imagery	will be qualitative measure	once per mile	high

Table 3-5: Driver Factors

Data Element	Data Stream	Accuracy	Frequency	Priority
Age and gender	driver questionnaire	N/A	N/A	High
Measures of riskiness	Questionnaire, roadway datasets	N/A	Once per trip/event	Medium
Driver distraction	Face imagery, video reduction datasets	Image Resolution (640x640)	15 (min) – 30 (preferred) Hz	High
Driver action before and after incident	Face imagery, roadway datasets, video reduction data	Image Resolution (640x640)	15 (min) – 30 (preferred) Hz	Medium
Alcohol and drug usage	Video reduction data	Image Resolution (640x640)	15 (min) – 30 (preferred) Hz	Medium
Driver fatigue	Face imagery, video reduction data	Image Resolution (640x640)	15 (min) – 30 (preferred) Hz	Medium

**note: accuracy is N/A: not applicable since majority are qualitative measure.

Table 3-1: Vehicle Factors

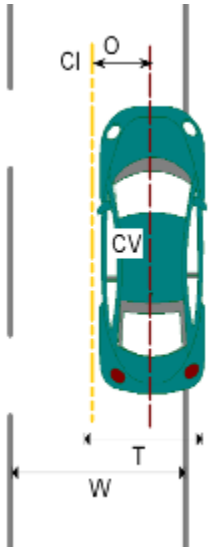
Data Element	Data Stream	Accuracy	Frequency	Priority
vehicle position (lat, long)	GPS	Best possible (± 6.6 ft {2 m})	10 Hz	high
Distance between vehicle and strikeable objects	Spatial location of vehicle/objects or radar	± 3.0 ft (0.914m)	N/A	high
lane position, lane offset	Measured by lane position tracking system using forward or other outward facing video, GPS, and other data streams	±0.1 ft (0.305 m)	10 Hz	high
a_x and v_x	Accelerometer or OBD	±0.1 ft/sec^2 and 0.1 ft/sec (0.0305 m/sec)	10 Hz	high
a_y and v_y	Accelerometer or OBD	±0.1 ft/sec^2 and 0.1 ft/sec (0.0305 m/sec)	10 Hz	high
pitch, roll, yaw	Accelerometer		10 Hz	high
Distance between vehicles	Imagery, radar	± 3.0 ft (0.914m)	N/A	high

Early Conclusions

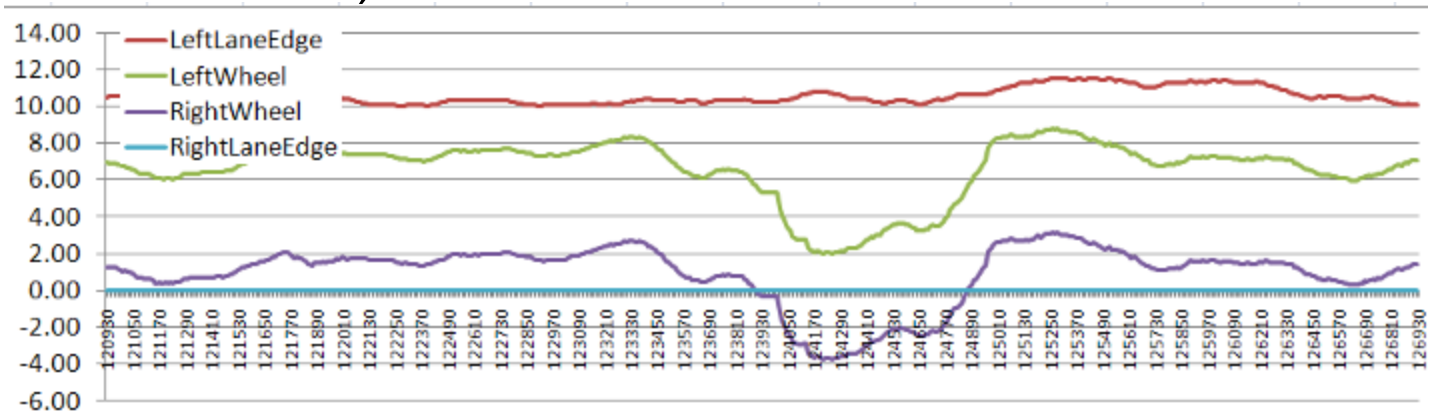
- Concern about sampling of rural roadways in SO7
- Roadway mapping specifications adequate for most purposes
  - lane width not adequate for lane tracking if necessary
  - Cannot collect changing roadway elements
    - Edge drop-off, pavement marking wear, surface friction
- Vehicle instrumentation appeared adequate for most purposes (accuracy of GPS highly relevant but unknown)
- Various other sources for needed data (aerial imagery, forward imagery, state databases)
- Accurate lane tracking system is critical for lane departure questions
- Ability to collect TTC depends on spatial accuracy of vehicles and objects or forward radar
- Data dictionaries developed for SO4 and SO7 should clearly state accuracy, frequency, resolution of items collected
  - Status of eyes-forward monitor and traffic signal state unknown

DATA REDUCTION FOR PRELIMINARY ANALYSIS OF LANE DEPARTURE QUESTIONS

Data Reduction –UMTRI



- Focused on rural paved 2-lane roads
- Identified and extracted lane departures incidents as well as normal driving
- Incidents
  - initially identified from RDCW alerts,
  - Selected based on lane position, and confirmed with forward imagery
  - > 0. 1 meter deviation from edge of lane (UMTRI's definition)



UMTRI Data Reduction

- 16 drivers – rural 2-lane paved only
- Data partioned by events (lane departure) or consistent roadway and environmental characteristics
  - Consistent cross-section, tangent vs. curve, wet vs. dry, etc
  - Most driver factors not available
- Evaluated both events and continuous depending on analysis

Image source: ESRI, data source: UMTRI

UMTRI Data Reduction

- Event based
  - Identified 22 right side and 52 left side lane departure (all encroachments, no crash/near crash)
  - Aggregated normal driving by driver, presence of curve, cross-section, environmental characteristics, etc
    - 739 epochs of normal driving weighted by time (from continuous 0.1 sec intervals)
- Continuous data for both incidents and normal driving
  - ~ 80 0.1 sec intervals for incidents
  - Varying length for normal driving
  - > 113, 000 0.1 sec intervals

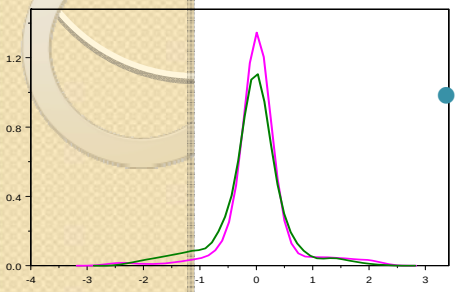
Data Elements Available from UMTRI Continuous Data

- **Vehicle variables**: Offset, longitudinal speed, lateral speed, position, heading, yaw rate, roll rate, lateral accel, longitudinal accel, offset, track width, available maneuvering room, brake status, wiper status, cruise control status, headlamp status

- **Driver variables**: driver age, gender, trip, time

- **Roadway variables for segment**: lane width, posted speed, advisory speed, AADT

UMTRI Data Reduction



Distribution of acceleration for Drivers 6 and 12 (m/sec^2)

- Data elements extracted from aerial imagery, crash data, forward imagery, or continuous data
- **Vehicle variables**:
  - position in relation to lane lines
  - speed in relationship to posted or advisory speed limit
- **Driver variables**:
  - Propensity for speeding (% of time traveling >= 5 or 10 mph over posted speed or 10 or 15 mph over advisory curve speed)
  - Following forward vehicle (not following, following, or following closely)
  - Number of times passes other vehicles

>= 5 mph over posted speed limit	41%
>= 10 mph over posted speed limit	6%

Driver 8: Amount of time over posted speed limit on rural 2-lane

Extraction of vehicle following, Image source: UMTRI

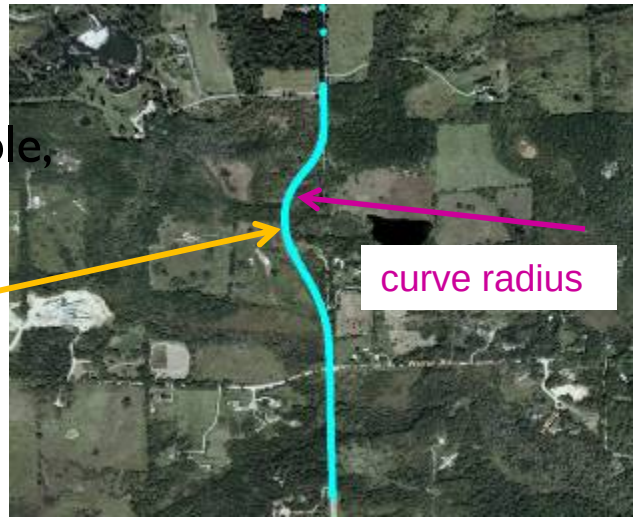
UMTRI Data Reduction

- Data elements extracted from aerial imagery, crash data, forward imagery, or continuous data

Highly visible pavement markings—Image source: UMTRI

- **Roadway variables**
  - shoulder width and type
  - roadway surface type (only paved used, lane keeping not valid on gravel)
  - posted speed or advisory speed when not indicated (forward imagery)
  - curve begin and end, radius, curve left or right from driver perspective, signing (chevrons, etc)
  - Pavement marking condition (obscure, visible, etc)

Driver NB traversing right hand curve—Image source: UMTRI



UMTRI Data Reduction

- Data elements extracted from aerial imagery, crash data, forward imagery, or continuous data

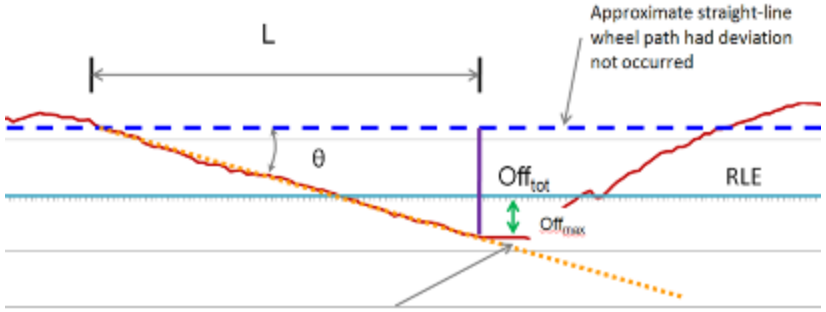
- **Environmental variables**
  - Ambient conditions
  - Roadway surface condition
  - Day, night, dawn/dusk
- **Exposure**
  - On-coming vehicle density
  - Right driveway density

Wet pavement
Image source: UMTRI

Low visibility due to fog, dust, etc Image source: UMTRI

UMTRI Data Reduction

- Event variables
  - Distance beyond lane edge
  - Departure angle
  - Begin and start point of event



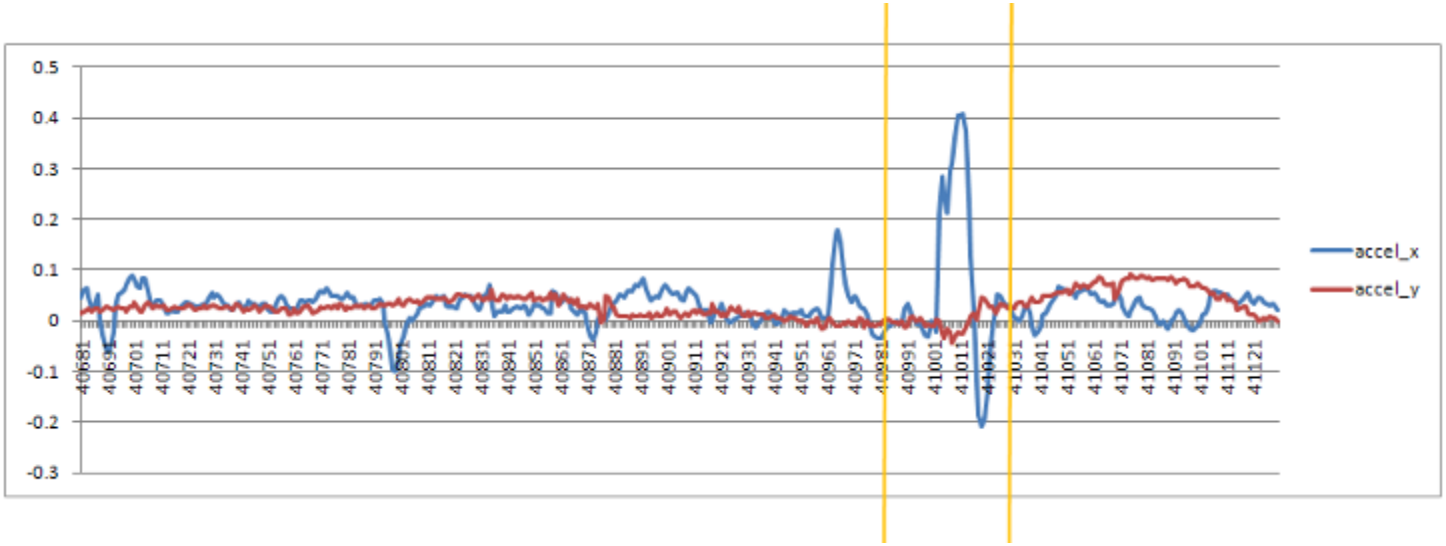
- Linked extracted variables to continuous data as well as event data

VTTI Data

- already reduced by event
  - Driver
    - Behaviors, impairment, distractions, driver reaction, control, obstructions, hands on wheel, fault
  - Vehicle
    - Maneuver, precipitating event
  - Roadway
    - Flow, lanes, density, traffic control, relation to junction, alignment
  - Environmental
    - Surface condition, weather
  - Event
    - Type, severity, number of vehicles

VTTI Continuous Data

- Continuous
  - Forward speed and accel, lateral accel, throttle position, time, event start and end, yaw rate, side acceleration



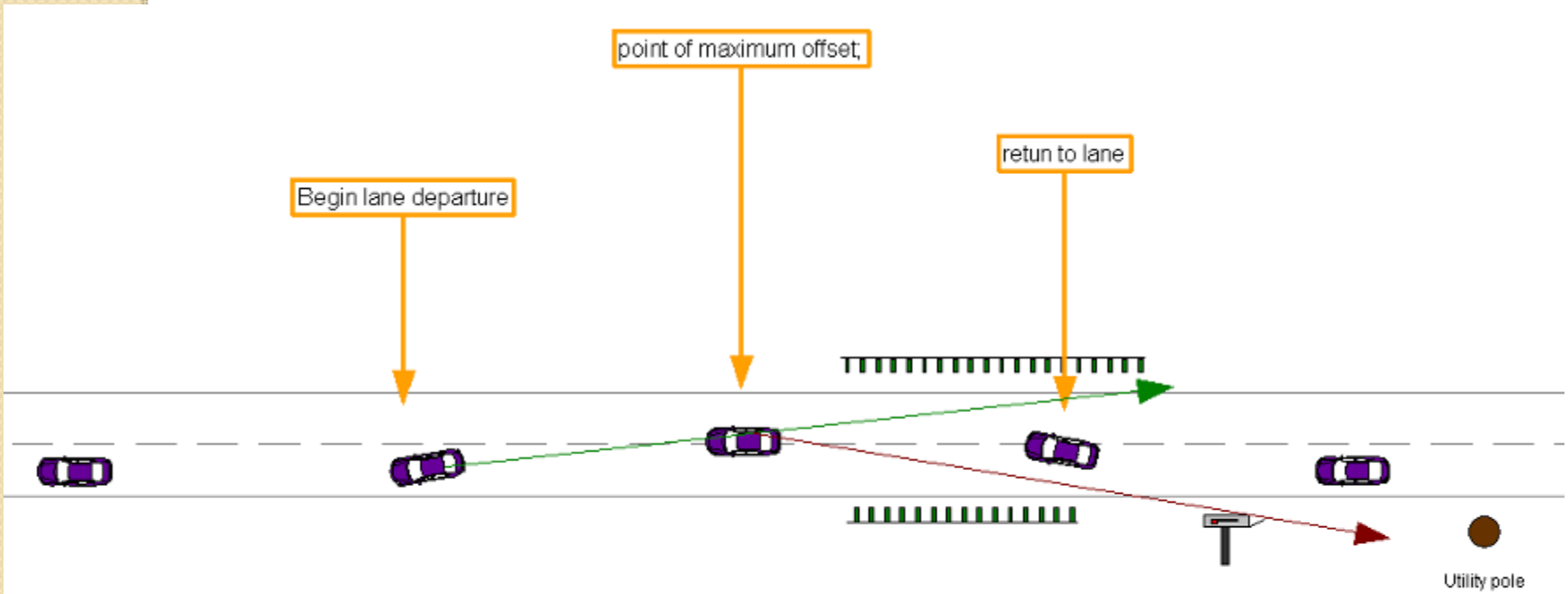
Lateral and forward acceleration before and after event: data source: VTTI

APPROACHES TO ANSWERING RESEARCH QUESTIONS

RQ 1: Identify Kinematic Variables to define crash surrogates

- Define crash surrogates
- Varies by surrogate and possible outcome(s) – hazard
- Potential surrogates
  - Non-departure lateral drift
  - Encroachment
  - Lane departure conflict (near-crash)
  - Lane departure crash

Potential outcome 1: continue path and strike guardrail (TTC = 1.05 sec)
Potential outcome 2: return to lane, over correct exit roadway, strike mailbox, (TTC = 1.34)
Potential outcome 3: encroach into gravel portion of roadway, lose control



Non-departure lateral drift

- Hazard: crossing lane line
- surrogate
  - Distance or time to lane departure
  - Departure angle

Encroachment

http://www.autoblog.com/tag/GrandVitara

- Low, medium, high risk
- FHWA and Iowa DOT lane departure – encroachments with one or unpaved shoulder are high risk events
- Hazard — shoulder (friction differential between roadway and shoulder surface can lead to loss of control)
  - Surrogate:
- Amount of encroachment
- Distance or time to edge of shoulder or ratio of shoulder used
- Roll potential

$$\text{rollover threshold (RT)} = \frac{a_{y,threshold}}{g} = \frac{t}{2h_{cg}} + \varphi - \frac{v^2}{Rg}$$

  - Determined equation based on what factors were likely to be available with naturalistic driving study and roadway data
    - i.e. no coefficient of friction or tire condition, super elevation

Encroachment

- Hazard — object or vehicle
  - Surrogate
    - Time to collision

Lane departure conflict

- Requires significant evasive maneuver
- Crash margin is less than some threshold (Campbell et al, 2003)
- Similar measures as for encroachment

Lane departure crash

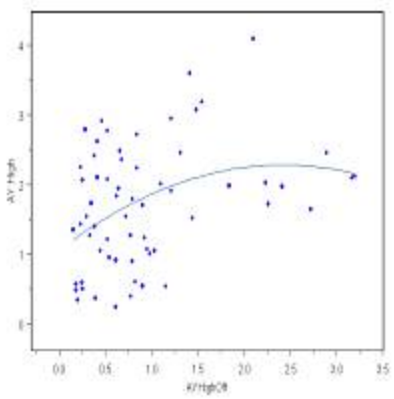
- Reported and unreported
- Strikes object or vehicle
- Overturns
- Vehicle inadvertently leaving roadway during winter weather event and coming to stop on shoulder or median without striking object or overturn??

Identify Kinematic Variables to define crash surrogates

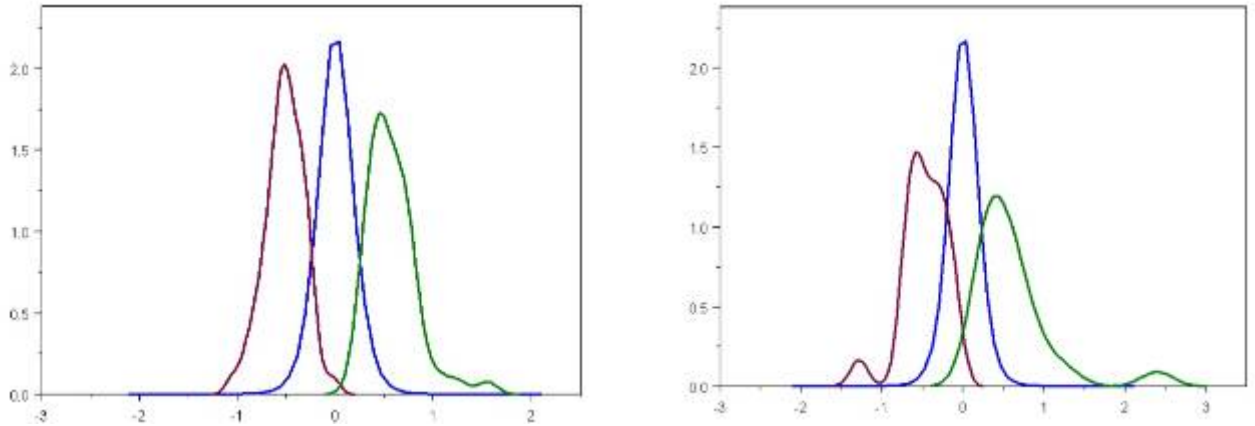
- Set threshold levels (triggers) to identify in full-scale study
  - e.g. lateral acceleration > 0.35 g
  - Setting thresholds too high "misses" events, too low includes many non-events (significant data reduction)
- May vary by driver, vehicle, roadway, environmental characteristics

Identify Kinematic Variables to define crash surrogates

- Continuous data provided vehicle kinematic variables
  - UMTRI – encroachments
  - VTTI – near-crash, crash



Scatter plot for Maximum Distance from Left Lane Line Versus Maximum Side Acceleration



Distributions of Lateral Speed (m/s) for Normal Driving Compared to Maximum Positive and Negative Values from Left Side (left image) and Right Side (right image) Lane Departures

Identify Kinematic Variables to define crash surrogates

- Compared incident to normal driving (UMTRI) data
  - Compared distributions
    - Forward and side acceleration, yaw rate, pitch rate, roll rate,
    - T-test or wilcoxon rank sum test
    - Differences between incidents and normally driving were usually significant but significant overlap exists for encroachment and normal driving
  - Addressed sample size needs
    - $N = \frac{(Z\sigma)^2}{(d)^2} = \frac{(2.58*0.256)^2}{(0.05)^2} = 173.5$ samples

Threshold Values

Table 1: Range of Maximum Negative and Positive Values for Left Lane Departure Events for UMTRI Data

Lateral speed (m/sec)		Yaw rate (deg/sec)		Side acceleration (g)	
Max negative	Max positive	Max negative	Max positive	Max negative	Max positive
-1.04 to -0.03	0.20 to 1.56	-13.3 to -0.2	0.10 to 6.15	-0.23 to -0.01	0.02 to 0.42
Forward acceleration (m/sec^2)		Roll rate (deg/sec)		Pitch rate (deg/sec)	
-0.13 to -0.03	0.03 to 0.13	-8.70 to -0.06	1.45 to 8.54	-5.64 to -0.13	0.48 to 10.19

Table 2: Range of Maximum Negative and Positive Values for Right Lane Departure Events for UMTRI Data

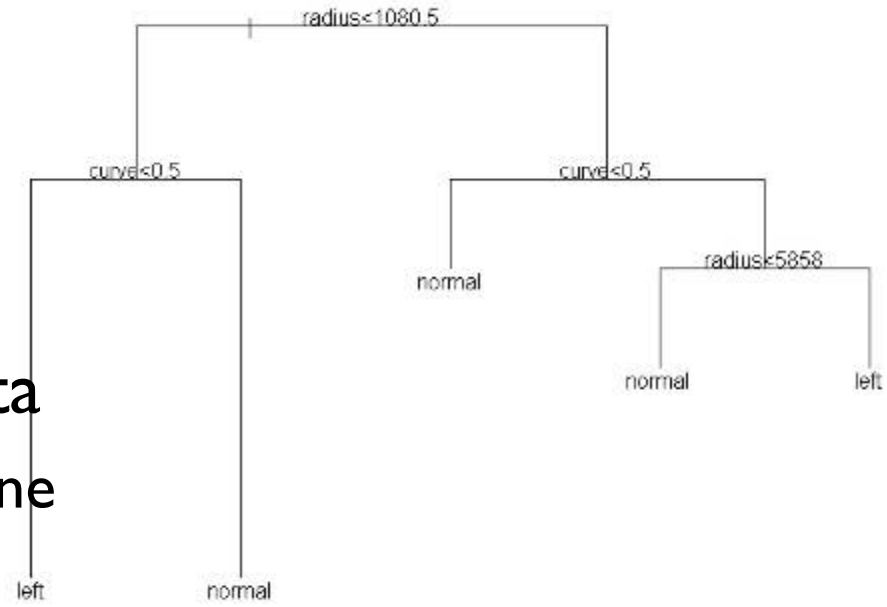
Lateral speed (m/sec)		Yaw rate (deg/sec)		Side acceleration (m/sec^2)	
Max negative	Max positive	Max negative	Max positive	Max negative	Max positive
-1.28 to -0.08	0.22 to 2.40	-1.90 to -0.05	0.15 to 12.20	-0.26 to -0.01	0.01 to 0.1
Forward acceleration (m/sec^2)		Roll rate (deg/sec)		Pitch rate (deg/sec)	
-0.14 to -0.02	0.01 to 0.07	-7.43 to -0.76	0.69 to 8.29	-5.86 to -0.81	1.05 to 6.26

Table 3: Range of Maximum Negative and Positive Values for VTTI Crash and Near-Crash Events

	Side acceleration (g)		Forward acceleration (g)	
	Max negative	Max positive	Max negative	Max positive
Left lane departure	-0.68 to -0.05	0.03 to 0.23	-0.80 to -0.03	0.03 to 0.74
Right lane departure	-2.69 to -0.01	0.08 to 0.29	-1.90 to -0.11	0.05 to 0.95

RQ 2: Identify factors related to lane departures (3 approaches)

- Data mining (Regression Tree Analysis)
  - Identify patterns in data
    - Relationship between lane departures and curve radius not consistent (i.e. radius < 700 meters similar relevant)
  - Screen variables
    - focus costly data reduction costly
    -



UMTRI data for left departures – initial results indicated curve radius, curve direction, and shoulder type were most relevant

RQ 2: Identify factors related to lane departures

- Event based analysis
  - Odds ratio
  - Logistic regression
  - Bayesian

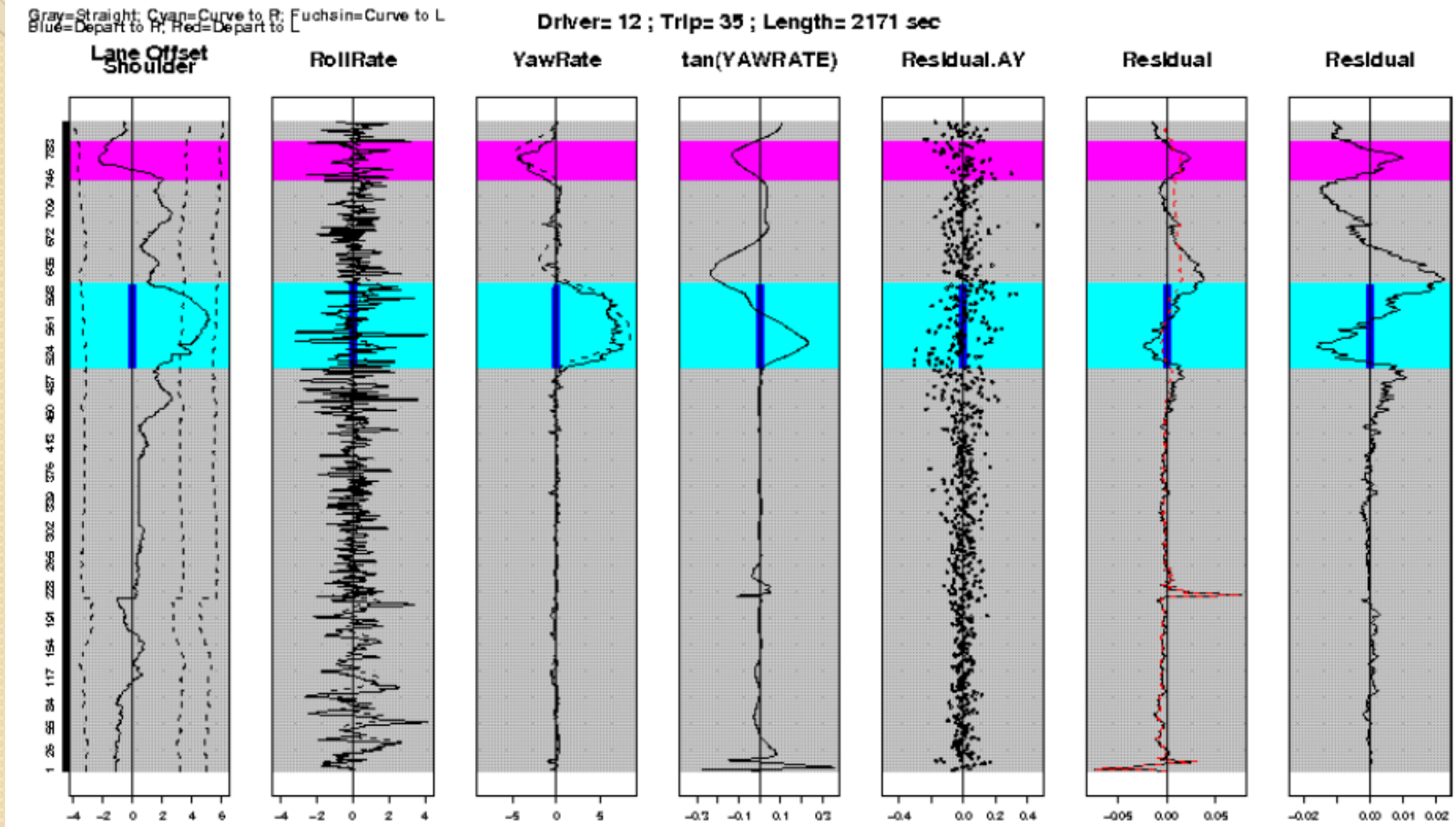
Variable	Left versus normal	CI	Right versus normal	CI
Radius < 200 m	10.9	(9.7, 12.3)	29.2	(25.4, 33.5)
400 Radius > = 200 m	32.8	(30.1, 35.9)	10.9	(9.6, 12.4)
600 m> radius >= 400 m	19.7	(17.8, 21.8)	22.1	(18.8, 25.9)
600 m >= radius	20.4	(18.4, 22.7)	13.6	(11.3, 16.4)
Wet vs. dry roadway	0.97	(0.9, 1.1)	Not enough samples	
Day vs. night/dusk	1.8	(1.7, 1.9)	0.38	(0.3, 0.4)
Male vs. female	0.8	(0.7, 0.8)	0.9	(0.8, 1.0)
Lane departure crash density for segment < 0.01 vs. >= 0.01	1.5	(1.3, 1.7)	1.1	(1.0, 1.1)
Shoulder width < 6 feet vs. >= 6 feet	1.0	(0.9, 1.1)	Not enough sample	

Odds ratio for left and right lane departure encroachments – UMTRI data
Curve radius most relevant
Limited analysis due to sample size

RQ 2: Identify factors related to lane departures

- Continuous data – Curve fitting model
  - Predicting driver behavior at time (t) as a function of driver responses, roadway factors, environmental factors using model fitting
  - Account for conditions in previous time steps (driver distraction, etc, time t-1)
  - Structure of relationships of variables (for one driver)
    - Response variables at time t (Y_t) are affected by
      - response variables before time t ($Y_{<t}$),
      - covariates at time t (X_t) and
      - covariates variables before time t ($X_{<t}$),
    - For each observed sequence (Y_1, Y_2, …., Y_t)
      The likelihood of observe this sequence is
      $f(Y_1|X_1)\ f(Y_2|Y_1, X_{\leq 2})\ f(Y_3|Y_{<3}, X_{\leq 3})$ ……$f(Y_t|Y_{<t}, X_{\leq t})$

RQ 2: Identify factors related to lane departures



RQ: Develop relationships between crash surrogates and crashes

- Developed crash surrogates and threshold levels
- Not enough data to conduct initial analysis

Products

- White paper SO1(E)-2: Methodology for Extraction of Data Elements from the UMTRI Naturalistic Driving Study Dataset
- White paper SO1(E)-3: Methodology for Extraction of Data Elements from the VTTI Naturalistic Driving Study Dataset
- White paper SO1(E)-4: Roadway, Driver, Environmental, and Vehicle Data Needs and Limitations to Address Lane Departures Using Naturalistic Driving Study Data
- White paper SO1(E)-5: Defining Crash Surrogate Thresholds Using Naturalistic Driving Study Data

Acknowledgements

- Thanks to
  - UMTRI and VTTI for sharing naturalistic driving study data
  - Michigan DOT for crash and roadway data
  - Iowa DOT for data