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TRANSPORTATION RESEARCH BOARD

Design of Interchange Loop Ramps and Pavement/ Shoulder Cross-Slope Breaks

Monday, November 13, 2017

2:00-3:30PM ET

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RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Examine how to design roundabout intersections that are right-sized for all modes of travel at the specific location.

Learning Objectives

At the end of this webinar, you will be able to:

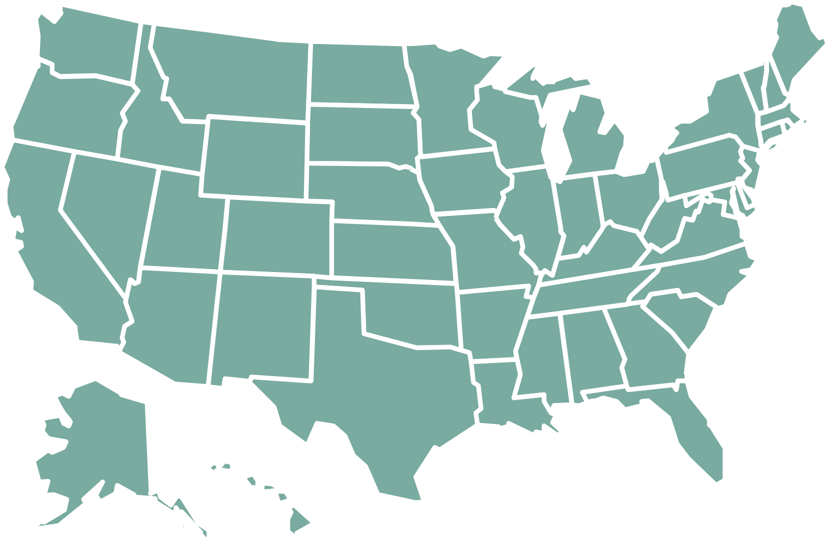
- Describe how to use the new design guidelines for loop ramps at service interchanges in both rural and urban areas
- Describe how to implement the Highway Safety Manual ramp crash prediction methodology to analyze the safety impacts of loop ramps and other ramp configurations
- Summarize research that supports AASHTO's current design policy for cross-slope breaks on superelevated horizontal curves
- Apply mitigation measures that reduce maximum roll angles experienced by errant vehicles that encroach onto the shoulders

NCHRP Web-Only Document 227: Design of Interchange Loop Ramps and Pavement/Shoulder Cross-Slope Breaks

NCHRP Project 3-105

NCHRP is a State-Driven Program

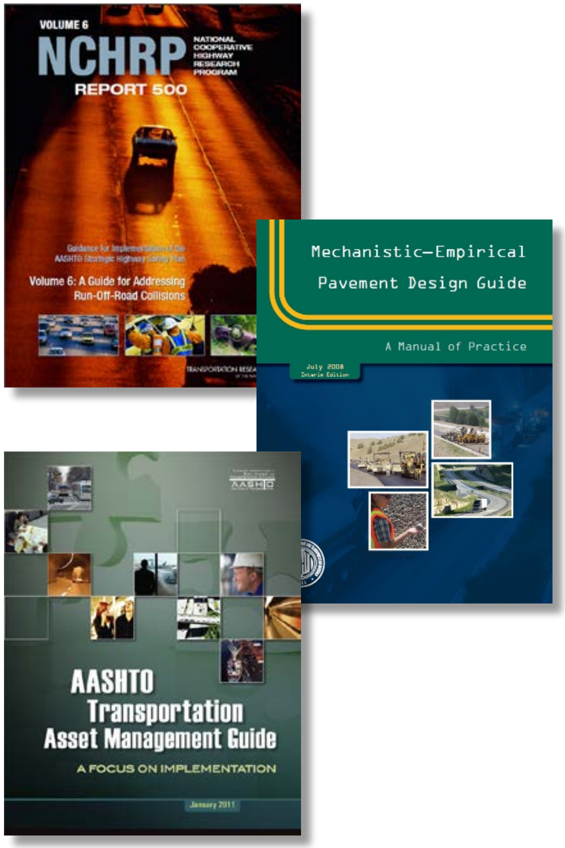
- Sponsored by individual state DOTs who
  - Suggest research of national interest
  - Serve on oversight panels that guide the research.



- Administered by TRB in cooperation with the Federal Highway Administration.

Practical, ready-to-use results

- Applied research aimed at state DOT practitioners
- Often become AASHTO standards, specifications, guides, syntheses
- Can be applied in planning, design, construction, operations, maintenance, safety, environment



Today's Speakers

- Speaker 1: Darren Torbic, Ph.D., MRIGlobal
  - Title: *Design Guidance for Interchange Loop Ramps*
- Speaker 2: Marcus Brewer, P.E., PMP, Texas A&M Transportation Institute
  - Title: *Assessment of Design Criteria for Pavement/Shoulder Cross-Slope Breaks*
- Moderator: Aaron Frits, P.E., Kansas DOT

NCHRP Web-Only Document 227: Part 1 Design Guidance for Interchange Loop Ramps

Darren Torbic,
MRIGlobal

TRB Webinar
November 13, 2017

Acknowledgements

- MRIGlobal
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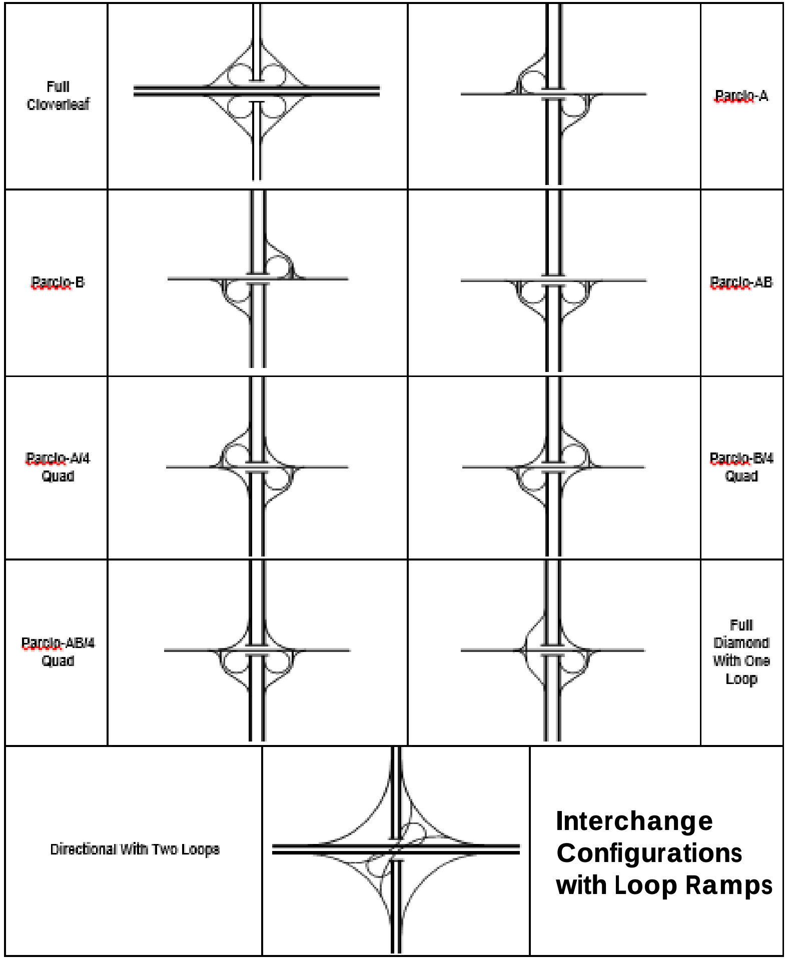
  - Raul Avelar
  - Michael Pratt

Outline

- Background
- Research objective
- Literature review
  - Current design policy on loop ramps
  - Safety and geometric design research
- Observational field study of loop ramps
- Application of HSM ramp crash prediction method to loop ramps
- Design guidance
- Conclusions and future research

Background

- Interchange projects are among most complex and expensive projects constructed by highway agencies
- Design decisions should be made wisely, considering factors such as safety, operations, right-of-way and environmental constraints, and nearby traffic generators
- Despite their long use, little research has been conducted on the design, safety, and operational characteristics of loop ramps



Interchange Configurations with Loop Ramps

Research Objective

- Develop improved design guidance for interchange loop ramps
- Key issues investigated:
  - Relationship between speed and lane position of vehicles and key design elements of ramp proper
  - Impact of key design elements on safety of loop ramps
  - Difference in performance on ramp proper of single-lane and multi-lane loop ramps

Current Design Policy on Loop Ramps

- Design guidance for loop ramps in *Green Book* is limited
  - *Green Book* Table 10-1 provides guidance for ramp design speeds
    - Ramp design speeds are specified for upper, middle, and lower range values given various conditions and ramp types
    - For loop ramps minimum values usually control

Guide Values for Ramp Design Speed as Related to Highway Design Speed

U.S. Customary										
Highway design speed (mph)	30	35	40	45	50	55	60	65	70	75
Ramp design speed (mph)										
Upper range (85%)	25	30	35	40	45	48	50	55	60	65
Middle range (70%)	20	25	30	33	35	40	45	45	50	55
Lower range (50%)	15	18	20	23	25	28	30	30	35	40
Corresponding minimum radius (ft)	See *Green Book* Table 3-7									

Current Design Policy on Loop Ramps

- Additional design guidance on loop ramps in *Green Book*
  - Practical radii of loop ramps
    - 100 to 170 ft for minor movements with highway design speeds of 50 mph or less
    - 170 to 250 ft for more important movements with higher highway design speeds
  - Design capacity for a single-lane loop ramp is between 800 to 1,200 vph

Current Design Policy on Loop Ramps

- Loop ramps located beyond a structure usually need parallel deceleration lane due to potential sight restrictions
  - A speed-change lane (SCL) should be developed on near side of structure and carried across structure if sight distance is limited
- A two-lane loop ramp should not be preceded or followed by another loop ramp
  - Radius of inner edge of traveled way of loop ramp should not be less than 180 to 200 ft
- *Green Book* refers to *ITE's Freeway and Interchange Geometric Design Handbook* for additional details on design of two-lane loop ramps

Review of Safety and Geometric Design Research

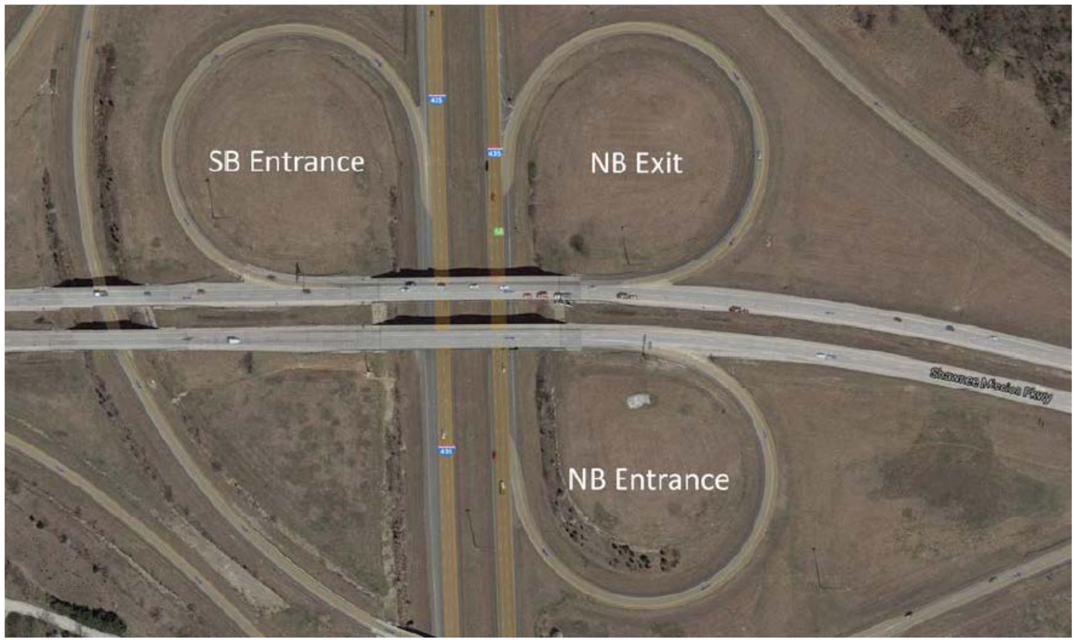
- Studies that investigated safety performance of loop ramps and relationship to geometric design elements:
  - Speed differentials between merging vehicles and vehicles on freeway are nearly identical for diagonal and loop ramps
  - Drivers exiting loop ramps tend to reduce their speed in freeway lane more, and decelerate along SCL at greater rate, than drivers exiting on diagonal ramps
  - Comparing diagonal, loop, and outer connection ramps, more crashes occur on exit ramps than entrance ramps
  - Loop ramps have higher crash rates than diagonal ramps
    - Exception is urban, free-flow loop ramps which have lower crash rates than diagonal ramps

Observational Field Study of Loop Ramp Proper

Observational Field Study of Loop Ramp Proper

- Observational field study of driver behavior and vehicle operations on ramp proper of loop ramps conducted to address:
  - Relationship between speed and lane position of vehicles and key design elements of ramp proper
  - Difference in performance on ramp proper between single- and multi-lane loop ramps
- Data collected at
  - 15 entrance and 13 exit ramps
    - 25 ramps located in urban areas and 3 located in rural areas
    - Ramps located in California, Kansas, Missouri, and Texas
    - All ramps located at service interchanges

Aerial Image of 3 Study Ramps



I-435 / Shawnee Mission Parkway
(Image Credit: Google Earth™ Mapping Service)

Characteristics of Study Locations and Ramp Proper

Ramp ID	State	Freeway	Freeway design speed (mph)	Posted speed limit on freeway (mph)	Crossroad	Posted speed limit on crossroad (mph)	Type of curve	Ramp design speed (mph)	Advisory speed for ramp (mph)	Number of lanes	Controlling Curve						Overall length of curves on ramp (ft)	Overall length of ramp (ft)
											Radius (ft)	Length (ft)	Super (%)	Inside shoulder width (ft)	Lane width (ft)	Outside shoulder width (ft)		
Entrance Ramps																		
1	MO	I-435	70	65	US 24	35	Comp	15	None	1	150	416	0.05	2.5	20.5	4.0	577	1225
2	KS	I-435	70	70	Shawnee Mission Pkwy	55	Comp	20	25	1	250	1030	0.05	9.5	14.6	6.8	1318	1418
3	KS	I-435	70	70	Shawnee Mission Pkwy	55	Comp	20	25	1	250	1018	0.05	10.1	14.4	7.5	1306	1406
4	MO	I-70	70	70	MO 65	65	Comp	15	25	1	177	344	0.05	6.3	17.3	5.3	1432	1747
5	TX	I-30	70	60	Hampton Rd	35	Comp	20	20	1	312	1434	0.04	6.0	14.5	4.0	1635	2007
6	TX	SH 360	70	60	E. Mid Cities Blvd	40	Simple	15	None	1	230	940	0.04	6.5	21.0	4.0	940	1445
7	TX	US-67	60	60	Loop 12	45	Comp	15	20	1	150	333	0.04	1.0	16.0	1.0	910	910
8	TX	US-67	60	60	Loop 12	45	Comp	15	20	1	125	254	0.04	1.0	16.0	1.0	888	951
9	TX	I-35	75	75	US-77/SH 579	60	Comp	15	None	1	200	458	0.04	8.0	14.0	2.0	1206	1253
10	TX	I-35	50	60	Commerce St	30	Comp	15	None	1	110	220	0.04	1.0	20.5	3.0	564	564
11	TX	FM 2818	50	50	Wellborn Rd	45	Simple	20	25	1	200	748	0.06	6.0	14.5	2.5	748	911
12	CA	I-5	65	65	Arena Blvd	40	Comp	20	None	2	186	377	0.07	8.0	13.1	3.75	537	787
13	CA	US 50	65	65	E. Bidwell	45	Simple	20	None	2	154	698	0.07	9.5	13.3	3.5	698	1448
14	CA	I-80	65	65	Elkhorn Rd	45	Simple	20	None	2	123	571	0.07	8.0	13.5	4.0	571	667
15	CA	I-80	65	65	Elkhorn Rd	45	Simple	20	None	2	122	566	0.07	6.5	14.0	4.0	566	766
Exit Ramps																		
16	MO	I-435	70	65	US 24	35	Comp	20	25	1	181	424	0.05	3.5	18.7	7.1	706	1384
17	KS	I-435	70	70	Shawnee Mission Pkwy	55	Comp	20	25	1	250	1048	0.05	10.3	15.0	6.8	1336	1436
18	MO	I-70	65	55	US 40	35	Comp	15	25	1	160	411	0.03	4.4	20.0	5.4	890	960
19	MO	I-70	65	55	US 40	35	Comp	15	25	1	160	447	0.05	4.2	20.9	4.3	822	892
20	KS	I-435	70	70	95th St.	40	Comp	20	None	1	300	861	0.05	12.8	15.2	6.6	1107	1307
21	MO	I-70	70	70	MO 65	65	Comp	15	25	1	218	809	0.04	6.0	17.2	6.25	1106	1263
22	TX	I-35E	50	60	Commerce St	30	Comp	20	20	1	104	260	0.05	1.0	20.0	4.0	458	575
23	TX	I-635	70	60	Freeport Pkwy	35	Simple	15	20	1	200	461	0.02	7.0	17.0	2.0	461	546
24	TX	I-635	70	60	Freeport Pkwy	35	Simple	15	20	1	200	461	0.02	7.0	17.0	3.0	461	551
25	TX	I-30	70	60	Hampton Rd	35	Comp	20	20	1	246	970	0.05	6.0	14.0	2.0	1477	1962
26	TX	SH 360	70	60	E. Mid Cities Blvd	40	Simple	15	30	1	230	1050	0.04	7.0	16.0	4.5	1050	1415
27	TX	FM 2818	50	50	Wellborn Rd	45	Simple	25	30	1	250	601	0.06	6.0	14.5	2.0	601	763
28	CA	SR 99	65	65	Sheldon Rd	45	Simple	20	30	3	171	557	0.07	8.5	14.2	3.5	557	1719

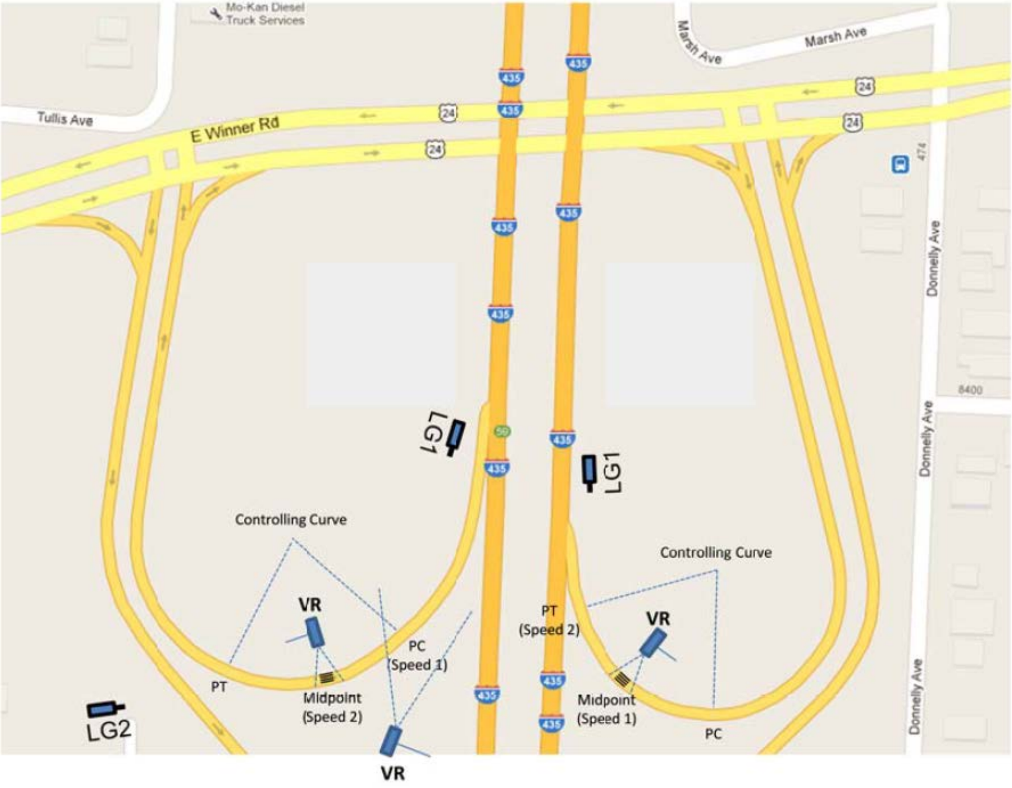
Field Data Collection

- Similar data collection activities at both entrance and exit ramps
- Data collected on weekdays, during non-peak hours

Primary Measures Collected in Field

- Entrance Ramps
  - Speeds of vehicles at midpoint and end of controlling curve in direction of travel on ramp
  - Positions of vehicles within roadway at midpoint of controlling curve
- Exit Ramps
  - Speeds of vehicles at beginning and midpoint of controlling curve in direction of travel on ramp
  - Positions of vehicles within roadway at midpoint of controlling curve
  - Unusual or critical behavior near beginning of controlling curve
    - For example: braking, swerving, or use of shoulder

Sample Field Setup



LG1 – Laser gun 1 LG2 – Laser gun 2 VR – Video recorder

Sample Images to Document Lane Positioning

Sample Images to Document Unusual or Critical Maneuvers at Exit Ramps

Analysis of Observational Data

- Vehicle speed
  - Entrance: 1,535 passenger vehicles, 252 trucks
  - Exit: 1,433 passenger vehicles, 146 trucks
- Lane position
  - Entrance: 1,526 passenger vehicles, 112 trucks
  - Exit: 1,465 passenger vehicles, 118 trucks
- Exit maneuvers
  - 1,286 passenger vehicles, 105 trucks

Analysis of Vehicle Speeds

- Developed regression models to estimate effect of key design elements on vehicle speeds
- Design elements considered in analyses included:

  - Ramp length
  - Design speed of controlling curve
  - Radius of controlling curve
  - Superelevation of controlling curve
  - Length of controlling curve
  - Inside shoulder width of controlling curve
  - Lane width of controlling curve
  - Outside shoulder width of controlling curve
  - Freeway speed limit
  - Crossroad speed limit
  - Vertical profile (grade, up or down)
  - Type of speed-change lane
  - Type of horizontal curvature (simple or compound curve)
  - Type of crossroad traffic control
  - Vehicle type

Speed Prediction Models to Estimate Vehicle Speeds at Midpoint and End of Controlling Curve on Ramp Proper of Entrance Loop Ramps

- At midpoint of controlling curve on entrance loop ramps, keeping everything else constant, vehicle speeds:
  - **Increase** by approximately:
    - 4.0 mph for every 100-ft incremental increase in **radius** of controlling curve (measured to inside of traveled way)
    - 0.3 mph for every 1-ft incremental increase of **lane width** of controlling curve
    - 0.9 mph for every 1-ft incremental increase of **outside shoulder width** of controlling curve
    - 0.7 mph for every 1-ft incremental increase of **inside shoulder width** of controlling curve
  - Vehicle speeds in outside lane of multilane ramp are approximately 2 mph faster than speeds in inside lane
  - Truck speeds are approximately 4.3 mph slower than speeds of passenger vehicles
- At end of controlling curve on entrance loop ramps, keeping everything else constant, vehicle speeds:
  - **Increase** by approximately:
    - 5.4 mph for every 100-ft incremental increase in **radius** of controlling curve (measured to inside of traveled way)
    - 1.1 mph for every 1-ft incremental increase of **outside shoulder width** of controlling curve
  - Vehicle speeds in outside lane of multilane ramp are approximately 1.4 mph faster than speeds in inside lane
  - Truck speeds are approximately 4.0 mph slower than speeds of passenger vehicles

Speed Prediction Models to Estimate Vehicle Speeds at Midpoint and Beginning of Controlling Curve on Ramp Proper of Exit Loop Ramps

- At midpoint of controlling curve on exit loop ramps, keeping everything else constant, vehicle speeds:
  - **Increase** by approximately:
    - 5.4 mph for every 100-ft incremental increase in **radius** of controlling curve (measured to inside of traveled way)
    - 1.0 mph for every 1-ft incremental increase of **outside shoulder width** of controlling curve
  - Vehicle speeds in outside lanes of multilane ramp are approximately 1.2 mph faster than speeds in inside lane
  - Truck speeds are approximately 4.9 mph slower than speeds of passenger vehicles
  - Vehicle speeds at midpoint of simple curve are approximately 3.6 mph faster than on ramps with compound curves
  - Vehicle speeds are expected to be approximately 2.9 mph faster following a lane drop, 4 mph faster following a parallel SCL, and 4.3 mph faster following a weave area compared to vehicle speeds on an exit loop ramp with a tapered SCL

- At beginning of controlling curve on exit loop ramps, keeping everything else constant, vehicle speeds:
  - **Increase** by approximately:
    - 9.0 mph for every 100-ft incremental increase in **radius** of controlling curve (measured to inside of traveled way)
  - Truck speeds are approximately 6.0 mph slower than speeds of passenger vehicles

Models to Estimate Vehicle Lane Position at Midpoint of Controlling Curve on Ramp Proper of Entrance and Exit Loop Ramps

- At midpoint of controlling curve on entrance loop ramps, keeping everything else constant, vehicle are expected to position themselves approximately:
  - 2 in. closer to inside lane line for each 1-ft increase in **outside shoulder width**
  - 5.3 in. closer to inside lane line for each 1-percent increase in **superelevation**
  - 1.7 in. closer to inside lane line for each 100-ft increase in controlling curve **length**
  - 15 in. closer to inside lane line if loop ramp is on an **upgrade**
  - 2.3 in. farther away from inside lane line for each 1-ft increase in **lane width**
  - 10 in. farther away from inside lane line when traveling in **outside lane** of multi-lane ramp compared to traveling in inside lane
  - No significant difference in lane positions between passenger vehicles and trucks

- At beginning of controlling curve on exit loop ramps, keeping everything else constant, vehicle are expected to position themselves approximately
  - 2.9 in. closer to inside lane line for each 1-percent increase in **superelevation**
  - 4.9 in. farther away from inside lane line for each 1-ft increase in **lane width**
  - 20.3 in. farther away from inside lane line when traveling in **outside lane** of multi-lane ramp compared to traveling in inside lane
  - 13.7 in. farther away from inside lane line if SCL preceding loop ramp is a **drop lane**
  - **Trucks** are positioned approximately 6.6 in. farther away from inside lane line than passenger vehicles

Key Findings from Qualitative Analysis of Exiting Maneuvers on Loop Ramps

- Majority of drivers entered loop ramps in a controlled manner
- Of 139 encroachments and critical maneuvers observed
  - 3 involved swerving or severe braking
  - 136 involved encroachments onto the shoulder
- Trucks are not overrepresented in number of encroachments and/or critical maneuvers that were observed
- Combinations of narrower lane width and higher approach speed at beginning of controlling curve showed a higher proportion of observed encroachments and critical maneuvers

Application of HSM Ramp Crash Prediction Method to Loop Ramps

Application of HSM Ramp Crash Prediction Method to Loop Ramps

- The HSM crash prediction methodology for ramp segments presented in HSM Chapter 19 does not separate procedures for specific ramp configurations, such as loop and diamond ramps
  - The same safety performance functions (SPFs) and crash modification factors (CMFs) are applied to both loop and diamond ramps
- Objective was to investigate how well HSM prediction method represents the safety performance of two ramp types (loop and diagonal) with distinctly different geometrics

Steps in Validation Approach

- Select sample of loop ramps for investigation, including both rural and urban ramps and both entrance and exit ramps
- Select similar sample of diamond ramps
- Review aerial photographs and highway agency records and obtain, for each ramp, all data needed to apply HSM crash prediction method for "ramp proper" area (i.e., not including ramp terminals)
- Apply HSM ramp crash prediction method to each loop and diamond ramp to obtain predicted number of ramp crashes per year, by severity level
- From highway agency records, obtain actual observed crash frequency, by severity level, for "ramp proper" area, for five-year period
- Compare predicted and observed crash frequencies, by ramp type and ramp configuration, to obtain calibration factors and compare appropriateness of HSM predictions for loop and diamond ramps

Study Ramps

- Database included 235 loop ramps and 243 diamond ramps
- Ramps were located in California and Washington
- Data were available from FHWA Highway Safety Information System (HSIS) to identify the location and configuration of specific ramps
- All ramps were located at service interchanges
- Loop ramps included both parclo loop ramps (which typically have a stop-controlled ramp terminal at the crossroad) and free-flow loop ramps (which typically have a free-flow speed-change lane at the crossroad)

Data Collection

- All data necessary to apply HSM ramp crash prediction method were obtained either from HSIS data files or measuring aerial photographs. Data included:

- Crash data from 2007 to 2011
- Area type (urban/rural)
- Ramp type (entrance or exit ramp)
- Ramp configuration (parclo or free-flow loop)
- Ramp average daily traffic volume (vpd)
- Ramp terminal characteristics
- Ramp length (mi)
- Number of lanes
- Lane width (ft)
- Ramp curve lengths (mi) and radii (ft)
- Shoulder widths (right and left) (ft)
- Freeway speed limit (mph)
- Speed limit at crossroad ramp terminal (mph)
- Ramp curve entry speeds (based on HSM Ch. 19 speed-prediction model)
- Barrier presence and length (mi)
- Presence/absence of ramp metering

Comparison of Predicted to Observed Crash Rates

State	Ramp type	Ramp configuration	Number of ramps	Crash rate per MVMT		Ratio of predicted to observed total crash rate	95% Confidence limits of ratio		Ratio significantly different from 1 at 5% significance level?
				Predicted	Observed		Lower	Upper	
TOTAL CRASHES (all crash severity levels combined)									
CA	Exit	Diamond	60	0.88	0.37	2.39	0.99	5.75	No
		Loop	**72**	**8.60**	**1.80**	**4.78**	**3.39**	**6.76**	**Yes**
	Entrance	Diamond	54	1.18	0.86	1.37	0.64	2.91	No
		Loop	**106**	**3.69**	**1.49**	**2.48**	**1.65**	**3.72**	**Yes**
WA	Exit	Diamond	48	1.40	1.36	1.03	0.56	1.90	No
		Loop	**21**	**6.57**	**2.45**	**2.68**	**1.53**	**4.68**	**Yes**
	Entrance	Diamond	48	0.73	0.43	1.69	0.67	4.21	No
		Loop	**30**	**3.12**	**0.94**	**3.30**	**1.66**	**6.55**	**Yes**
FATAL-AND-INJURY CRASHES									
CA	Exit	**Diamond**	**60**	**0.42**	**0.13**	**3.29**	**1.11**	**9.77**	**Yes**
		Loop	**72**	**3.10**	**0.62**	**4.97**	**3.04**	**8.15**	**Yes**
	Entrance	Diamond	54	0.42	0.17	2.41	0.53	10.98	No
		Loop	**106**	**1.39**	**0.36**	**3.87**	**1.77**	**8.46**	**Yes**
WA	Exit	Diamond	48	0.33	0.25	1.34	0.35	5.16	No
		Loop	**21**	**2.94**	**0.75**	**3.94**	**1.50**	**10.36**	**Yes**
	Entrance	Diamond	48	0.37	0.17	2.16	0.53	8.76	No
		Loop	**30**	**1.15**	**0.33**	**3.50**	**1.10**	**11.11**	**Yes**

Validation Results of HSM Ramp Crash Prediction Method to Loop Ramps

- Results indicate that HSM ramp crash prediction models in HSM Chapter 19 can be applied to both diamond and loop ramps
  - Without calibration, models overpredict effect of curvature on ramps
  - Overprediction of crashes is greater on loop ramps than on diamond ramps
  - Overprediction can be compensated by calibration of models
- To make accurate comparisons between loop and diamond ramps, separate calibration of HSM model for loop and diamond ramps is needed
  - If models are not calibrated separately, loop ramps will appear to have unrealistically high crash frequencies relative to diamond ramps
  - This could discourage designers from using loop ramps in situations where they would, in fact, perform well

Design Guidance

Design Guidance

- Based on research findings and existing design policies, design guidance related to ramp proper of loop ramps was developed addressing the following topics:
  - Recommended lane and shoulder widths
  - Multilane ramps
  - Safety prediction of design alternatives

Design Guidance: Recommended Lane and Shoulder Widths for Loop Ramps

- Speed prediction and lane position models were used along with ISATe safety prediction procedures to develop recommended lane and shoulder widths for ramp proper of loop ramps

- Guidance developed based on three general steps:
  - Apply speed prediction models for estimating speeds at midpoint of controlling curve
  - Use ISATe to compare predicted crash frequencies for different alternatives
  - Apply lane position model to remove alternatives that result in vehicles encroaching on shoulder or adjacent lane

Recommended Lane and Shoulder Widths Combinations for Controlling Curve on Entrance Loop Ramps

Design speed (mph)	Radius (ft)	Lane width (ft)	Outside shoulder width (ft)	Inside shoulder width (ft)
20	100	14 - 16	2	2
25	150	14	2	2 - 6
			3	3 - 5
		16	2	2 - 5
			3	3 - 4
		18	2	2 - 4
			3	3
		20	2	2 - 3
25	200	14	2	2 - 3
		16 - 20	2	2
30	200	14	2	4 - 10
			3	3 - 9
			4	4 - 8
			5	5 - 6
		16	2	3 -10
			3	3 - 8
			4	4 - 7
			5	5 - 6
		18	2	2 - 8
			3	3 - 7
			4	4 - 6
			5	5
		20	2	2 - 6
			3	3 - 5
			4	4
30	250	14	2	2 - 8
			3	3 - 6
			4	4 - 5
		16	2	2 - 7
			3	3 - 5
			4	4
		18	2	2 - 6
			3	3 - 4
		20	2	2 - 5
			3	3 - 4
30	300	14	2	2 - 5
			3	3
		16	2	2 - 4
			3	3
		18	2	2 - 3
		20	2	2
35	300	14	3	4 - 10
			4	4 - 9
			5	5 - 8
		16	2	5 - 10
			3	3 - 9
			4	4 - 8
			5	5 - 7
			6	6
		18	2	4 - 8
			3	3 - 7
			4	4 - 6
			5	5
		20	2	3 - 6
			3	3 - 5
			4	4

Recommended Lane and Shoulder Widths Combinations for Exit Loop Ramps **(Simple Curves)**

Design speed (mph)	Radius (ft)	Lane width (ft)	Outside shoulder width (ft)	Inside shoulder width (ft)
20	100	16	2	8 - 10
		18		6 - 8
		20		4 - 6
25	150	16	2	8 - 10
		18		6 - 8
		20		4 - 6
25	200	16	2	8 - 10
		18		6 - 8
		20		4 - 6
30	200	16	2	8 - 10
		18		6 - 8
		20		4 - 6
		16	3	7 – 9
		18		5 – 7
		20		3 – 5
30	250	16	2	8 – 10
		18		6 – 8
		20		4 – 6
35	300	16	2	8 – 10
		18		6 – 8
		20		4 – 6
		16	3	7 – 9
		18		5 – 7
		20		3 – 5

Recommended Lane and Shoulder Widths Combinations for Exit Loop Ramps **(Compound Curves)**

Design speed (mph)	Radius (ft)	Lane width (ft)	Outside shoulder width (ft)	Inside shoulder width (ft)
20	100	16	2	8 - 10
		18		6 - 8
		20		4 - 6
25	150	16	2	8 - 10
		18		6 - 8
		20		4 - 6
		16	3	7 - 9
		18		5 - 7
		20		3 - 5
		16	4	6 – 8
		18		4 – 6
		20		4
25	200	16	2	8 - 10
		18		6 - 8
		20		4 - 6
30	200	16	3	7 - 9
		18		5 - 7
		20		3 - 5
		16	4	6 – 8
		18		4 – 6
		20		4
		16	5	5 - 7
		18		5
30	250	16	2	8 - 10
		18		6 - 8
		20		4 - 6
		16	3	7 - 9
		18		5 - 7
		20		3 - 5
		16	4	6 – 8
		18		4 – 6
		20		4
35	300	16	3	7 - 9
		18		5 - 7
		20		3 - 5
		16	4	6 – 8
		18		4 – 6
		20		4
		16	5	5 - 7
		18		5

Design Guidance: Multilane Ramps

- Based upon speeds and lane positions of vehicles on multilane loop ramps, no special design considerations are necessary for multilane loop ramps to accommodate large differentials in speeds of vehicles traveling in outside lane or to accommodate vehicles in outside lane that encroach on inside travel lane

- For multilane loop ramps, outside lane widths of 12-ft for entrance ramps and 14-ft for exit ramps are sufficient to accommodate traffic comprised primarily of passenger vehicles
  - Where outside lane is expected to accommodate moderate to high volume of trucks, outside lane width should be increased

Design Guidance: Safety Prediction of Design Alternatives

- When implementing HSM ramp crash prediction methodology to estimate predicted and/or expected crash frequencies for individual ramps, separate calibration factors should be calculated for diamond and loop ramps
  - Will provide better comparison of safety performance of these two ramp types

Conclusions and Future Research

Conclusions: Entrance Ramps

- Speeds of vehicles at end of controlling curve are slightly higher than speeds at midpoint, indicating that vehicles accelerate while traversing controlling curve on ramp proper
- Key roadway and cross-sectional design elements that significantly influence vehicle speeds at midpoint of controlling curve include:
  - Curve radius
  - Lane width
  - Inside (right) shoulder width
  - Outside (left) shoulder width
- Key roadway and cross-sectional design elements that significantly influence vehicle speeds at end of controlling curve include:
  - Curve radius
  - Outside (left) shoulder width
- Key roadway and cross-sectional design elements that significantly influence lane position at midpoint of controlling curve include:
  - Lane width
  - Outside (left) shoulder width
  - Curve length
  - Superelevation
  - Grade
- As vehicles traverse an entrance loop ramp, passenger vehicles and trucks are positioned approximately an equal distance from inside lane line
  - Aside from offtracking issues associated with larger trucks, there are no major concerns associated with differences between lane positions of trucks and passenger vehicles

Conclusions: Exit Ramps

- Vehicle speeds are slightly higher at beginning of controlling curve than at midpoint, indicating that vehicles decelerate from freeway mainline ramp terminal along ramp proper
- Key roadway and/or cross-sectional design elements that significantly influence vehicle speeds at beginning of controlling curve include:
  - Curve radius
- Key roadway and cross-sectional design elements that significantly influence vehicle speeds include at midpoint of controlling curve include:
  - Curve radius
  - Outside (left) shoulder width
  - Type of curvature (simple or compound)
  - Type of mainline freeway ramp terminal
- Key roadway and cross-sectional design elements that significantly influence lane position at midpoint of controlling curve include:
  - Lane width
  - Type of mainline freeway ramp terminal
- Trucks are typically positioned farther away from inside lane line than passenger vehicles, and most passenger vehicles are positioned within travel lane
  - Positioning of trucks does not raise concerns about encroachment onto inside shoulder of exit ramp

Conclusions:

- Multilane ramps
  - Vehicles in outside lane (or lanes) travel at speeds approximately 1 to 2 mph faster than vehicles in inside lane
  - Vehicles traveling in outside lane are positioned slightly farther from inside lane line than vehicles traveling in inside lane
- HSM ramp crash prediction method
  - HSM ramp crash prediction methodology is better at predicting diamond ramp crashes than predicting loop ramp crashes
  - Separate calibration factors are needed for diamond and loop ramps for more accurate comparisons of safety performances of these different ramp types

Future Research

- Performance of trucks on multilane loop ramps
  - Few trucks were observed in outside lane of multilane loop ramps in current study
  - Desirable to expand upon this research and further evaluate difference in performance of single- and multilane ramps, focusing on performance of trucks operating in outside lanes
- Capacity of loop ramps
  - *Highway Capacity Manual* does not provide methodology to estimate capacity of loop ramps
  - More could be learned by further investigating capacity of loop ramps
- Practical size of loop ramps
  - Research needed to determine the "practical size" of a loop ramp, considering issues such as tradeoffs between desired speed, distance traveled, and construction and right-of-way costs

Questions?

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NCHRP Web-Only Document 227: Design of Interchange Loop Ramps and Pavement/Shoulder Cross-Slope Breaks

http://www.trb.org/Publications/Blurbs/175608.aspx

Effects of Cross-Slope Break on Roadway Departure Recovery of Trucks on Horizontal Curves

Marcus A. Brewer,
Texas A&M Transportation Institute

TRB Webinar
November 13, 2017

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  - Ray Derr

Background

- Tanker truck crash in 2009
- NTSB: review AASHTO policy on pavement/shoulder cross-slope break (CSB) on horizontal curves
- Became part of NCHRP 3-105

Image: Indiana State Police / NTSB

AASHTO Policy (Green Book)

- May be desirable for shoulder slope to be similar to travel way
- Cross-slope break (CSB) limited to about 8% and may be rounded
- Largely unchanged since at least 1990

Previous Research on CSB

- Basis for current policy: FHWA study in early 80’s by Glennon et al
- Developed 95th percentile vehicle path using moderate departure angle (HVOSM)
- Considered a single model of passenger car (no trucks)

Previous Research on Driver Behavior & Vehicle Trajectory

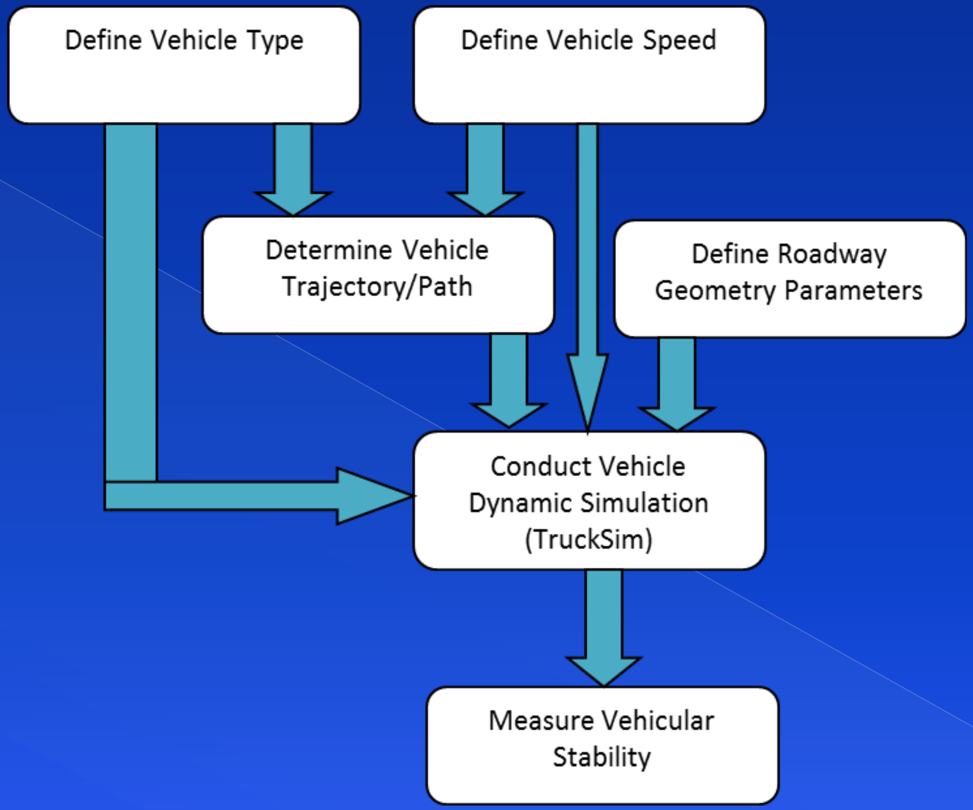
- SAE (1977)
  - avoidance steering angle of 210-230 degrees
  - no braking, 37 mph, 1.3 s to collision
- Kim et al (2005)
  - computer-assisted driving simulator study
  - maximum steering angle of 120-180 degrees
  - no braking, 31 mph, 1.3 s

Critical Design Elements

- Harwood et al (NCHRP Report 505):
  - CSB criteria sufficient for then-current fleet
  - Min. rollover threshold for trucks: 0.35 - 0.40 g
- Torbic et al (NCHRP Report 774):
  - Compared wet friction and skidding friction of cars and trucks

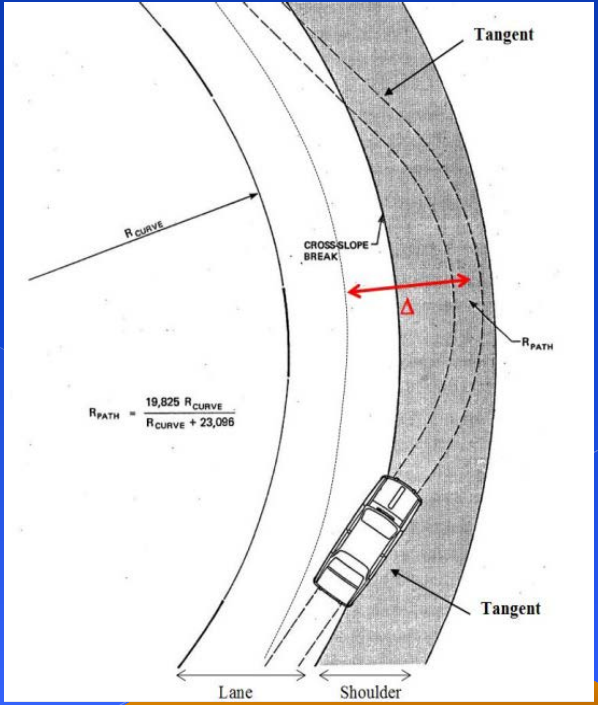
Vehicle Dynamics Simulation

- Crash-based analysis had small sample size
- Determine effect of CSB on recovery
- Combination of vehicle variables and roadway variables
- 12-ft travel lane, *Green Book* curve radii


Define Vehicle Type
Define Vehicle Speed
Determine Vehicle Trajectory/Path
Define Roadway Geometry Parameters
Conduct Vehicle Dynamic Simulation (TruckSim)
Measure Vehicular Stability

Vehicle Variables

- Type: 1 or 2 van trailers, 1 tanker trailer
- Trajectory/path:
  - Partial moderate departure
  - Full moderate departure
  - Full severe departure



Roadway Variables

- Superelevation: 4, 6, 8 percent
- CSB: 0, 4, 6, 8, 10 percent
- Design speed: 30, 50, 60, 70 mph
  - All vehicles initially simulated traveling at design speed of curve

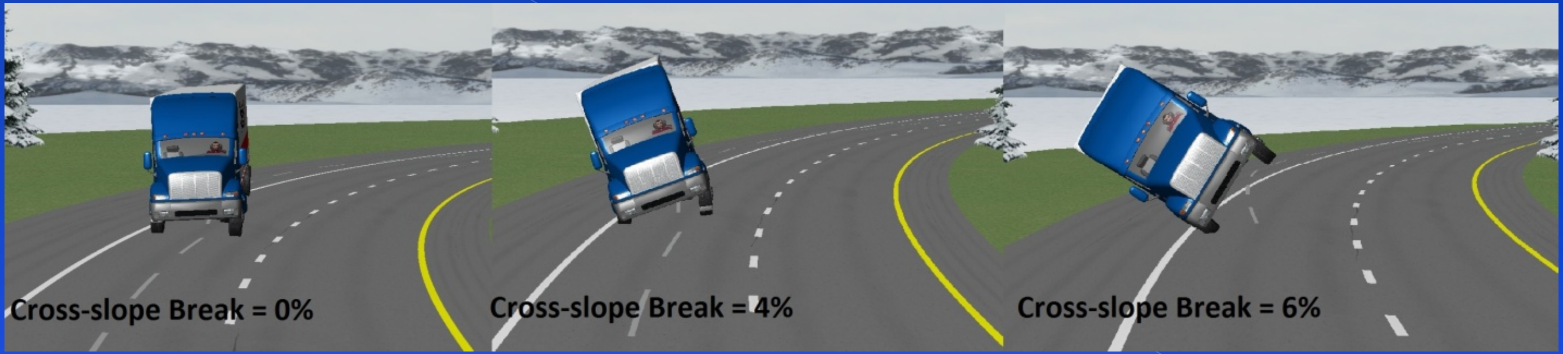
Preliminary Simulations (Full Severe Departure)

- Single-van trailer truck, superelevation = 4%

CSB	0%		4%		6%	
Speed (mph)	50	60	50	60	50	60
Recover?	Y	Y	Y	N	N	N/A
Max Neg Roll Angle	-6.2	-8.7	-9.1	N/A	N/A	N/A
Max Pos Roll Angle	8.4	11.8	21.5	N/A	N/A	N/A

Visual Illustration of Simulation

- Single-van trailer, 50 mph, 4% super



Summary of Simulation Results

- 186 scenarios
  - 116 single-van trailer
  - 53 tanker trailer
  - 17 double-van trailer
- Stability based on maximum positive roll angle and recovery

Results: Single-Van Trailer

- Maximum roll angle:
  - Increased with CSB
  - Decreased with superelevation
  - Decreased with vehicle speed, up to 60 mph
- Recovered for all moderate departure
- Recovered for severe with CSB < 6% and/or speed = 30 mph

Recovery from Moderate Departure

Single-van trailer, 70 mph, 8% super, 8% CSB

Rollover from Severe Departure

Single-van trailer, 70 mph, 8% super, 8% CSB

Results: Tanker Trailer

- Eight scenarios with rollover potential in single-van trailer, same roll angle trends
- Recovered for all moderate departure
- Recovered for severe departure with:
  - CSB = 0% and speed ≠ 60 mph
  - CSB = 6% and speed = 30 mph

Results: Double-Van Trailer

- Full-wheel departure scenarios with rollover potential in single-van trailer
- Higher roll angles than single-van trailer
- Recovered for all moderate departure
- Did not recover for any severe departure

Summary

- Maximum roll angles varied by departure
- Rollovers in positive direction
- Roll angles increased with CSB
- Roll angles decreased with superelevation
- Roll angles mostly decreased with speed
- Tanker and single-van trailers similar

Conclusions

- No evidence to suggest a change to the 8% threshold in the *Green Book*
- Some evidence to suggest 10% with high super, but existing 8% is more conservative
- Research on tanker liquid dynamics when more sophisticated models are available
- Research to increase sample of crash data

Questions?

- Marcus A. Brewer, P.E.

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