DRIVER BEHAVIOR AND BICYCLE SAFETY ON RURAL ROADS WITH RUMBLE STRIPS

NCHRP 17-106

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Overview

- **Roadway departure crashes**
  - Cross over centerline, edge line, or leave travelway
  - 66% of fatal crashes on rural two-lane roads
- **Rumble strips**
  - Cost-effective countermeasure
  - Concerns with noise, pavement durability, bicyclists
- **Rumble strips impact on bicyclist safety?**

Objectives

1. Characterize motorist behavior while passing bicyclists
2. Quantify safety impacts of rumble strips on bicyclist safety
3. Develop guidance for rumble strips application

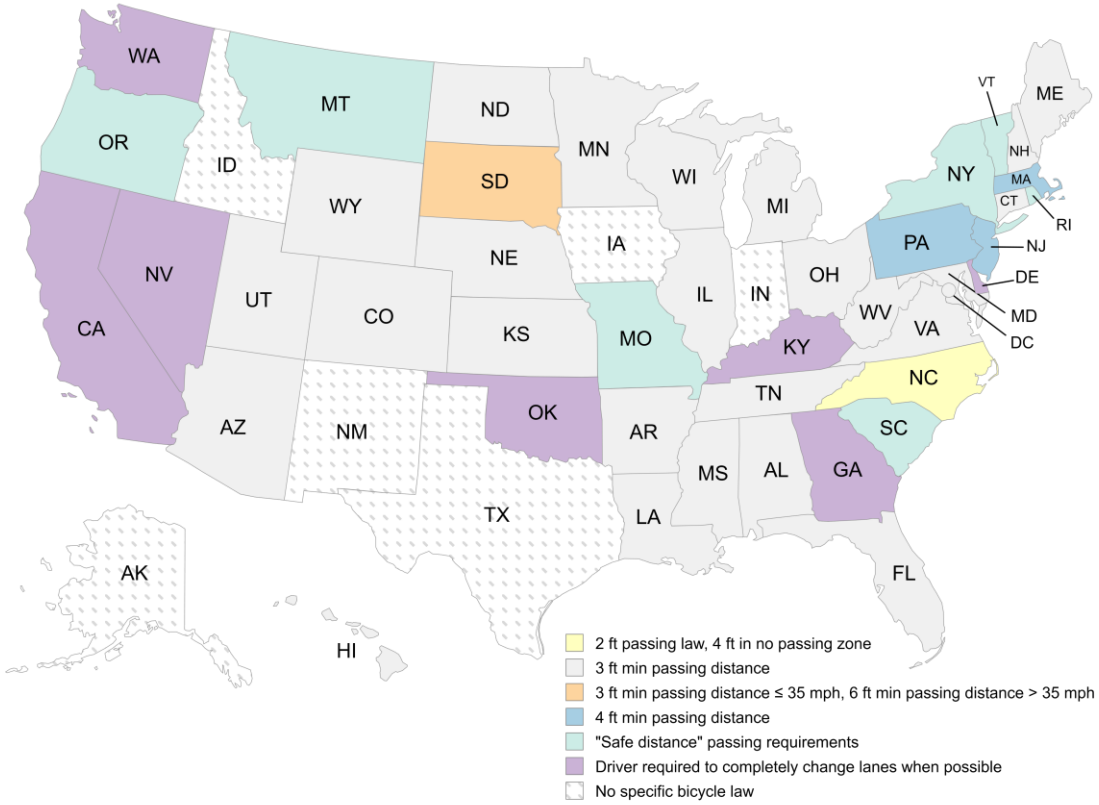
State Laws

Minimum passing distance

State laws

Minimum passing distance

- 36 states at least 3 ft
- No-passing zones
- Speed based
- Safe distance
- Change lanes



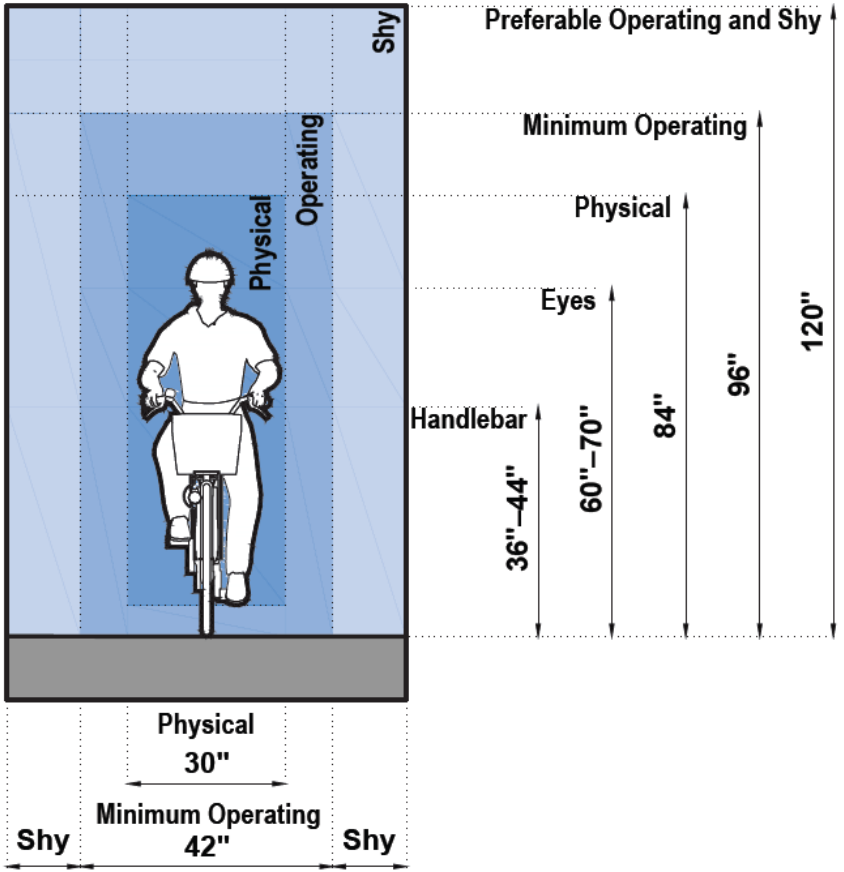
Design guidance

Rumble strips

Design guidance

Typical bicyclist

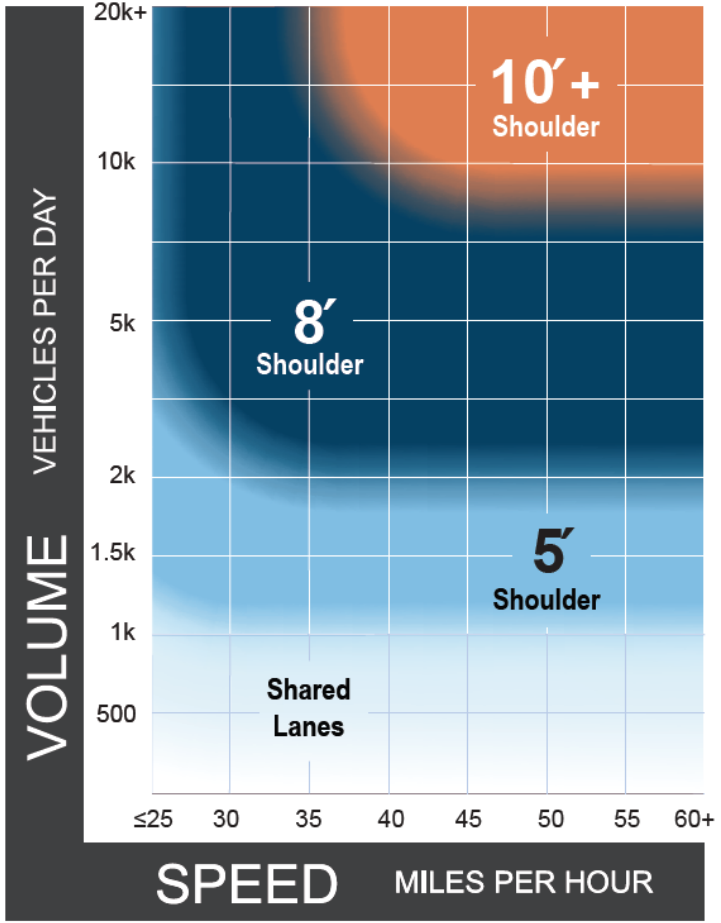
- Physical space
- Operating space
- Shy space



Design guidance

Shoulder width

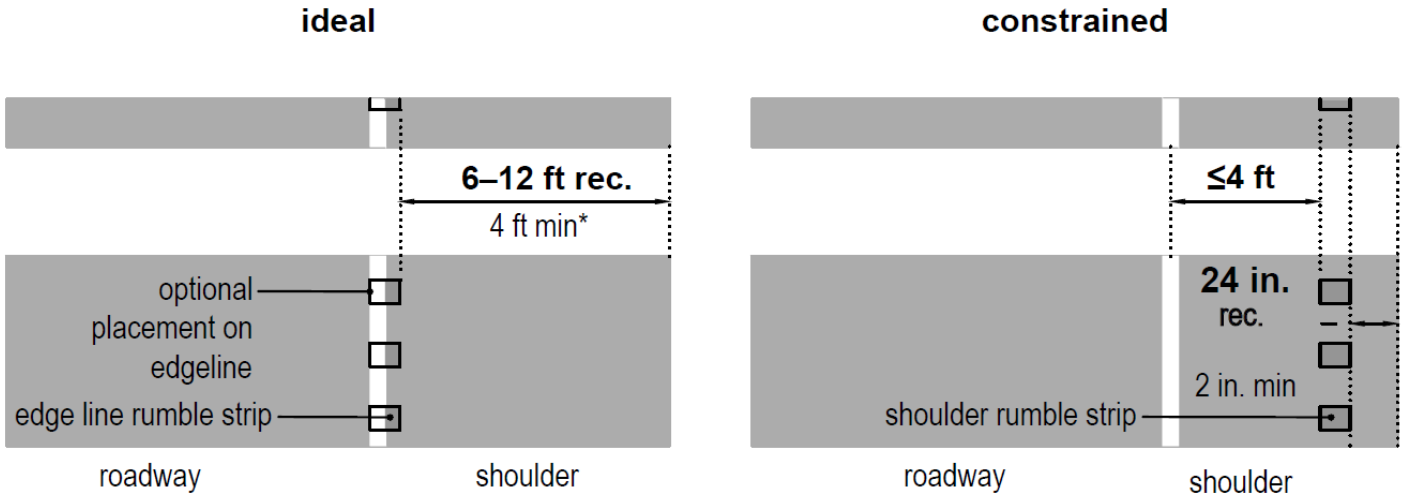
- Speed limit
- Vehicles per day



Design guidance

Rumble strip configuration

- 4 ft min clear shoulder space
- Ideal and constrained space



* 5 ft minimum if adjacent curb, guardrail, vertical element, or obstacle

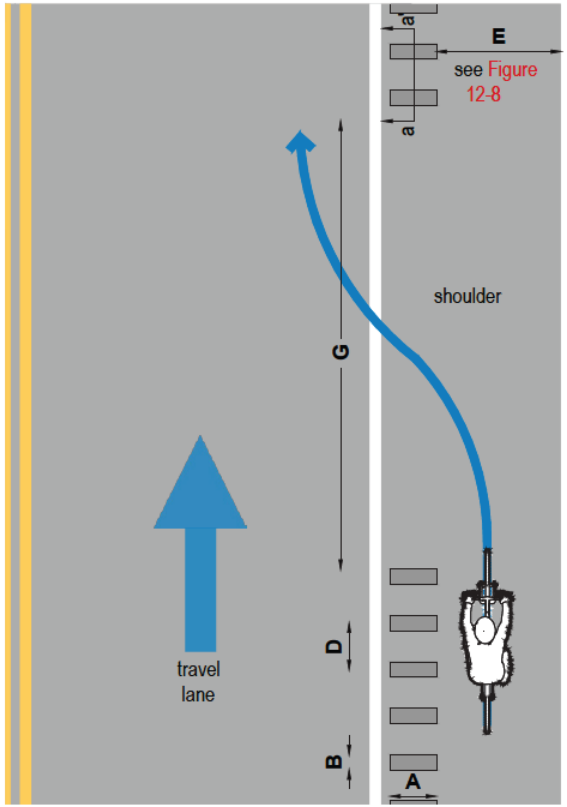
Design guidance

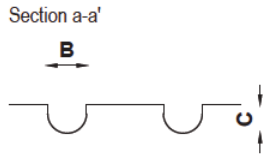
Rumble strip gaps

- Lane change
- High speed
- Shoulder debris
- Blocked shoulder

Definitions	
Length (A)	Dimension of rumble strip measured lateral to the travel lane
Width (B)	Dimension of rumble strip measured parallel to the travel lane
Depth (C)	Vertical distance measured from top of pavement surface to bottom of a rumble strip pattern
Spacing (D)	Dimension between rumble strip patterns
Clear Path (E)	Distance from outside (for example, right) edge of rumble strip to oustide edge of paved shoulder
Gap (G)	Distance measured parallel to roadway, between groups of rumble strip patterns

*Note: Figure not to scale.



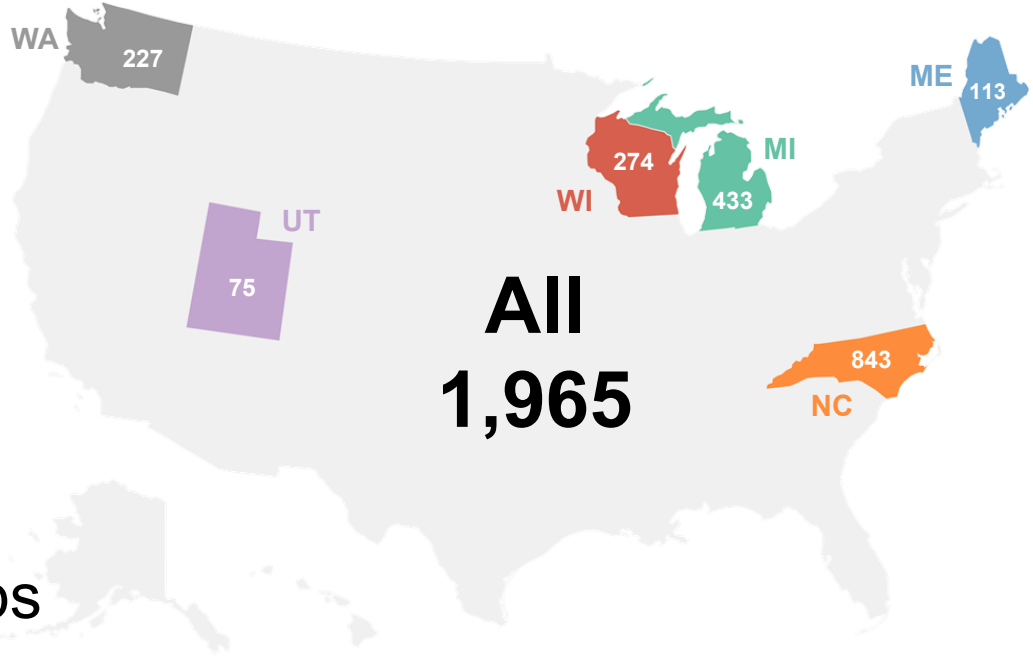


Bicycle Crash Analysis

Descriptive statistics
Crash patterns
Crash severity modeling
Crash frequency modeling

Bicycle crash data

- **Crash reports**
  - 6 states
  - 1,965 crashes
  - Manual review
- **Crash patterns**
- **Injury severity**
- **Crash frequency**
  - 2 states (WI and MI)
  - Sites with rumble strips



Descriptive statistics

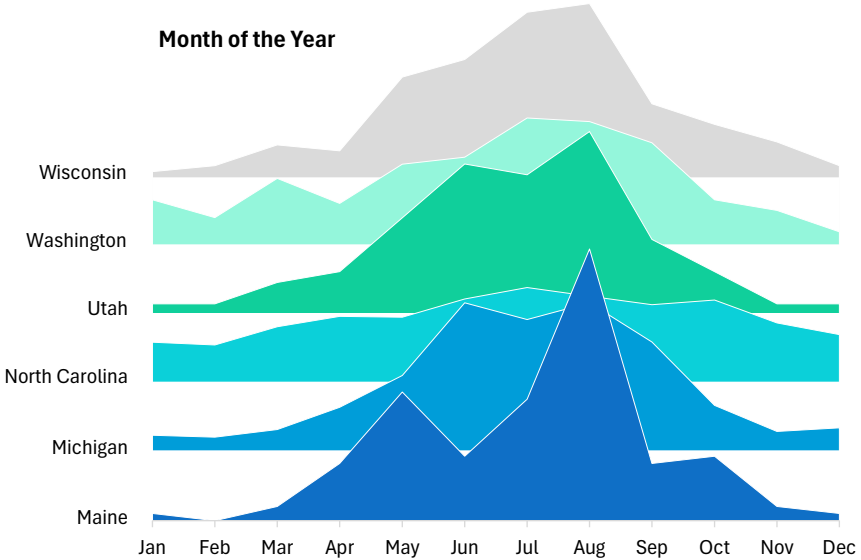
Road features

Roadway features		Maine		Michigan		North Carolina		Utah		Washington		Wisconsin		All	Weighted distribution
Speed limit	40 mph	0	*0.0%*	0	*0.0%*	0	*0.0%*	33	*44.0%*	24	*10.6%*	11	*4.0%*	**68**	***1.0%***
	45 mph	55	*48.7%*	0	*0.0%*	271	*32.1%*	10	*13.3%*	59	*26.0%*	76	*27.7%*	**471**	***25.8%***
	50 mph	38	*33.6%*	1	*0.2%*	33	*3.9%*	11	*14.7%*	88	*38.8%*	4	*1.5%*	**175**	***5.2%***
	55 mph	20	*17.7%*	424	*97.9%*	539	*63.9%*	9	*12.0%*	42	*18.5%*	183	*66.8%*	**1,217**	***67.2%***
	60 mph	0	*0.0%*	1	*0.2%*	0	*0.0%*	5	*6.7%*	11	*4.8%*	0	*0.0%*	**17**	***0.3%***
	65 mph	0	*0.0%*	7	*1.6%*	0	*0.0%*	7	*9.3%*	3	*1.3%*	0	*0.0%*	**17**	***0.4%***
Facility type	Segment	58	*51.3%*	290	*67.0%*	621	*73.7%*	45	*60.0%*	138	*60.8%*	169	*61.7%*	**1,321**	***70.6%***
	Intersection	36	*31.9%*	114	*26.3%*	148	*17.6%*	21	*28.0%*	67	*29.5%*	80	*29.2%*	**466**	***20.8%***
	Driveway	19	*16.8%*	29	*6.7%*	74	*8.8%*	9	*12.0%*	22	*9.7%*	25	*9.1%*	**178**	***8.6%***
Alignment	None	1	*0.9%*	154	*35.6%*	139	*16.5%*	19	*25.3%*	38	*16.7%*	73	*26.6%*	**424**	***20.5%***
	Vertical grade	53	*46.9%*	236	*54.5%*	374	*44.4%*	17	*22.7%*	118	*52.0%*	149	*54.4%*	**947**	***47.2%***
	Horizontal curve	4	*3.5%*	18	*4.2%*	38	*4.5%*	5	*6.7%*	10	*4.4%*	22	*8.0%*	**97**	***4.7%***
	Both	55	*48.7%*	25	*5.8%*	292	*34.6%*	34	*45.3%*	61	*26.9%*	30	*10.9%*	**497**	***27.6%***
Pavement marking	None	9	*8.0%*	4	*0.9%*	5	*0.6%*	5	*6.7%*	0	*0.0%*	40	*14.6%*	**63**	***1.8%***
	Centerline yellow	5	*4.4%*	39	*9.0%*	3	*0.4%*	6	*8.0%*	11	*4.8%*	31	*11.3%*	**95**	***3.0%***
	Edgeline white	0	*0.0%*	0	*0.0%*	0	*0.0%*	1	*1.3%*	0	*0.0%*	0	*0.0%*	**1**	***0.0%***
	Both	99	*87.6%*	390	*90.1%*	835	*99.1%*	63	*84.0%*	216	*95.2%*	203	*74.1%*	**1,806**	***95.2%***
Passing zone	Yes	14	*12.4%*	206	*47.6%*	104	*12.3%*	10	*13.3%*	54	*23.8%*	68	*24.8%*	**456**	***20.1%***
	No	92	*81.4%*	218	*50.3%*	735	*87.2%*	60	*80.0%*	173	*76.2%*	166	*60.6%*	**1,444**	***78.0%***
	Not applicable	7	*6.2%*	9	*2.1%*	4	*0.5%*	5	*6.7%*	0	*0.0%*	40	*14.6%*	**65**	***1.9%***
Paved shoulder	Yes	63	*55.8%*	247	*57.0%*	271	*32.1%*	60	*80.0%*	161	*70.9%*	115	*42.0%*	**917**	***39.8%***
	No	50	*44.2%*	186	*43.0%*	572	*67.9%*	15	*20.0%*	66	*29.1%*	159	*58.0%*	**1,048**	***60.2%***
Rumble strips	None	106	*93.8%*	329	*76.0%*	840	*99.6%*	63	*84.0%*	163	*71.8%*	260	*94.9%*	**1,761**	***93.5%***
	Centerline	7	*6.2%*	84	*19.4%*	1	*0.1%*	7	*9.3%*	47	*20.7%*	9	*3.3%*	**155**	***5.0%***
	Shoulder	0	*0.0%*	1	*0.2%*	0	*0.0%*	0	*0.0%*	3	*1.3%*	2	*0.7%*	**6**	***0.2%***
	Both	0	*0.0%*	19	*4.4%*	2	*0.2%*	5	*6.7%*	14	*6.2%*	3	*1.1%*	**43**	***1.4%***
Total crashes		**113**	***5.8%***	**433**	***22.0%***	**843**	***42.9%***	**75**	***3.8%***	**227**	***11.6%***	**274**	***13.9%***	**1,965**	***100.0%***

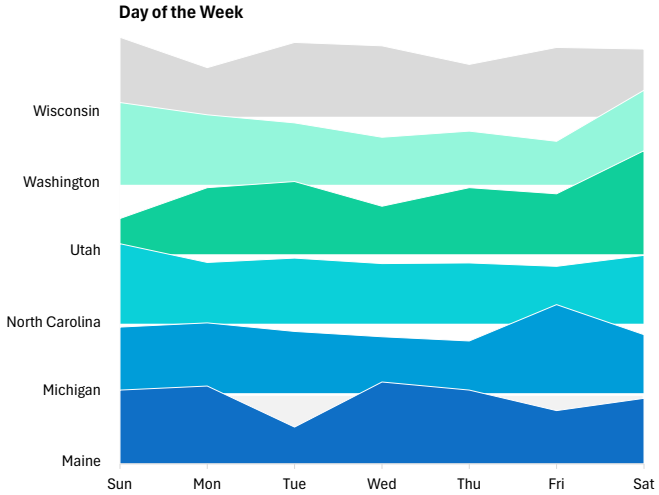
Notes: Crash count and *percentage*.

Temporal variation

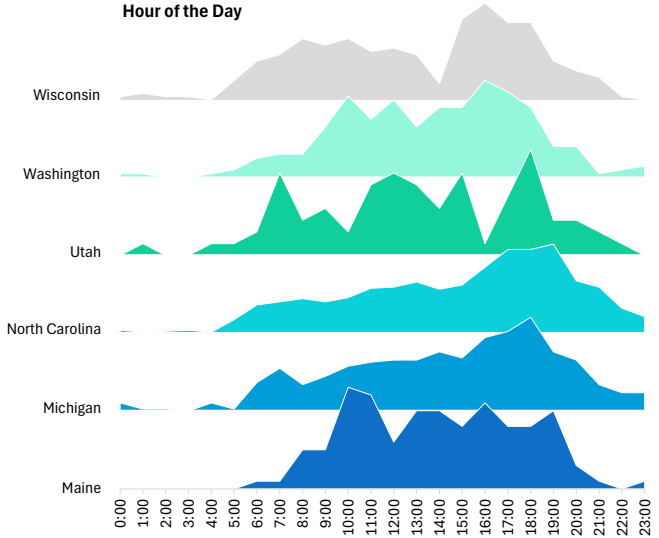
Month



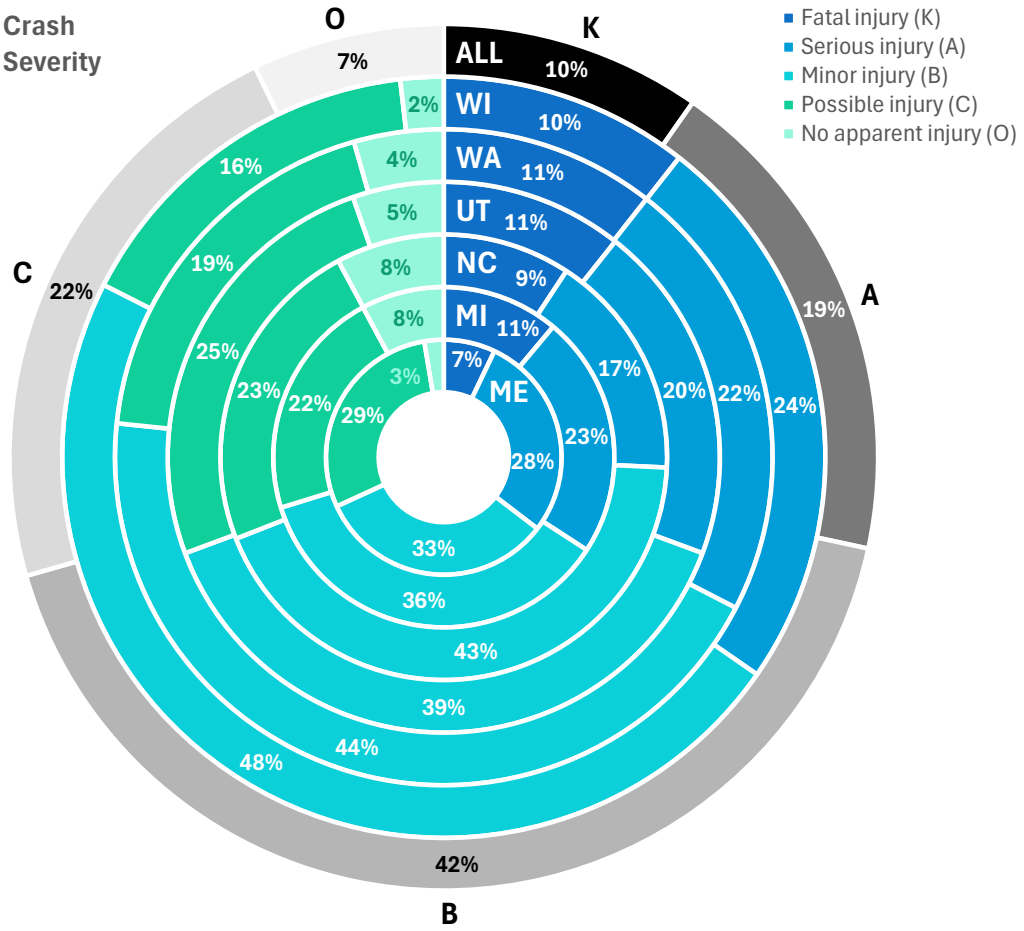
Day



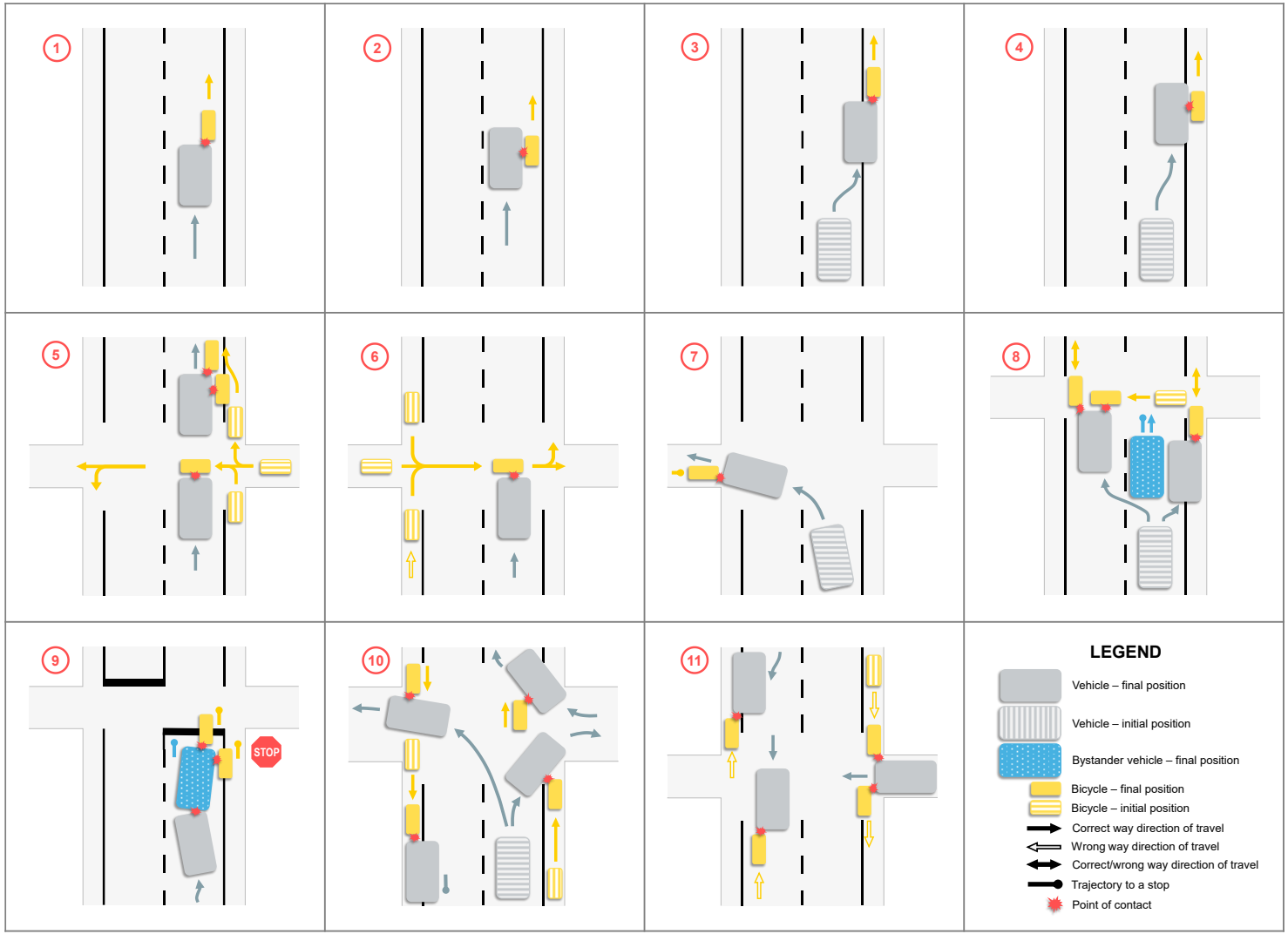
Hour



Crash severity



Crash patterns



Crash patterns

1. Rear end crash with bicyclist in the lane
2. Sideswipe crash with bicyclist in the lane
3. Rear end crash with bicyclist on the shoulder
4. Sideswipe crash with bicyclist on the shoulder
5. Bicyclist encroaching vehicle's right-of-way from the right side
6. Bicyclists encroaching vehicle's right-of-way from the left side
7. Sharp turning vehicle at intersection striking stopped bicyclist
8. Vehicle overtaking or shortening path at horizontal curves
9. Vehicle(s) loss of control at a stop intersection approach
10. Vehicle going over the bicyclist's right-of-way
11. Wrong-way bicyclist

Crash Type	Maine		Michigan		North Carolina		Utah		Washington		Wisconsin		All	Weighted Distribution
1	16	*14.2%*	65	*15.0%*	204	*24.2%*	2	*2.7%*	35	*15.4%*	42	*15.3%*	**364**	***21.2%***
2	10	*8.8%*	43	*9.9%*	158	*18.7%*	8	*10.7%*	28	*12.3%*	45	*16.4%*	**292**	***16.5%***
3	5	*4.4%*	61	*14.1%*	45	*5.3%*	7	*9.3%*	18	*7.9%*	21	*7.7%*	**157**	***7.2%***
4	16	*14.2%*	51	*11.8%*	59	*7.0%*	6	*8.0%*	24	*10.6%*	34	*12.4%*	**190**	***8.5%***
5	28	*24.8%*	120	*27.7%*	188	*22.3%*	16	*21.3%*	56	*24.7%*	53	*19.3%*	**461**	***23.2%***
6	1	*0.9%*	6	*1.4%*	32	*3.8%*	1	*1.3%*	9	*4.0%*	14	*5.1%*	**63**	***3.4%***
7	1	*0.9%*	3	*0.7%*	11	*1.3%*	0	*0.0%*	2	*0.9%*	4	*1.5%*	**21**	***1.2%***
8	2	*1.8%*	3	*0.7%*	14	*1.7%*	2	*2.7%*	2	*0.9%*	7	*2.6%*	**30**	***1.5%***
9	3	*2.7%*	5	*1.2%*	3	*0.4%*	2	*2.7%*	1	*0.4%*	1	*0.4%*	**15**	***0.5%***
10	24	*21.2%*	64	*14.8%*	86	*10.2%*	25	*33.3%*	45	*19.8%*	46	*16.8%*	**290**	***12.2%***
11	7	*6.2%*	12	*2.8%*	43	*5.1%*	6	*8.0%*	7	*3.1%*	7	*2.6%*	**82**	***4.4%***
Total	**113**	***5.8%***	**433**	***22.0%***	**843**	***42.9%***	**75**	***3.8%***	**227**	***11.6%***	**274**	***13.9%***	**1,965**	***100.0%***

Injury severity modeling

Ordinal logistic regression

- CLRS+SRS not statistically significant, when paved shoulders are wide enough for bicyclists
- When narrow or no paved shoulders, CLRS increase severity
- Rest of the variables are significant

Model Coefficients[1]		Value	Std. Error[2]	t value	p-value	Odds Ratio	CI (5%, 95%)[3]
Slope	SP	0.342	0.105	3.258	0.001	1.408	1.18, 1.67
	POS	0.198	0.114	1.741	0.082	1.219	1.01, 1.47
	LGH	0.237	0.108	2.191	0.028	1.268	1.06, 1.52
	AD	0.637	0.150	4.253	< 0.001	1.891	1.48, 2.42
	HR	-0.322	0.126	-2.551	0.011	0.724	0.59, 0.89
	CLRS	0.510	0.271	1.884	0.060	1.665	1.06, 2.60
	CLRS+SRS	-0.100	0.208	-0.480	0.632	0.905	0.64, 1.27
Intercept	C|B	-1.155	0.181	-6.369	< 0.001	N/A	N/A
	B|A	0.829	0.181	4.590	< 0.001	N/A	N/A
	A|K	2.179	0.190	11.451	< 0.001	N/A	N/A

Notes: [1] SP = speed limit, POS = bicyclist position, LGH = light condition, AD = alcohol or drugs, HR = hit and run, CLRS = centerline rumble strips, CLRS+SRS = centerline and shoulder rumble strips, K = fatal injury, A = serious injury, B = minor injury, C = possible injury; [2] Std. Error= standard error; [3] CI = confidence interval. N/A = not applicable.

Crash frequency modeling

Negative Binomial

LEN	= segment length in miles (mi)
AADT	= Annual Average Daily Traffic (vpd)
STR	= annual average Strava counts (bpy)
LN	= lane width in feet (ft)
SHW	= shoulder width in feet (ft)
SPD	= speed limit in miles per hour (mph)
CLRS	= centerline only rumble strips
SRS	= shoulder only rumble strips
CLRS+SRS	= centerline and shoulder rumble strips

Wisconsin model

Any rumble type vs no rumble

Variable	Coefficient	Estimate	Std. Error	z value	p value
Intercept	a	0.045	5.070	0.009	0.993
AADT	b	1.049	0.187	5.622	< 0.001
STR	c	0.334	0.082	4.044	< 0.001
LN	d	-0.680	0.407	-1.669	0.095
SHW	e	-0.087	0.042	-2.093	0.036
SPD	f	-0.139	0.036	-3.821	< 0.001
CLRS	g	-23.940	8.5E+5	0.000	1.000
SRS	h	0.303	1.093	0.277	0.782
CLRS+SRS	i	-0.273	0.488	-0.558	0.577
Overdispersion (k)			0.629		
Log-likelihood			-637.805		
AIC			657.81		

Michigan model

CLRS+SRS vs CLRS

Variable	Coefficient	Estimate	Std. Error	z value	p value
Intercept	a	-296.400	3.1E+06	0.000	1.000
AADT	b	0.784	0.175	4.469	< 0.001
STR	c	0.147	0.081	1.812	0.070
LN	d	-0.011	0.240	-0.046	0.963
SHW	e	-0.170	0.083	-2.054	0.040
SPD	f	5.169	5.6E+04	0.000	1.000
CLRS+SRS	g	-0.110	0.408	-0.268	0.788
Overdispersion (k)			1.325		
Log-likelihood			-596.032		
AIC			612.030		

Rumble strips did not have a statistically significant effect on crash frequency

Driving Simulator Study

Locations
Scenarios
Crowding

Driving simulator study

- **3 locations**
  - Oregon State University
  - University of Wisconsin-Madison
  - University of Massachusetts-Amherst
- **Validated sound and haptic replication of rumble strips within each driving simulator**
- **150 usable subjects**

Age Group	UW		OSU		UMass	
	Male	Female	Male	Female	Male	Female
18-34	8	8	10	6	9	8
35-54	8	8	11	7	6	6
≥ 55	12	6	6	10	11	10
Total	28	22	27	23	26	24

Scenarios

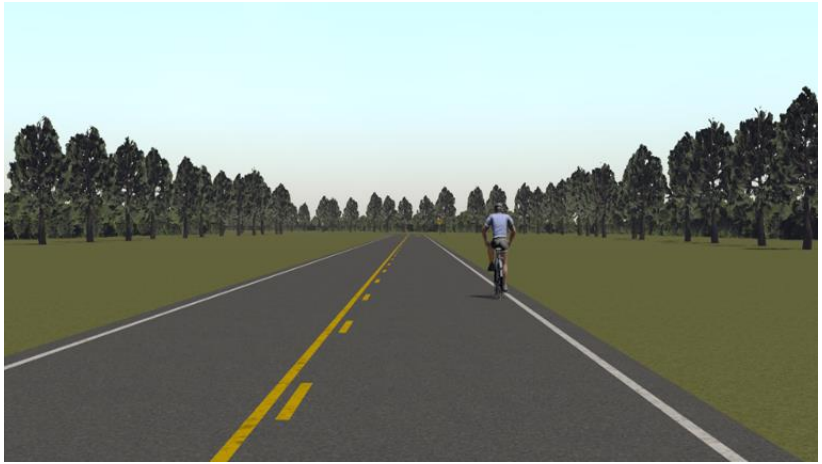
- Bicycle position (in lane and on shoulder)
- Lane width (10 and 12 ft)
- Rumble strips and shoulder (Base case, CLRS, CLRS+SRS)

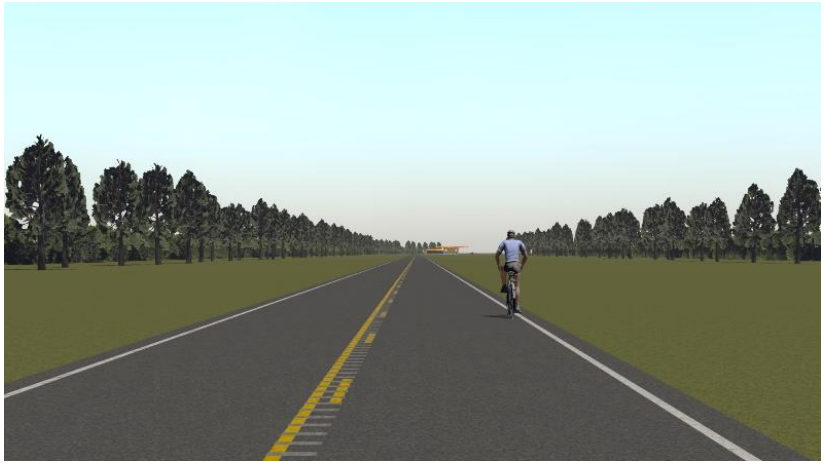
Scenario	Bicyclist Position	Lane Width (ft)	CLRS	SRS	Shoulder	Other considerations / Comments
1	In Lane (right)	10	No	No	No	Base case, No shoulder
2	In Lane (right)	10	Yes	No	No	CLRS only, No shoulder
3	On Shoulder	10	No	No	Yes	Base case, With shoulder
4	On Shoulder	10	Yes	No	Yes	CLRS only, With shoulder
5	On Shoulder	10	Yes	Yes	Yes	CLRS+SRS, With shoulder
6	On Shoulder	10	Yes	Yes	Yes	CLRS+ SRS, Crest vertical curve, No opposing traffic
7	On Shoulder	10	Yes	Yes	Yes	CLRS+ SRS, Crest vertical curve, with opposing traffic
8	In Lane (right)	12	No	No	No	Base case, No shoulder
9	In Lane (right)	12	Yes	No	No	CLRS only, No shoulder
10	On Shoulder	12	No	No	Yes	Base case, With shoulder
11	On Shoulder	12	Yes	No	Yes	CLRS only, With shoulder
12	On Shoulder	12	Yes	Yes	Yes	CLRS+SRS, With shoulder
13	On Shoulder	12	Yes	Yes	Yes	CLRS+ SRS, Crest vertical curve, No opposing traffic
14	On Shoulder	12	Yes	Yes	Yes	CLRS+ SRS, Crest vertical curve, with opposing traffic

Scenarios

- Bicycle position (in lane and on shoulder)
- Lane width (10 and 12 ft)
- Rumble strips and shoulder (Base case, CLRS, CLRS+SRS)

No shoulder



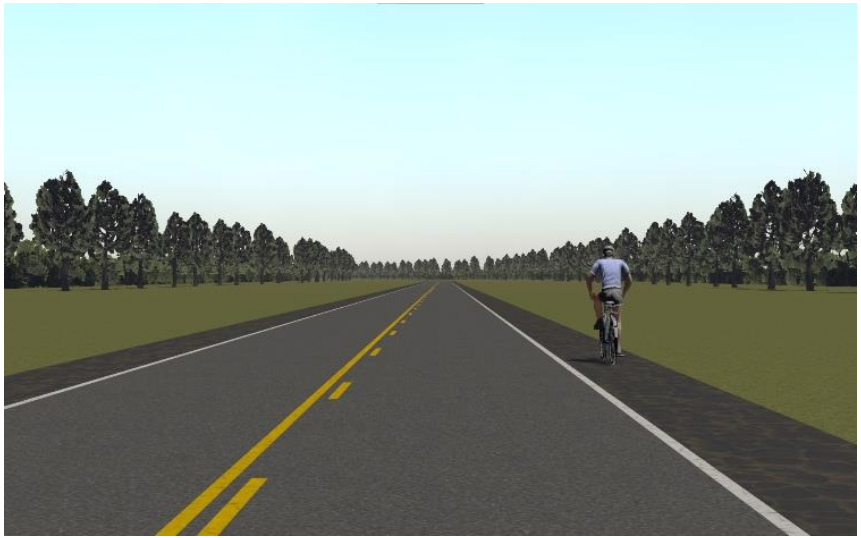


Scenario 1: 10ft lane, No rumble
Scenario 8: 12ft lane, No rumble

Scenario 2: 10ft lane, CLRS
Scenario 9: 12ft lane, CLRS

Scenarios

With shoulder



Scenario 3: 10ft lane, No rumble
Scenario 10: 12ft lane, No rumble

Scenario 4: 10ft lane, CLRS
Scenario 11: 12ft lane, CLRS

Scenarios

With shoulder and CLRS+SRS

Scenario 5: 10ft lane
Scenario 12: 12ft lane

Scenarios

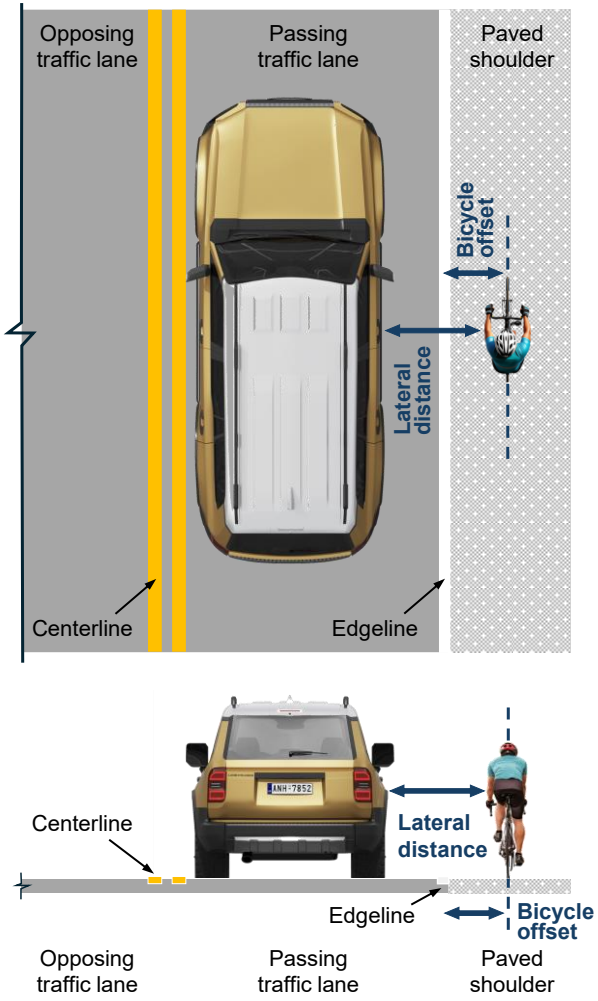
With shoulder, CLRS+SRS, and vertical curve

Scenario 6: 10ft lane, No opp. traffic
Scenario 13: 12ft lane, No opp. traffic

Scenario 7: 10ft lane, Opp. traffic
Scenario 14: 12ft lane, Opp. traffic

Crowding

Lateral distance ≤ 5 ft



Crowding analysis

- CLRS: no impact
- CLRS+SRS: marginally decrease crowding
- State, lane width, shoulder, vert. curve, opp. Traffic have significant effects

MA = Massachusetts
OR = Oregon
LN = lane width
SH = shoulder
CLRS = centerline only rumble strips
CLRS+SRS = centerline and shoulder rumble strips
VC = vertical curve
OPT = opposing traffic

Mixed-effects logistic regression

Variables	Coefficient	Estimate	Std. Error	z-value	p-value	Odds ratio	Marginal effect
Intercept	β_0	0.235	0.342	0.687	0.492	NA	NA
MA	β_1	-1.491	0.369	-4.044	< 0.001	0.225	-0.181
OR	β_2	-2.853	0.451	-6.318	< 0.001	0.058	-0.267
LN	β_3	-1.837	0.342	-5.378	< 0.001	0.159	-0.174
SH	β_4	-1.122	0.285	-3.931	< 0.001	0.326	-0.113
CLRS	β_5	-0.075	0.273	-0.273	0.785	0.928	-0.008
CLRS+SRS	β_6	-0.758	0.452	-1.676	0.094	0.469	-0.070
VC	β_7	1.696	0.458	3.706	< 0.001	5.450	0.180
OPT	β_8	1.307	0.345	3.789	< 0.001	3.690	0.144

Conclusions and Recommendations

Conclusions

- **Crash, driving simulator, and naturalistic data**
- **Crash data from 6 states**
  - Crash patterns
  - Injury severity modeling
- **MI and WI data**
  - Bicycle crash frequency modeling
- **Driving simulator experiment in MA, OR, and WI**

Conclusions

Crash Analysis

- **Applicability**
  - CLRS+SRS: paved shoulder sufficient to accommodate the bicyclists
  - CLRS: paved shoulders are narrow or not present
- **Crash frequency**
  - CLRS have no impact
  - CLRS+SRS may reduce
- **Crash injury severity**
  - CLRS increase the probability of higher severity
  - CLRS+SRS no impact

Conclusions

Simulator Analysis

- **Passing lateral distance**
  - WI < MA < OR
- **RS and Crowding/passing speed**
  - No impact
- **CLRS and crossing centerline**
  - No influence for a vast majority

Recommendations

- **Strive to install centerline and shoulder rumble strips to maximize safety for both drivers and bicyclists**
- **While installing shoulder rumble strips, states should:**
  - Follow guidance on minimum shoulder width
  - Use bicyclist-friendly rumble strips designs
  - Incorporate gaps in shoulder rumble strips
  - Maintain the shoulders free of debris
- **Roadways with centerline rumble strips only and significant bicycle volumes**
  - Consider developing a program to add shoulder rumble strips
  - Paved shoulder widening may be needed, elevating costs

Recommendations

- **Regional differences in lateral distance attributable in part to the differences in statutes**
  - Encourage revision of statutes to provide greater lateral distance
  - Several European countries: min. 5 feet on higher speed roads
  - Accompany statutory changes with robust education efforts

Questions

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