

Accidents and Safety Associated with Interchanges

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The primary objective of this study was to critically review, summarize, and document past safety research that associates accidents and safety with interchange features. Geometric layout, including alignment, ramp types, and interchange areas, and the effects of spacing between interchanges as they relate to accidents are discussed. Collectively, research results indicate that interchange ramps should be designed with flat horizontal curves (except in rural areas), and the maximum degree of curvature for a given design, speed, and superelevation should be avoided. Sharp curves at the ends of ramps and sudden changes from straight alignment to sharp curves should be avoided as well. Ramps of all types and sizes can be designed to connect two or more legs at an interchange. In summary, studies indicate that the design of cloverleaf ramps, scissor ramps, and left-side ramps should be avoided where possible. Collector-distributor roads should be considered in high-volume interchange designs and especially designs in which loop and cloverleaf ramps are used. Interchange areas include the areas along the freeway mainline between and including acceleration lanes, deceleration lanes, and their respective ramps. The relative safety of entrance and exit terminals is enhanced with geometric designs that provide 800-ft or longer acceleration or auxiliary lanes. The same is true for weaving lengths. The potential for accidents has been related to the volume of the ramp and through-lane traffic volumes. Interchange accident rates have been shown to increase as interchange spacing decreased in urban areas. It is concluded that interchange rehabilitation projects are effective in reducing accident experience.

An interchange is a system of interconnecting roadways that provides for movements between two or more grade-separated highways. This paper is focused on safety research related to interchange design. Interchange safety relates to how the interchange operates within the overall highway system and how the components of an interchange are interrelated.

In the overall highway system, the key elements of interchange safety research relate to interchange configurations, traffic controls, and spacing. Many interchange configurations are defined in the AASHTO Policy on Geometric Design of Highways and Streets, including cloverleaves, diamonds, trumpets, and directionals. Variations of each of these types are also defined, resulting in a total of 12 or more interchange types.

Safety research has been focused primarily on the most common types: diamonds and cloverleaves. Geometric safety research on individual interchanges has been focused on ramps, ramp terminals, speed change lanes, alignment, and spacing.

Ramp safety elements include acceleration lanes, deceleration lanes, weave sections, ramp alignment, and ramp terminals. Interchange alignment factors include grades, curves, vertical and horizontal clearances, and sight distance.

Geometric layout, including alignment, ramp types, and interchange areas, and the effects of spacing between interchanges as they relate to accidents are discussed here. Accident data and research results are presented to aid planners, designers, and decision makers in the implementation of safe highway design. This information can be used in the design of new interchanges and the increasingly important redesign of older interchanges that do not meet current needs.

SUMMARY OF RESEARCH

Alignment

Interchange alignment, specifically ramp geometry, at a particular site is determined by many factors. These include the number of intersecting legs, traffic volumes, topographic and environmental setting design controls, and their consistency with the overall roadway system they serve. Both horizontal and vertical alignment have been considered in safety research.

Horizontal Alignment

Horizontal alignment of ramps has been the subject of several safety studies in the past. The primary results of the studies have shown that (a) except for loop ramps in rural areas, all right-side and outer-connection ramps showed an increase in accident rates with increasing maximum curvature, and (b) outer-connection ramps in urban areas tend to show increasing accident rates with increasing average daily traffic (ADT). Straight outer-connections have lower accident rates than curved connections in urban and rural areas for all ADT levels, except 0 to 499 in urban areas (Table 1) (1).

Rural loops with low curvature have higher accident rate than rural loops with high curvature, whereas the reverse is true for urban loops (Table 2) (1).

Accident rates are grouped by ramp types and curvature in Table 3 (2). Off-ramps have the highest accident rate, which can be attributed to high speeds of vehicles entering ramp curves and ramp terminal capacity deficiencies.

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TABLE 1 Accident Rates on Outer Connections by Curvature and ADT (1)

ADT	Urban ^a		Rural ^a	
	Straight <1° ^b	Curved >1° ^c	Straight <1° ^b	Curved >1° ^c
0-499	0.74	0.64	0.00	0.67
500-1000	0.34	0.72	0.13	0.49
1001-1500	0.64	0.84	0.00	0.61
1501-2000	0.15	0.93	0.00 ^d	0.20
>2001	0.49	0.82	0.00 ^d	0.72
all volumes	0.44	0.81	0.05	0.56

^a Accidents per 100 million vehicles.

^b Less than 1 degree of curvature.

^c Greater than 1 degree of curvature.

^d Less than 10 units.

TABLE 2 Accident Rates on Loops by Curvature and ADT (1)

ADT	Urban		Rural	
	Low ^a <12° ^b	High ^a >36° ^c	Low ^a <12° ^b	High ^a >36° ^c
0-499	0.000 ^d	0.841	1.000	0.26
500-1000	0.000 ^d	0.960	0.810	0.37
1001-1500	1.320 ^d	0.690	0.000 ^d	0.00
1501-2000	0.000 ^d	0.720	0.000 ^d	0.00
>2001	0.141	1.000	0.000 ^d	0.00
all volumes	0.200	0.940	0.631	0.25

^a Accidents per 100 million vehicles.

^b Less than 12 degrees of curvature.

^c Greater than 36 degrees of curvature.

^d Less than 10 units.

Vertical Alignment

Ramp grades are generally constrained by the location of the crossing (intersecting) route, either overcrossing or undercrossing. The results of one study, classified by undercrossing and overcrossing accident rates by ramp type, are presented in Tables 4 and 5 (2). Trumpet ramps, cloverleaf ramps, loops

without collector-distributor roads, and left-side ramps have consistently higher accident rates than their counterparts, regardless of upgrade or downgrade. Overall, however, on-ramps have been found to have the same combined accident rates for downgrades and upgrades. Uphill off-ramps, however, have lower combined accident rates than downhill off-ramps.

Collectively, research concludes that interchange ramps should be designed with flat horizontal curves (except in rural areas), and the maximum degree of curvature for a given design, speed, and superelevation should be avoided. Sharp curves at the ends of ramps and sudden changes from straight alignment to sharp curves should be avoided as well. The crossing routes should be over the intersecting freeway based on safety, lower construction costs, and easier future mainline freeway traffic control during reconstruction.

Ramp Type

Ramps of all types and sizes can be designed to connect two or more legs at an interchange. Ramps provide the connection between crossing routes. Correlations have been developed between accident rates and types of freeway ramps (Table 6) (2). Left-side ramps and scissor ramps have much higher accident rates than other types, and their use is now generally discouraged. Diamond ramps have the lowest rate, but these rates do not account for crossroad and ramp intersection accidents.

Recent studies of the geometric design of ramps on which a high rate of truck accidents occurred concluded the following: (a) truck loss-of-control accidents on ramps are predominantly rollover and jackknife accidents; (b) jackknife accidents occur predominately at sites where inadequate pavement friction levels prevail during wet weather; (c) truck rollover accidents occur on ramps on which the trucks are traveling faster than the design speed of the ramp; (d) in designing horizontal curves to accommodate trucks, it is important to check for both rollover and skidding potential to determine which controls the design, and (e) the AASHTO policy of accepting ramp downgrades as high as 8 percent may be ill advised at sites at which an actively sharp curve remains to be negotiated toward the bottom of the grade (3).

TABLE 3 Accident Rates by Ramp Type and Curvature

Ramp	No. Ramps	No. ^a Accidents	MV ^b	Accident Rate ^c
On-ramps				
Straight	180	282	524.5	0.54
Curved	150	229	335.2	0.68
Off-ramps				
Straight	188	420	536.0	0.78
Curved	142	258	310.1	0.81
Total on & off				
Straight	368	702	1060.5	0.66
Curved	292	487	645.3	0.75

^a No. of Accidents

^b Million Vehicles.

^c Accidents per Million Vehicles.

TABLE 4 Ramp Accident Rates by Ramp Type, Overcrossing (2)

Type of Ramp	ON				OFF			
	No. Ramps	No. Accidents ^a	MV ^b	Accident Rate ^c	No. Ramps	No. Accidents ^a	MV ^b	Accident Rate ^c
Diamond Ramps	53	44	124.9	0.35	45	67	99.4	0.67
Trumpet Ramps	9	22	28.7	0.77	7	21	24.6	0.85
Cloverleaf Ramps w/o Collec. Dist.	48	83	111.2	0.75	59	135	155.8	0.87
Cloverleaf Ramps with Collec. Dist.	15	37	73.3	0.50	16	56	82.0	0.68
Cloverleaf Loops w/o Collec. Dist.	46	64	84.2	0.76	34	59	70.7	0.83
Cloverleaf Loops with Collec. Dist.	9	14	36.3	0.39	10	19	36.5	0.52
Left Side Ramps	5	14	18.9	0.74	11	81	46.4	1.74
Direct Connections	14	55	101.2	0.54	11	53	61.5	0.86
TOTAL^d	264	418	708.6	0.59	268	629	710.3	0.89

NOTE: If the crossroad crosses under the freeway (mainline), the ramps are associated with an undercrossing. If the crossroad crosses over the freeway (mainline), the ramps are associated with an overcrossing. Overcrossing on-ramps are generally downgrades and off-ramps are generally upgrades. Undercrossing on-ramps are generally upgrades and off-ramps are generally downgrades.

^a No. of Accidents.

^b Million Vehicles.

^c Accidents Per Million Vehicles.

^d Total includes other ramp types studied.

TABLE 5 Ramp Accident Rates by Ramp Type, Undercrossing (2)

Type of Ramp	ON				OFF			
	No. Ramps	No. Accident ^a	MV ^b	Accident Rate ^c	No. Ramps	No. Accident ^a	MV ^b	Accident Rate ^c
Diamond Ramps	32	44	95.4	0.46	44	73	109.8	0.66
Trumpet Ramps	2	5	3.5	1.43	0	--	--	--
Cloverleaf Ramps w/o Collec. Dist.	27	72	105.4	0.68	19	86	76.0	1.13
Cloverleaf Ramps with Collec. Dist.	5	2	14.3	0.14	5	3	13.0	0.23
Cloverleaf Loops w/o Collec. Dist.	17	44	53.7	0.82	19	47	50.0	0.94
Cloverleaf Loops with Collec. Dist.	5	3	8.0	0.38	5	1	13.2	0.08
Left Side Ramps	2	11	8.0	1.38	4	124	47.0	2.64
Direct Connections	2	10	28.6	0.35	2	30	29.9	1.00
TOTAL	92	191	316.9	0.60	98	364	338.9	1.07

NOTE: If the crossroad crosses under the freeway (mainline), the ramps are associated with an undercrossing. If the crossroad crosses over the freeway (mainline), the ramps are associated with an overcrossing. Overcrossing on-ramps are generally downgrades and off-ramps are generally upgrades. Undercrossing on-ramps are generally upgrades and off-ramps are generally downgrades.

^a No. of Accidents.

^b Million Vehicles.

^c Accidents Per Million Vehicles.

TABLE 6 Accident Rates by Type of Freeway Ramp (2)

<u>Ramp Type</u>	<u>On</u>	<u>Off</u>	<u>On & Off</u>
Diamond Ramps	0.40	0.67	0.53
Cloverleaf Ramps with Coll-Dist Roads ^a	0.45	0.62	0.61
Direct Connections	0.50	0.91	0.67
Cloverleaf Loops with Coll-Dist Roads ^a	0.38	0.40	0.69
Buttonhook Ramps	0.64	0.96	0.80
Loops with Coll-Dist Roads	0.78	0.88	0.83
Cloverleaf Ramps w/o Coll-Dist Roads	0.72	0.95	0.84
Trumpet Ramps	0.84	0.85	0.85
Scissor Ramps ^b	0.88	1.48	1.28
Left Side Ramps	0.93	2.19	1.91
Average	0.59	0.95	0.79

NOTE: Accident rates are per million vehicles.

^aOnly the On & Off rate includes the accidents occurring on the collector-distributor roads.

^bA ramp that has opposing traffic crossing the ramp traffic under stop sign control.

TABLE 7 Accident Rates by Interchange Unit and Area Type (4)

RURAL

<u>Interchange Unit</u>	<u>Vehicle Miles (100 Mil.)</u>	<u>No. Accidents^a</u>	<u>Accident Rate^b</u>
Deceleration lane	2.51	348	137
Exit Ramp	0.57	199	346
Area between speed change lanes	6.52	554	85
Entrance Ramp	0.59	95	161
Acceleration lane	3.68	280	76
Acceleration - deceleration lane	0.49	87	116
Total	14.36	1,563	109 ^c

URBAN

<u>Interchange Unit</u>	<u>Vehicle Miles (100 Mil.)</u>	<u>No. Accidents^a</u>	<u>Accident Rate^b</u>
Deceleration lane	5.83	1,089	186
Exit Ramp	1.48	546	370
Area between speed change lanes	11.87	1,982	167
Entrance Ramp	1.61	1,159	719
Acceleration lane	8.40	1,461	174
Acceleration - deceleration lane	2.45	555	227
Total	31.64	6,792	214 ^c

^aNo. of Accidents.

^bAccidents per 100 Million Vehicle-Miles.

^cAverage Accident Rate.

In summary, studies conclude that the design of cloverleaf ramps, scissor ramps, and left-side ramps should be avoided where possible. Collector-distributor roads should be considered in high-volume interchange designs and especially in designs for which loop and cloverleaf ramps are used.

Interchange Areas

Interchange areas include the areas along the freeway main-line between and including acceleration lanes, deceleration lanes, and their respective ramps.

Accident rates in interchange areas are presented in Table 7 by interchange unit and area type (4).

Urban interchanges have much higher accident rates than rural interchanges. The exceptionally high rate of accidents on urban entrance ramps may be a result of the inadequate acceleration lanes found on many urban interstates. The relative safety of entrance and exit terminals is enhanced with geometric designs that provide 800-ft or longer acceleration or auxiliary lanes.

Deceleration lanes 900 ft or longer reduce traffic friction on the through lanes and account for reduced accident rates. Geometric designs for weaving maneuvers should provide weaving sections that are at least 800 ft long.

Based on the results of interchange operational studies, the potential for accidents has been related to the volume of the ramp traffic and the relationship between the ramp and through-lane traffic volumes (5). A general conclusion is that it is safer to merge or diverge a given volume of vehicles with or from a freeway at several minor flow ramps than at single high-volume on- and off-ramps.

Interchange Systems

As more interchange areas operate at or near capacity, the likelihood of increased speed differentials between upstream freeway sections and interchange sections increases.

Interchange capacity relative to interchange spacing was addressed by Cirillo (4). No definitive correlation between capacity and safety was found, aside from the direct relationship of volume increase and accident frequency. She did find, however, that accident rates increase when speeds vary from the mean speed of the freeway section.

As shown in Table 8, accident rates have been shown to increase as interchange spacing decreased in urban areas. Conversely, in rural areas, the change in rates was less dramatic. The effect of the spacing of urban interchanges on accident rates is an important design consideration because of greater frequency of interchanges as a result of increased traffic demand.

Interchange Improvements

Many older interchanges on the nation's highway system are reaching the end of their design lives and must be redesigned or rehabilitated. Safety improvements are an important consideration in interchange rehabilitation.

TABLE 8 Accident Rates by Proximity to Interchange Ahead or Behind (4)

EXIT SIDE		
Dist. to exit-ramp nose ahead		
Urban	No. Acc. ^a	Acc. Rate ^b
Less than .2 miles	722	131
.2-.4 miles	1,209	127
.5-.9 miles	786	110
1.0-1.9 miles	280	75
2.0-3.9 miles	166	63
4.0-7.9 miles	19	69
More than 8 miles ^c	--	--
Rural		
Less than .2 miles	160	76
.2-.4 miles	459	75
.5-.9 miles	559	69
1.0-1.9 miles	479	69
2.0-3.9 miles	222	68
4.0-7.9 miles	46	62
More than 8 miles ^c	--	--

ENTRANCE SIDE		
Dist. to exit-ramp nose ahead		
Urban	No. Acc. ^a	Acc. Rate ^b
Less than .2 miles	426	122
.2-.4 miles	1,156	125
.5-.9 miles	1,655	105
1.0-1.9 miles	278	84
2.0-3.9 miles	151	59
4.0-7.9 miles	200	75
More than 8 miles ^c	--	--
Rural		
Less than .2 miles	117	80
.2-.4 miles	482	82
.5-.9 miles	560	72
1.0-1.9 miles	435	64
2.0-3.9 miles	169	51
4.0-7.9 miles	52	40
More than 8 miles ^c	--	--

^a No. of Accidents.

^b Accidents per 100 Million Vehicle-Miles.

^c No data available.

Evaluation of the effects of 37 interchange rehabilitation projects on traffic safety was documented in one recent study in which before and after accident rates were observed under control conditions (6).

The results of this safety analysis revealed a statistically significant reduction in accident rates for 13 projects, significant increases in accident rates for 2 projects, and no significant change in accident rates for 22 projects.

Table 9 presents the reduction in accident rates with different types of interchange rehabilitation. Modification refers to the element and level of improvement of the interchange modified during the rehabilitation projects. Modification to full diamonds may include lengthening of acceleration and deceleration lanes, adding ramp lanes, and optimizing existing or installing new traffic signals. Partial and full cloverleaf improvements may include the addition of collector distributor roads, lengthening of weave areas, and lengthening of acceleration and deceleration lanes. The combined results from interchanges in each category are presented in Table 9. Study results led to the conclusion that interchange

TABLE 9 Before and After Safety Comparison of Interchange Rehabilitation Projects (6)

Modification	Observed Percent Reduction in Accident Rate	Statistical Significance @ 95% Confidence Level
<u>Full Diamonds</u>		
Major Geometric	20.7	No
Minor Ramp	32.0	Yes
Minor Crossroad	33.1	Yes
Minor Ramp & Crossroad	21.2	Yes
<u>Full Cloverleafs</u>		
Major Geometric	-11.5 ^b	No
Minor Ramp & Collector-Distributor Rd	-55.8 ^b	No
Minor Ramp & Crossroad	-7.8 ^b	No
<u>Partial Cloverleaf</u>		
Major Geometric	38.4	Yes
Minor Ramp & Crossroad	45.5	Yes
<u>Other Interchange Configurations</u>		
Minor Ramp & Crossroad	8.2	No
<u>Summary By Project Type</u>		
Major Geometric	23.7	Yes
Minor Ramp & Crossroad	16.3	Yes
All Projects	18.7	Yes

^a Accidents per Million Vehicles.
^b Signifies an increase in Acc. Rate

rehabilitation projects are effective in reducing the number of accidents.

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