Safety Effectiveness of Highway Design Features

Volume IV: INTERCHANGES

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Safety Effectiveness of
Highway Design Features

VOLUME IV

INTERCHANGES

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PREFACE

This is the fourth volume in a series of six publications providing research results on the safety effectiveness of highway design features. This series provides designers and traffic engineers with useful information on the relationship between accidents and highway geometrics.

The Scientex Corporation, the Highway Safety Research Center at the University of North Carolina, Chapel Hill, and Michael Baker Jr., Inc., have compiled this Compendium under contract with the Federal Highway Administration. The six volumes include:

Volume I:	Access Control
Volume II:	Alignment
Volume III:	Cross Sections
Volume IV:	Interchanges
Volume V:	Intersections
Volume VI:	Pedestrians and Bicyclists

Authors with extensive experience in each subject area have reviewed past research, and significant findings are summarized here, along with an additional bibliography for reference.

INTERCHANGES

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FOREWORD

In the early 60's, the highway community became increasingly interested in the safety effects of geometric design. The first attempt to quantify the state of knowledge on this topic was undertaken by the Highway Users Federation for Safety and Mobility (HUFSAM) in 1963 and 1971.

Considerable research on geometrics and safety was then initiated, and in the late 1970's, the Federal Highway Administration (FHWA) provided a consolidated resource for the safety impacts of various geometric and traffic control alternatives. This document, the Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volumes I and II (FHWA Report Nos FHWA-TS-82-232 & 233), which updated the earlier HUFSAM reports, served a critical and useful purpose by providing valuable geometric/accident relationships.

This present compendium is the result of the FHWA implementing one of the 23 recommendations contained in TRB Special Report 214, "Designing Safer Roads - Practices for Resurfacing, Restoration and Rehabilitation." This report specifically responds to the recommendation, calling for the FHWA to "...develop, distribute, and periodically update a compendium that reports the most probable safety effects of improvements to key highway design features..."

As an initial task, all available United States literature potentially relating a geometric feature with traffic accidents was identified. Resources included the Transportation Research Information Service, libraries at the University of North Carolina and United States Department of Transportation, and the personal documents of the project team. In addition, accident/geometric data bases were identified as possible sources of data which could be used to develop needed relationships.

This identification effort revealed a lack of many new (post-1973) documents for several geometric topic areas. Accordingly, some major pre-1973 reports, along with the post-1973 reports were included for critical review.

Critical reviews of these reports involved determination of the appropriateness of the study design, the adequacy of the sample size, the application of proper statistical tests and correct interpretation of results. Only information meeting all of these criteria is reported in each volume of this report. These documents are listed in the reference section at the end, and an additional bibliography section is included, covering related research of interest, but not used in this report.

INTERCHANGES

INTRODUCTION

An interchange is a system of interconnecting roadways that provides for movements between two or more grade separated highways. This volume focuses on safety research related to interchange design. Interchange safety relates to how the interchange itself operates within the overall highway system environment and how the individual components of an interchange interrelate to one another.

Within the overall highway system, the key elements of interchange safety research relate to interchange configurations, traffic controls and spacing. There are many interchange configurations defined in the American Association of State Highway and Transportation Officials (AASHTO) Policy on Geometric Design of Highways and Streets, including cloverleafs, diamonds, trumpets, and directionals. Variations of each of these types are also defined, resulting in a total of 12 or more interchange types.

However, safety research has focused primarily on the most common types, which are diamonds and cloverleafs. Within an individual interchange, geometric safety research has 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/horizontal clearances and sight distance.

This volume describes geometric layout, including alignment, ramp types, and interchange areas, as well as the effects of spacing between interchanges as they relate to accidents. This volume offers planners, designers and decision makers accident data and research results that will aid 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, in particular 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. Safety research has considered both horizontal and vertical alignment.

Horizontal Alignment

Horizontal alignment of ramps has been the subject of several safety studies in the past. Figure 1 shows the various elements of a cloverleaf interchange.

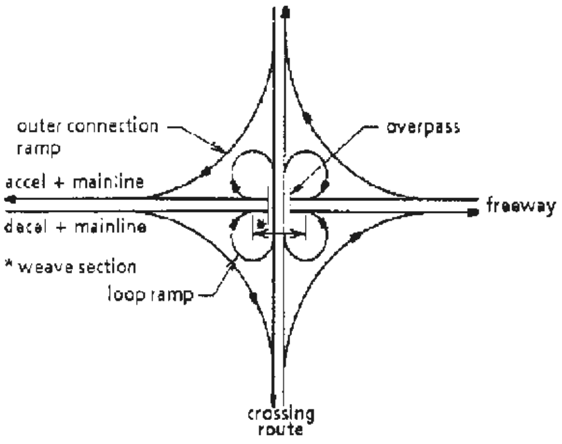

Figure 1. Cloverleaf interchange elements.

The primary results of the studies have shown that: 1) except for loop ramps in rural areas, all righthand side and outer-connection ramps showed an increase in accident rates with increasing maximum curvature and 2) 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 ADTs, except 0 to 499 in urban areas (see table 1).[1]

Table 1. Accident rates on outer connections by curvature and ADT.[1]

	Urban[a]		Rural[a]	
	Strt	Crv	Strt	Crv
ADT	≤1°[b]	≥1°[c]	≤1°[b]	≥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

Strt = Straight, Crv = Curved
[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.

Rural loops with low curvature have higher accident rates than rural loops with high curvature, while the reverse is true for urban loops (see table 2).[1]

Table 3 groups accident rates by ramp types and curvature.[2] This table shows that off-ramps have the highest accident rate. The high occurrence of off-ramp accidents can be attributed to high vehicles speeds entering ramp curves and ramp terminal capacity deficiencies.

Table 2. Accident rates on loops by curvature and ADT.[1]

	Urban		Rural	
	L[a]	H[a]	L[a]	H[a]
ADT	≤12°[b]	≥36°[c]	≤12°[b]	≥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

L = low, H = High
[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. Table 4 shows the results of one study classified by undercrossing and overcrossing accident rates by ramp type.[2] Figure 2 shows the various ramp types and figure 3 illustrates the typical overcrossing and undercrossing interchange configurations. Table 4 shows that trumpet ramps, cloverleaf ramps without collector-distributor roads and

Table 3. Accident rates by ramp type and curvature.[2]

Ramp	No. Ramps	NA[a]	MV[b]	AR[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	1422	583	10.1	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.

left side ramps have consistently higher accident rates than their ramp counterparts, regardless of grade situations. However, overall, on-ramps have been found to have the same combined accident rates for downgrade and upgrade situations. Uphill off-ramps, however, have lower combined accident rates than downhill off-ramps.

Collectively, research concludes that it is desired to design interchange ramps with flat horizontal curves (except in rural areas) avoiding maximum degree of curvature for a given design, speed, and superelevation. Sharp curves at the end of the ramps and sudden changes from straight alignment to sharp curves should be avoided. 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 at an interchange 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 (see table 5).[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/ramp intersection accidents.

Recent studies of the geometric design of ramps which were heavily involved in truck accidents concluded: 1) truck loss of control accidents on ramps are pre-dominantly rollover and jackknife events, 2) jackknife accidents predominate at sites where inadequate pavement friction levels prevail during wet weather, 3) truck rollover accidents occur on ramps where the trucks are traveling above the design speed of the ramp, 4) 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 5) AASHTO policy of accepting ramp downgrades as high as 8 percent may be ill advised at sites on which an actively sharp curve remains to be negotiated towards the bottom of the grade.[3]

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 designs where loop and cloverleaf ramps are used.

Interchange Areas

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

Table 4A. Ramp accident rates (ACC/MV) by ramp type, Overcrossing.[a(2)]

	ON				OFF			
Type of Ramp	No. Ramps	No. Acc.[b]	MV[c]	Rate[d]	No. Ramps	No. Acc.[b]	MV[c]	Rate[d]
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	264	418	708.6	0.59	268	629	710.3	0.89

Table 4B. Ramp accident rates (ACC/MV) by ramp type, Undercrossing.[a(2)]

	ON				OFF			
Type of Ramp	No. Ramps	No. Acc.[b]	MV[c]	Rate[d]	No. Ramps	No. Acc.[b]	MV[c]	Rate[d]
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	50.07	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	0.38	2	30	29.9	1.00
TOTAL	92	191	316.9	0.60	98	364	338.9	1.07

[a] 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.
[b] No. of Accidents.
[c] Million Vehicles.
[d] Accidents per Million Vehicles.

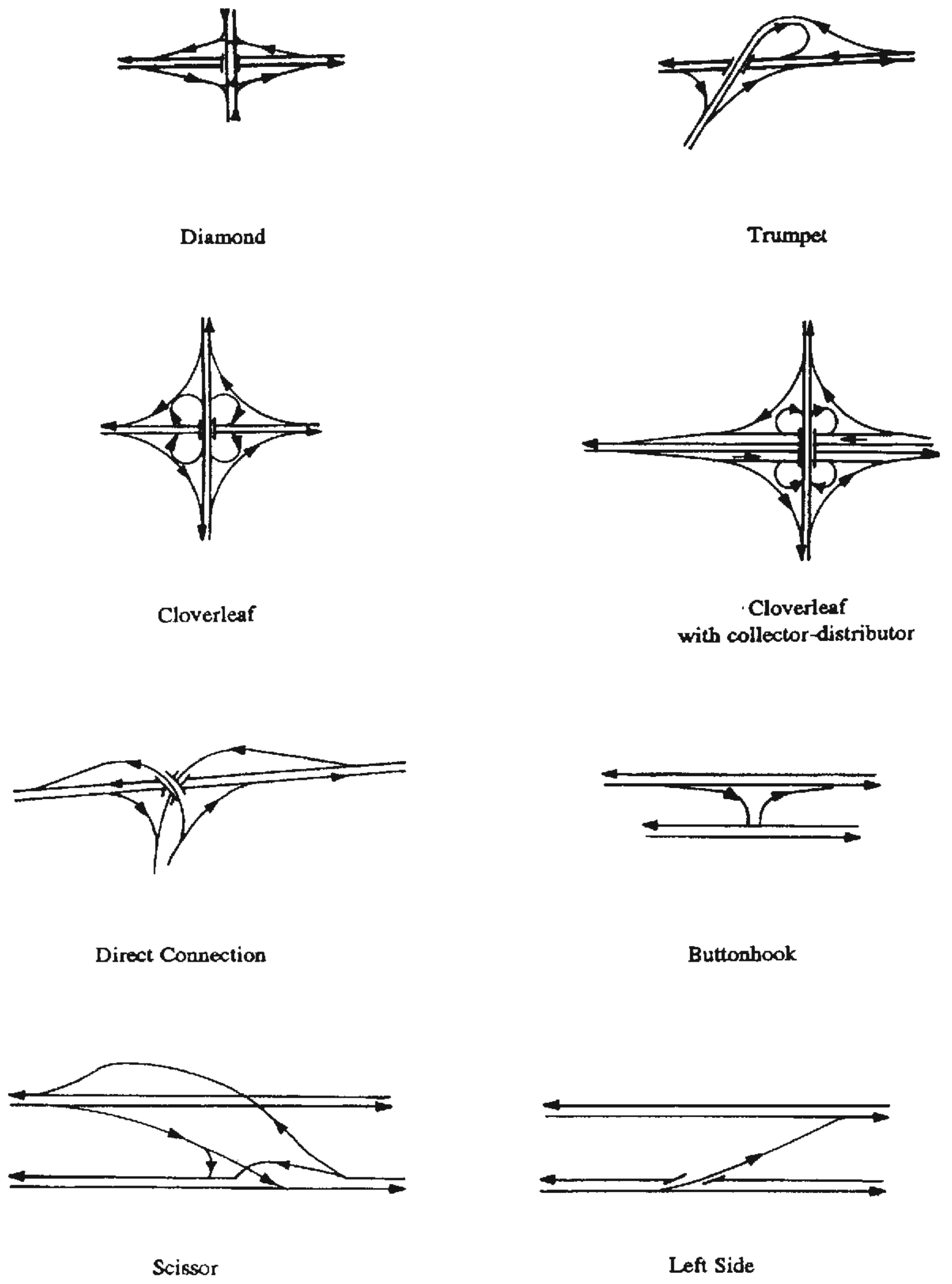

Figure 2. Typical interchange ramps.

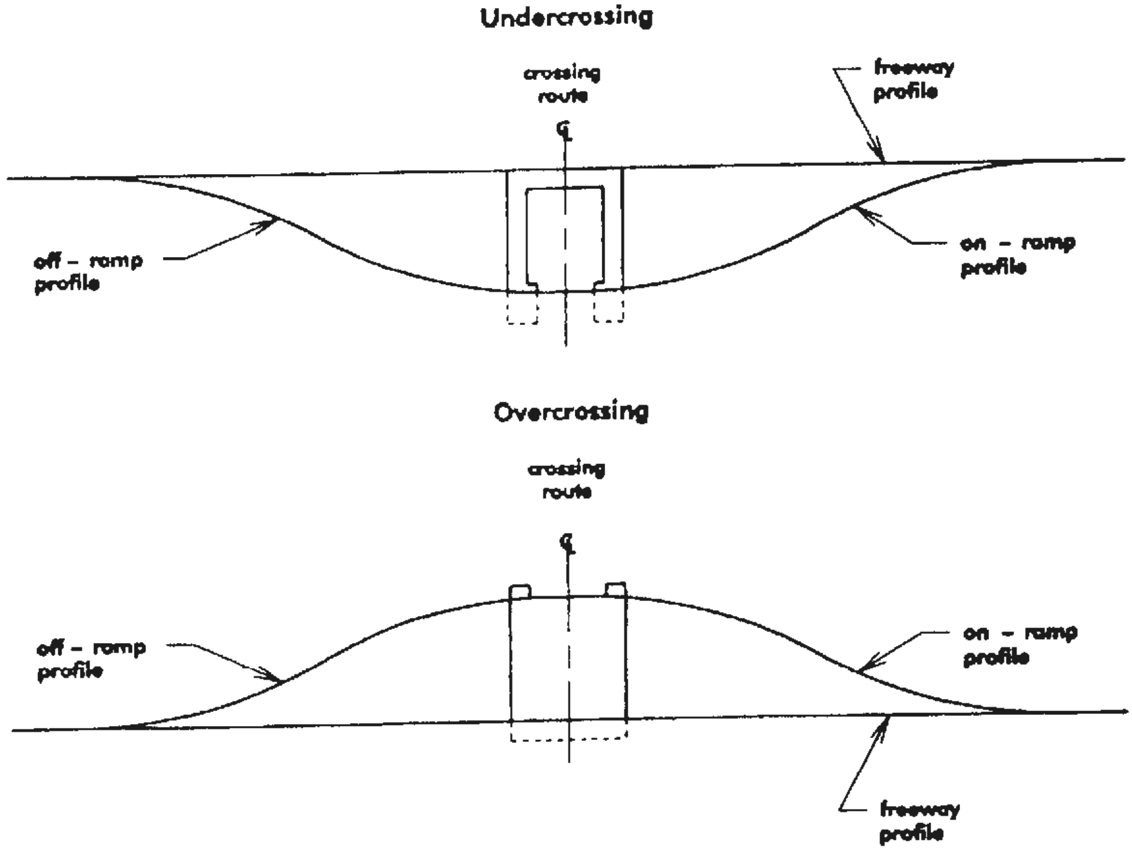

Figure 3. Overcrossing and Undercrossing interchange elements.

Table 5. Accident rates by type of freeway ramps.[a][2]

Ramp Type	On	Off	On & Off
Diamond Ramps	0.40	0.67	0.53
Cloverleaf Ramps with Coll-Dist Roads[b]	0.45	0.62	0.61
Direct Connections	0.50	0.91	0.67
Cloverleaf Loops with Coll-Dist Roads[b]	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[c]	0.88	1.48	1.28
Left Side Ramps	0.93	2.19	1.91
Average	0.59	0.95	0.79

[a]Accidents per Million Vehicles
[b]Only the On & Off rate includes the accidents occurring on the collector-distributor roads.
[c]A ramp that has opposing traffic crossing the ramp traffic under stop sign control.

Table 6 shows accident rates within interchange areas 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 due to inadequate acceleration lanes found on many urban interstates. The relative safety of entrance and exit terminals is enhanced with geometric designs that provide long acceleration or auxiliary lanes of 800 ft or more in length.

Deceleration lanes with a length of 900 ft or more 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 in length.

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 differential between upstream freeway sections and interchange sections exists.

Interchange capacity relative to interchange spacing was addressed by Cirillo.[4] No definitive correlation between capacity and safety was found other than 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.

Table 6. Accident rates by interchange unit and area type.[4]

Interchange Unit	Vehicle miles 100 Mil.	No. Acc.[a]	Acc. Rate[b]
RURAL			
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			
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]

[a]No. of Accidents.
[b]Accidents per 100 Million Vehicle-Miles.
[c]Average Accident Rate.

As shown in table 7, between interchange 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. This urban area interchange spacing effect on accident rates is an important design consideration, because of greater frequency of interchanges due to increased traffic demand.

Interchange Improvements

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

Evaluation of the effects of 37 interchange rehabilitation projects on traffic safety was documented in one recent study by observing before and after accident rates 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 8 shows the reduction in accident rates with different types of interchange rehabilitation. The modification shown refers to the element and level of improvement which was 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 cloverleafs improvements can include the addition of collector-distributor roads, lengthening of weave areas, and lengthening of acceleration and deceleration lanes.

Table 8 reflects the combined results from interchanges in each category. The study concluded that interchange rehabilitation projects are effective in reducing accident experience.

Table 7. Accident rates by proximity to interchange ahead or behind.[4]

Dist. to exit-ramp nose ahead	No. Acc.[a]	Acc. Rate[b]
EXIT SIDE		
URBAN		
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		
URBAN		
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.

Table 8. Before-After safety comparison of interchange rehabilitation projects.[6]

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

Notes:

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

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	ac
ha	hectares	2.47	acres	mi^2
km^2	square kilometers	0.386	square miles	
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)