Evolution of Interchange Design in North America

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Abstract – Evolution of Interchange Design in North America

There has been a significant evolution in interchange forms and interchange geometric design criteria since the first interchange (cloverleaf) was constructed in Woodbridge, NJ in 1928. The first cloverleaf interchange in Canada was the Port Credit interchange completed in 1937 on the QEW between Toronto and Niagara Falls which was the first freeway in Canada. This presentation will chronicle the following:

- Evolution of interchange forms from the cloverleaf to the double crossover diamond (diverging diamond).
- Evolution of interchange geometric design criteria from the 1930's to the present.
- Application of driver characteristics and expectations in interchange design, operations and signing guidelines in the Transportation Association of Canada (TAC) and the American Association of State Highway and Transportation Officials (AASHTO) design policies and the Manual on Uniform Traffic Control Devices (MUTCD).

The interchange forms to be presented include 17 diamond interchange forms, 10 partial cloverleaf forms and 16 system (freeway to freeway) interchange forms with their design and operational characteristics. The early interchanges (1928-1955) in the US and Canada will provide the base from which the multitude of interchanges have evolved.

Geometric design of ramp exit and entrance design, geometric design of ramps, and basic design criteria for freeways will be presented demonstrating the evolution of design criteria from the 1940's to present day based on TAC and AASHTO criteria.

Application of the research associated with driver characteristics and expectations on freeways and interchanges and the resultant development of design criteria will be presented. Most of these guidelines were developed by Jack E. Leisch, who taught at the University of Waterloo and was VP and Chief Engineer for De Leuw Cather of Canada in the 1960's.

INTRODUCTION

The birth of the interchange began more than 100 years ago with a US patent of a cloverleaf in 1912. The first interchange (cloverleaf), however, was not constructed in North America until 1928. Chronicled in this paper are the following concerning the evolution of interchange design in North America:

- The Beginning -- 1912 – 1956
- Design, Construct, Experience and Improve -- 1956 – 1984
- Applying What We Learned and New Ideas – 1984 – 2014
- The Future – 2014 and Beyond

The Beginning describes our efforts to design interchanges with little knowledge and no experience in interchange design, operations and safety. Fortunately there were a few intuitive engineers involved in the late 1930's into the early 1950's that *paved the way* for the development of the Interstate System in the US and freeway systems in major cities in Canada as well as the Trans Canada Highway.

Design, Construct and Experience and Improve covered three (3) decades of construction of the US Interstate System and development of freeways and interchanges in many of the Canadian Provinces. Along with this significant effort came human factors research on driver characteristics and expectations. Research on safety (crash experience) related to freeway and interchange geometrics was accomplished. Traffic capacity and traffic operational research led to better procedures to determine traffic operational characteristics of freeways, ramps, weaving sections and intersections. This research led to changes in design criteria, modification of existing interchange forms and development of new interchange forms as well as changes in signing and pavement marking compatible with driver information comprehension, processing and performance.

Applying What We Learned and New Ideas brings us into the 21st century. New interchange forms were developed, implemented and researched leading to improvements in traffic operations and reduction in crashes. Much of this period was also spent correcting the constructed designs from the 1950's and 1960's that were based on design criteria from the 1940's and early 1950's. Research continued at an even greater rate than in the previous decades leading to further improvements in design criteria, more sophisticated operational analysis procedures and a continuing reduction in crash experience.

The Future holds opportunities for further improvement in all areas of design, traffic operations and crash reduction. It will be up to transportation planners, designers and traffic engineers along with environmentalists and the public to incorporate public transportation, vehicle guidance technology, such as connected vehicles, and evolving intelligent transportation system (ITS) technology to accomplish a more efficient and safer transportation system.

THE BEGINNING

In the beginning man created the interchange with a US patent in 1912 of a cloverleaf. It was not until 16 years later that the first interchange (cloverleaf) was constructed in Woodbridge, New Jersey in 1928. Figure 1 shows the drawing in the original patent and a photograph of the first cloverleaf. Construction began on the QEW in 1932 in Ontario, Canada from Niagara Falls to Toronto. In 1937 a cloverleaf on the QEW opened to traffic (figure 2). Other interchanges opened to traffic over the next several years as well including a diamond interchange with a traffic circle also shown in Figure 2.

Until the early 1940s all controlled access highways were linear including the QEW in Ontario and highways in the US as the Henry Hudson Parkway in New York, the Merritt Parkway in Connecticut, and Lake Shore Drive in Chicago. It was the Pentagon Road Network (known as the "Mixing Bowl") in Northern Virginia that was designed as a system of controlled access roadways to connect Washington, DC with the Pentagon, Arlington Cemetery, and roadways leading into Washington, DC from Virginia. The Pentagon Road Network comprised of 10 miles (16km) of controlled access roadways with 11 bridges and 10 interchanges – most were cloverleaf interchanges.

In 1941 the first diamond interchanges with intersections at the ramp(s) intercept with the cross roads was constructed on the Pasadena Freeway in the Los Angeles area. The freeway construction was a flood control project, channelizing the Arroyo Seco (Dry River). Because of the limited right-of-way diamond interchanges were constructed (Figure 3).

During the remainder of the 1940s and into the mid-1950s freeway and interchange construction energetically continued primarily by local governments or by toll authorities. Sections of the Pennsylvania Turnpike first opened to traffic in 1937 with trumpet interchanges. The QEW was completed. Design began on Highway 401 in Toronto. Sections of the Ohio Turnpike opened to traffic. Detroit constructed the first depressed freeway with frontage/service roads. Los Angeles began construction of its freeway system with all directional system interchanges (freeway to freeway). Chicago developed its freeway system concept and began construction of two freeways with diamond and cloverleaf interchanges. Partial cloverleaf interchanges (fewer than 4 loop ramps) were also constructed (Figure 4).

By the mid-1950s every basic interchange form had been designed and constructed. Figure 5 shows all the basic forms (3-Leg, diamonds, partial cloverleaf, cloverleaf, and all directional or directional with loop ramps).

DESIGN, CONSTRUCT, EXPERIENCE AND IMPROVE

President Eisenhower signed the Interstate and Defense Highway Act in 1956. With 90% federal funding for design and construction of a 50,000 mile (80,000 km) freeway and interchange system. US State Highway Departments with consulting engineering firms support embarked on the world's largest public works project. Canada followed shortly thereafter, in part learning from some of the US failures. One of those failures was construction of the system interchange (freeway to freeway) in two locations of the US. One of those is shown in Figure 6. This interchange has two exits on each approach to the interchange, one to go right on the right and one to go left on the left. It is based on a schematic of this interchange form which appeared in the 1954, 1957, and 1965 AASHO Design Policies. Unfortunately, engineers assumed that if it appeared in the AASHO Policy it must be good. What was learned through experience and research that two exit design increases signing requirements on the freeway resulting in greater driver information processing, left exits have a higher crash experience than right exits, curves have a higher crash experience then tangents. The result is less efficient operation and more crashes. Cloverleaf interchanges were also a relatively common system interchange as well as a service interchange in suburban areas. The cloverleaf also has two exits as well as four weaving sections.

By the late 1960s nearly 45,000 miles (72,000 km) of the US Interstate Highway System had been constructed. Canada had constructed several thousand miles of freeways with hundreds of interchanges mostly in metropolitan areas, particularly in Ontario, and Vancouver, Calgary, Edmonton, and Montreal were not far behind. The experience gained over the decade following the signing of the Interstate and Defense Highway Act gave planners and engineers the opportunity to observe and experience their accomplishments. What they learned by experience and observation along with research gave direction to improvements in future interchange design criteria, design and signing to better meet driver characteristics and expectations, and even more efficient and safer Interchange forms. AASHO produced a new Design Policy and the second generation of the Highway Capacity Manual was published providing engineers the new tools for designing interchanges.

By the late 1960s, through the 1970s and into the 1980s more efficient and safer interchanges were being constructed and ones constructed in the 1950s and early 1960s were being modified and improved to reflect the experiences and research accomplished. The Compressed Diamonds of the 1950s were being replaced with higher capacity and safer designs. Three of these designs are shown in Figure 7 (Single Point Urban Interchange, Tight Urban Diamond, and the 3-Level Diamond). The Single Point Urban Interchange (SPUI) has a single intersection utilizing basic 3-phase signal control and takes less right-of-way (ROW) than the Compressed Diamond. The Tight Urban Diamond (TUDI) has two intersections approximately 300' (90m) apart utilizing a coordinated 4-phase overlap signal phasing and timing system – it also takes less ROW than the previous Compressed Diamond Interchanges. The 3-level Diamond has the highest capacity of all diamond forms because the two interchanging roadways are grade separated and only the turning traffic between the two interchanging roadways pass through coordinated 2-phase signalized intersections. Of course it is the highest construction cost of the three.

During this same time period more efficient partial cloverleaf designs were being developed and implemented in suburban areas. Some of these were modifications of existing cloverleaf interchanges. Two of these are shown in Figure 8, the first on 401 in Toronto and the second on Deerfoot Trail in Calgary. Both of these designs have higher capacity than most of the diamond interchange forms.

System interchanges evolved also from cloverleaf designs and other designs (see Figure 6) to ones with single exit design and no weaving between loop ramps. Two designs are shown in Figure 9. The first is an all directional interchange (no loop ramps) first developed in Los Angeles and often referred to as the "California 4-Level Stack" where both interchanging freeways and all left-turning directional ramps pass through a common point in the center of the interchange. The second system interchange in the figure is the conversion of a cloverleaf to a directional interchange with loop ramps in opposite quadrants to eliminate weaving within the interchange.

During this period from the 1950s through the mid-1980s significant strides were made in developing design and operational guidelines for interchanges and systems of interchanges based on experience and human factors research. Some of these first appeared in the 1973 American Association of State Highway Officials (AASHO), *A Policy on the Design of Urban Highways and Urban Streets* and all were documented in the first American Association of State Highway and Transportation Officials (AASHTO), Green Book, *A Policy on Geometric Design of Highways and Streets*, 1984. These guidelines were documented in the Roads and Transportation Association of Canada (RTAC) Design Manuals and of course are included in the latest 1999 Transportation Association of Canada (TAC), *Geometric Design Guide for Canadian Roads.*

The engineer that conceived and developed these guidelines was Jack Leisch. Mr. Leisch began formulating the guidelines in the late 1950s and continued into the late 1970s based on his experience and understanding of the driver human factors research. During much of this time he was Chief Highway Engineer for De Leuw Cather and Company in Chicago and teaching at Northwestern University and in the 1960s Vice President and Chief Highway Engineer of De Leuw Cather of Canada and teaching at the University of Waterloo.

The guidelines he developed included the following:

- Appropriate interchange form for the conditions
- Route continuity through interchanges
- Basic through lanes on a freeway
- Single exit on the right in advance of the cross road at an interchange resulting in simplified signing
- Lane balance at ramp exits and entrances to reduce lane changing and increase capacity
- Ramp spacing guidelines to reflect driver perception, decision and maneuver capabilities
- Decision sight distance (first referred to as anticipatory sight distance)

For selection of the basic interchange forms for a particular location Mr. Leisch established four considerations:

1. Location – rural, suburban or urban
2. Classification of the interchanging roadways – freeway/primary highway, freeway/arterial street, freeway/local road or street, freeway/collector street
3. Traffic volume
4. Right-of-way availability and cost

The matrix in figure 10 is his original sketch from the late 1950s that appears more formalized in the AASHTO Design Policy and the TAC Design Policy.

In the early 1960's Mr. Leisch conceived of the route continuity concept. Figure 11 is his original sketched concept which appears more formalized in the AASHTO and TAC Policies. Also in the figure is Highway 407 near Toronto demonstrating the application of route continuity from lower left to upper left in the photo and all exits and entrances on the right.

For an interchange single exit on the right in advance of the crossroad to simplify signing Mr. Leisch conceived of the graphic in Figure 12. The figure includes the artist's (Warren Carroll) concept of the driver's view on the approach to every interchange, no matter the form. Application of this concept simplifies the driver's task along the freeway in negotiating through interchanges.

For ramp spacing Mr. Leisch, based on his experience, involvement with development of the 1965 and 1985 Highway Capacity Manuals and understanding of driver characteristics, developed guidelines for all ramp combinations. The table in Figure 13 is the original he developed in 1975 and first appeared in the 1984 AASHTO Design Policy. Since that time AASHTO and TAC have reduced the table to only include minimum values. Recent research on ramp and interchange spacing related to geometrics, traffic operations and safety by the Federal Highway Administration (FHWA) has shown that the "desirable" values in Mr. Leisch's original table are more appropriate.

All of these accomplishments and their application during the decades from the mid-1950s, 1960s, and 1970s and into the mid-1980s had a significant impact on improved traffic operations and crash reduction on our freeways and interchanges.

APPLYING WHAT WE LEARNED AND NEW IDEAS

The next 30 years resulted in further application of what was learned during the previous 30 years and continuing reduction in crash experience on our freeways and interchanges. Research continued on human factors, operational and capacity analysis procedures, geometric design criteria and signing and pavement marking. During that time all related publications were updated several times. The latest of these are: 1)1999 TAC Design Guide, 2) 2011 AASHTO Design Policy, 3) 2011 Highway Capacity Manual, 4) 2010 Manual on Uniform Traffic Control Devices, 5) 1st Edition of the Highway Safety Manual (2010).

Two new interchange forms were conceived and constructed in a number of locations. The first of these is an interchange with roundabout treatments where the freeway ramps intersect with the crossroad. It is recognized that these solutions are not high capacity, however, low crash rates and are appropriate in suburban or rural areas. Two are shown in Figure 14. The first is a diamond interchange in the US and the second is a partial cloverleaf in British Columbia. Traffic circles have existed for two hundred years, however, the modern roundabout for approximately 25 years which has significantly different design and operational characteristics than traffic circles producing safer and more efficient traffic operations.

The second new interchange is the Double Crossover Diamond (DCD) or Diverging Diamond Interchange (DDI). It was first developed in France and brought to North America about 12 years ago. Figure 15 shows the first constructed in North America. Unique in this design is the crossover or transposing of the two directions of travel on the street crossing over or under the freeway. This results in 2-phase signal control at each of the ramp terminal intersections with the cross road and potentially higher capacity than more traditional diamond interchanges as the compressed, single-point and tight-urban. It is becoming increasingly popular among planners and engineers as a retrofit of the 1950s and 1960s compressed diamonds and as a solution at a proposed new interchange in a suburban area where a freeway interchanges with an arterial street. Research is on-going investigating its geometric design elements, operational characteristics, signal coordination and crash experience.

Additional research and experience was gained related to Mr. Leisch's interchange and ramp design guidelines. Several of these were researched corroborating the concepts and others by observation and experience. Other elements as left entrances and exits and weaving sections were studied and conclusions reached related to their operational and crash impacts on freeways and interchanges. Figure 16 is a table that summarizes many of the design elements and their impact on traffic operations and safety. From the 1940s/1950s to the 21st Century significant changes in freeway and interchange design criteria were made based on research and experience. Figure 17 specifically addresses freeways. For interchanges and ramps the following improvements were made:

- Ramp merge and diverge taper lengths were increased.
- 2-lane exit and entrance ramp designs developed
- Design speed relationship between freeway and ramp controlling curve guide lines established
- Requirements for Ramp width guidelines related to design vehicle and curve radius
- Intersection sight distance requirements
- Decision sight distance refined and expanded to other roadways
- Height of object for stopping sight distance and decision sight distance modified

Research continues into the foreseeable future in interchange geometric design, interchange operations and safety. Two research projects that may be funded by the National Cooperative Highway Research Program (NCHRP) in the near future include two-lane loop ramp design and spacing between system and service interchanges.

THE FUTURE, 2014 AND BEYOND

Have we exhausted all the different interchange forms over the last 100+ years - who knows? There was only one entirely new interchange form developed in the last 30 years, the double crossover diamond. There is, however, one in process called the double crossover roundabout. It is a hybrid of the double crossover diamond and the roundabout diamond. At least two are in design and soon to be constructed in Missouri near Kansas City. These are also retrofits of existing compressed diamond interchanges. It will be interesting to see how they operate and if they are viable solutions under the appropriate conditions.

Below is a general list of programs that for sure will be occurring in the foreseeable future.

- Sophistication in vehicle guidance technology leading to increased capacity and crash reduction on our freeways and interchanges
- Further advancements in intelligent transportation systems (ITS) to increase system capacity and travel reliability for all users
- Based on continuing research, refinement of design criteria to improve operational and safety characteristics of interchanges

There have been many highway and traffic engineering visionaries in the past. There will be more in the future to guide us into even more efficient and safe interchange forms and geometric designs.

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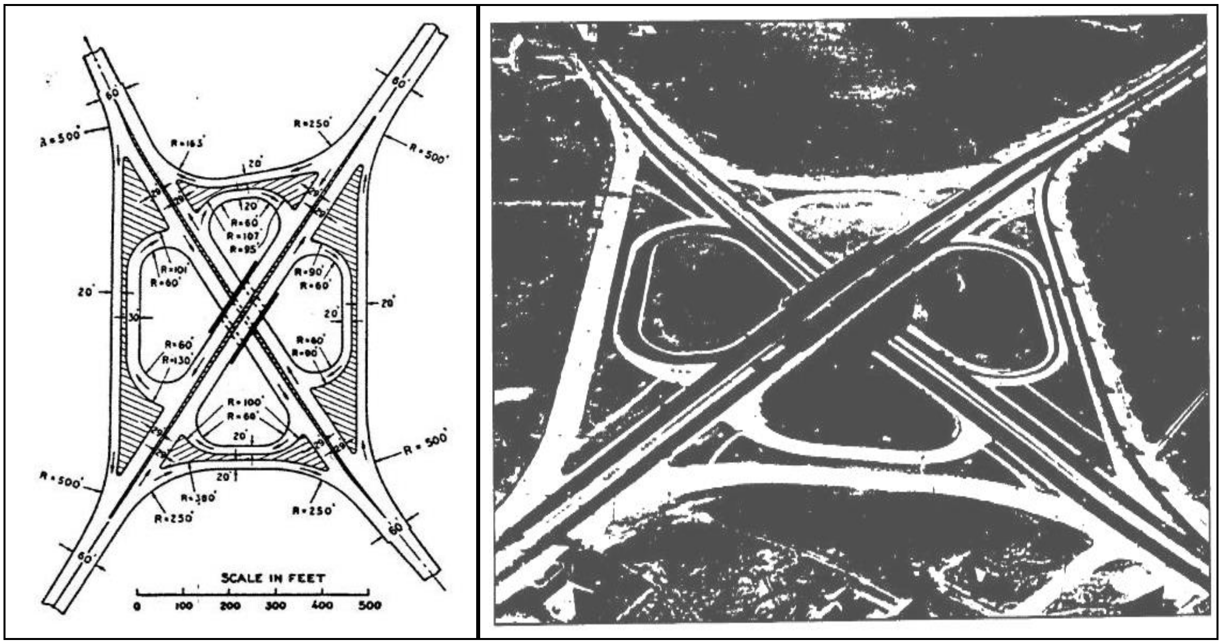


Figure 1 – US Patent Drawing (1912) and First Cloverleaf Interchange (1928)

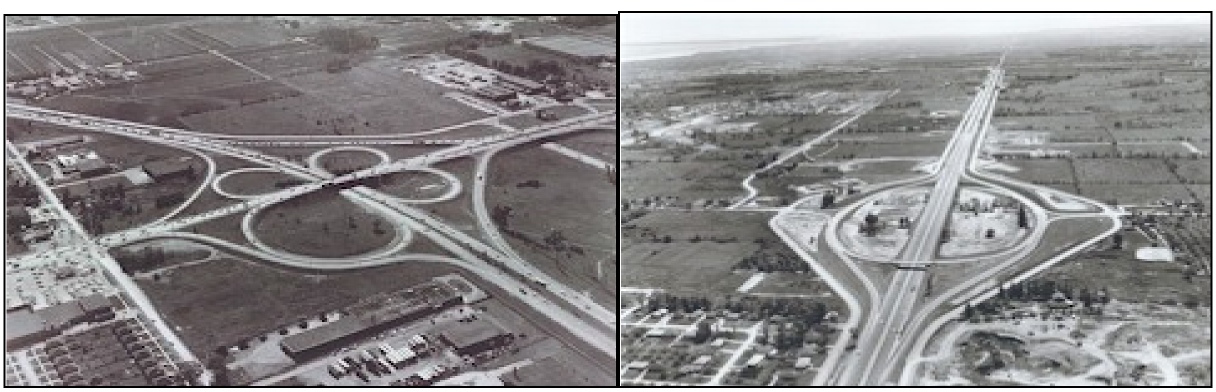


Figure 2 – Cloverleaf and Diamond/Traffic Circle Interchanges on the QEW, 1937-1940

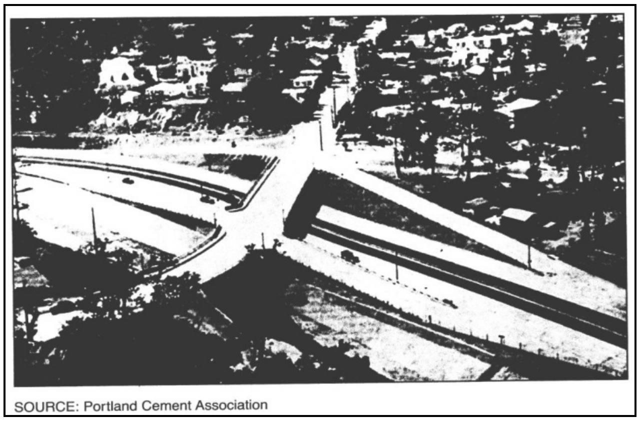


Figure 3 – First Diamond Interchange, 1941

Figure 4 – Partial Cloverleaf, 1950

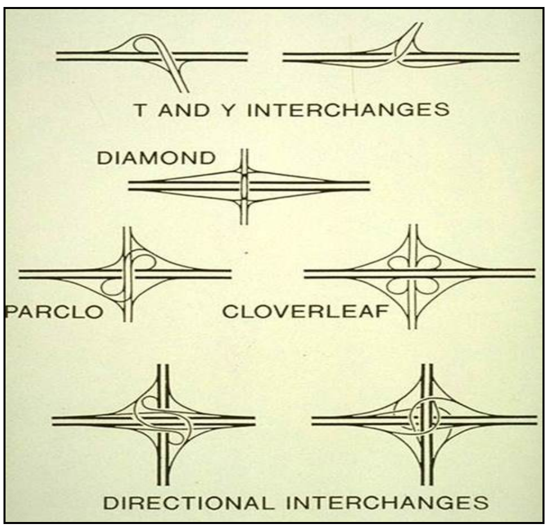


Figure 5 – Basic Interchange Forms, 1956

Figure 6 – System Interchange, 1950s-1960s

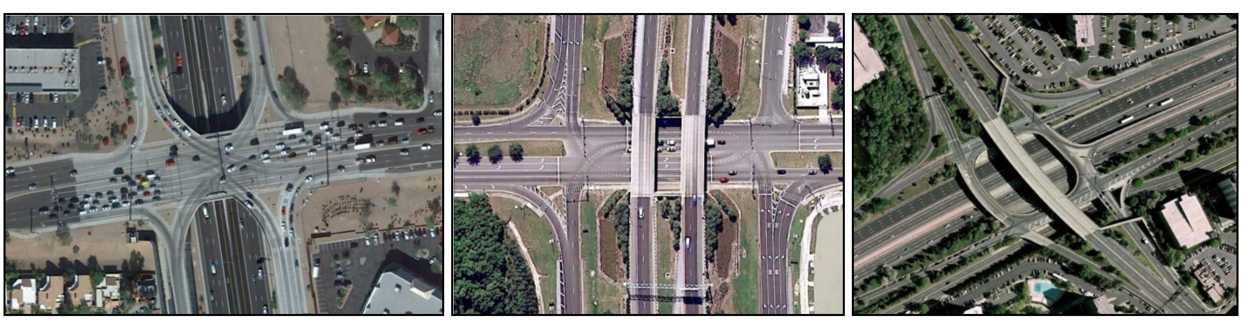


Figure 7 – Single Point Urban Interchange, Tight Urban Diamond, 3-Level Diamond

Figure 8 – ParClo A, Hwy. 401, Toronto and ParClo B, Deerfoot Trail, Calgary

Figure 9 – All Directional Interchange and Directional with Two Loop Ramps

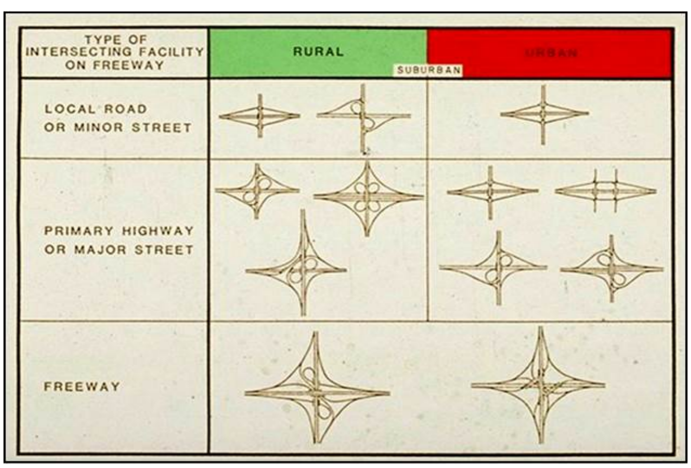


Figure 10 – Interchange Selection

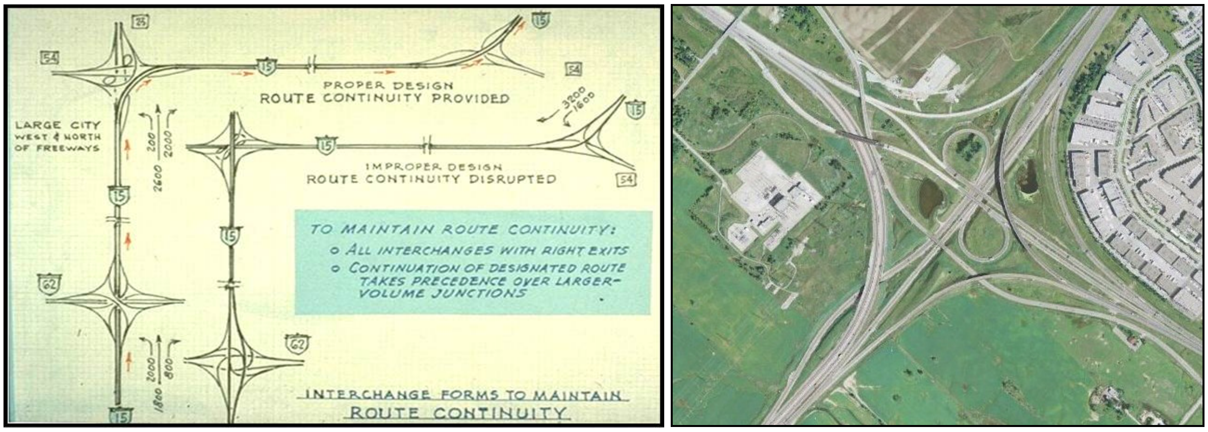


Figure 11 – Route Continuity Concept, Hwy. 407 Near Toronto

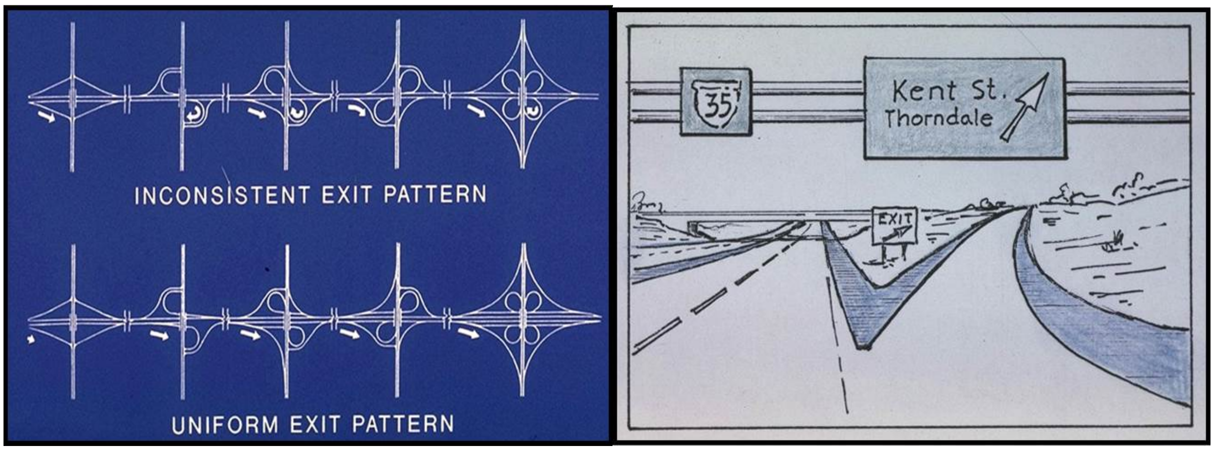
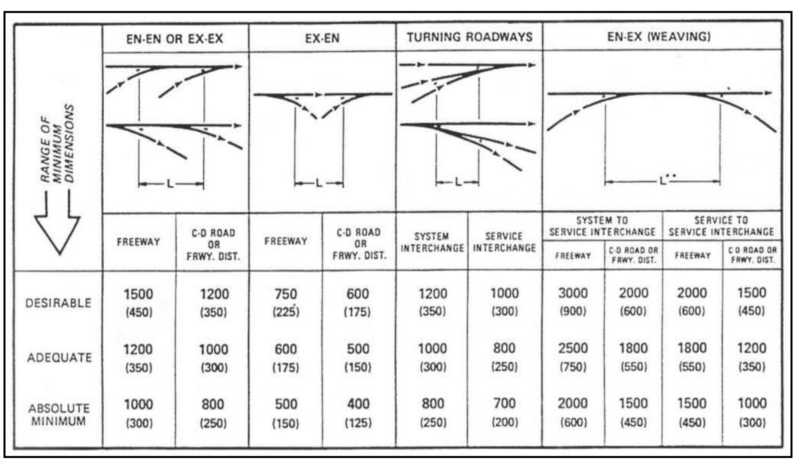


Figure 12 – Single exit, on right, advance of crossroad, simplified signing



RANGE OF MINIMUM DIMENSIONS	EN-EN OR EX-EX		EX-EN		TURNING ROADWAYS		EN-EX (WEAVING)			
							SYSTEM TO SERVICE INTERCHANGE		SERVICE TO SERVICE INTERCHANGE	
	FREEWAY	C-D ROAD OR FRWY. DIST.	FREEWAY	C-D ROAD OR FRWY. DIST.	SYSTEM INTERCHANGE	SERVICE INTERCHANGE	FREEWAY	C-D ROAD OR FRWY. DIST.	FREEWAY	C-D ROAD OR FRWY. DIST.
DESIRABLE	1500 (450)	1200 (350)	750 (225)	600 (175)	1200 (350)	1000 (300)	3000 (900)	2000 (600)	2000 (600)	1500 (450)
ADEQUATE	1200 (350)	1000 (300)	600 (175)	500 (150)	1000 (300)	800 (250)	2500 (750)	1800 (550)	1800 (550)	1200 (350)
ABSOLUTE MINIMUM	1000 (300)	800 (250)	500 (150)	400 (125)	800 (250)	700 (200)	2000 (600)	1500 (450)	1500 (450)	1000 (300)

Figure 13 – Jack Leisch Original Table (1975) for Ramp Spacing Guidelines

Figure 14 – Interchanges with Roundabouts

Figure 15 – Double Crossover Diamond/Diverging Diamond

Geometric Feature	Operational Effect	Safety Impact
Lack of route continuity	Excessive lane changing Violate driver expectations Increased signing requirements	Moderate
No lane continuity (basic lanes)	Excessive lane changing	Moderate
No lane balance (exit entrances)	Increased lane changing	Moderate
Inadequate application of auxiliary lanes	Capacity reduction Increased lane changing	Moderate
Left exits/entrances	Increased lane changing Two-sided weaving (across all lanes) Increased signing requirements	High
Two exits/interchanges	Increased signing requirements Potential driver confusion	Moderate
Exit beyond cross road	Reduce exit visibility Driver comfort/convenience	Moderate
Inadequate exit/entrance design Short taper/parallel Small radius at exit/entrance gore	Inadequate merge/diverge opportunities Inadequate speed for entering vehicles Exiting vehicles slow on mainline-speed differential	Moderate
Inadequate exit ramp length	Queuing onto main traveled way	High
Inadequate weaving sections Short weaving section Two-sided weaving section	Capacity reduction Excessive lane changing Lane changing across all lanes Speed differential between vehicles–all lanes	High
Inadequate decision sight distance	Driver confusion/indecision Driver comfort/convenience	Moderate

Figure 16 – Operational and Safety Impacts of Interchange Design Elements

DESIGN SPEED	1940s	21st Century
• Urban	50-60 mph	60 mph
• Rural	70 mph	70-80 mph Alignment Consistency Operating Speed
CROSS SECTION		
• Lane Width	10'-13'	12'
• Shoulders	Right - 6'-10' Left - 0-2'	10'-12' 4'-10'
• Side Slopes	2:1 - 3:1	3:1 - 6:1
• Safety Appurtenances	Few if any	Concrete Barrier Guardrail End Trtmt. Attenuation Devices Frangible Supports
MEDIAN		
• Urban • Rural	4' 16'	24'-30' 60'-100' (Variable)
SIGHT DISTANCE		
• Stopping • Decision	4" Object None	Tail Light (Object) Yes

Figure 17 – Evolution of Freeway Design Criteria