ABSTRACT

ZHONG, HANTAO. Free-flow Parclo Interchange vs. the Cloverleaf Interchange with C-D Roads and the All-Directional Four-level Interchange: A Comparison of Geometrics, Construction Cost, and Right of Way Requirements (Under the direction of Dr. Joseph E. Hummer).

This thesis introduces the free-flow parclo interchange, a new modification of the cloverleaf interchange, created by Mr. Antonio Loro. The free-flow parclo interchange contains no weaving sections, has right-hand side entrances and exits only, has two loop ramps, and requires as few as two bridges. The objective of this thesis is to provide a geometric design for the free-flow parclo interchange, mainly based on A Policy On Geometric Design of Highways and Streets, and use it to estimate the cost and right-of-way of the free-flow parclo interchange relative to standard designs. I designed the free-flow parclo interchange at three different ramp design speeds (30, 40, and 50 mph) and used 70 mph as the design speed for the mainlines.

In the design process, the main purpose was saving the cost and right-of-way while ensuring the basic geometry and ramp pattern of the free-flow parclo interchange. To achieve this, I used straight bridges and avoided using retaining walls. I also chose proper deflection angles for the indirect ramps and used proper shapes of direct ramps to save the right-of-way.

As a comparison, I also finished the geometric designs of cloverleaf interchanges with collector-distributor (C-D) roads and four-level interchanges using different design speeds. These two kinds of interchanges are good comparable targets since the free-flow parclo interchange is a modification of the cloverleaf interchange and the four-level interchange is the reigning champion of urban system interchange designs in the United States.

After the geometric design, I did the right-of-way and cost comparison among the three kinds of interchanges at the three ramp design speeds. The costs mainly come from the structure costs of the bridges. The required rights-of-way of the free-flow parclo interchange, cloverleaf interchange with C-D roads, and four-level interchange range from 114 to 274 acres, 138 to 242 acres, and 75 to 130 acres, respectively. The structure costs of the free-flow parclo interchange, cloverleaf interchange with C-D roads, and four-level interchange range from $4.05M to $4.38M, $3.97M, and $8.5M to $15.6M, respectively. In addition, only the four-level interchange needed retaining walls. The free-flow parclo fell between the other two interchanges for cost and right-of-way, costing less than the four-level and needing less right-of-way than the cloverleaf with C-D roads.

Overall, the new free-flow parclo has a promising niche in system interchange design, perhaps in suburban areas. Safety and capacity analyses of the free-flow parclo interchange should be good topics for future detailed study. Designers also can try different design strategies, such as curving bridge and different ramp patterns, to try to reduce the right-of-way needed. Finally, this I recommended several other modifications of the cloverleaf interchange that can be compared with the free-flow parclo interchange. These modifications require different numbers, heights, and lengths of the bridges, so the structure costs and required rights-of-way vary

Free-flow Parclo Interchange vs. the Cloverleaf Interchange with C-D Roads and the All-Directional Four-level Interchange: A Comparison of Geometrics, Construction Cost, and Right of Way Requirements

by
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The author is interested in transportation structure geometric design. With the help and advises of Dr. Joseph E. Hummer, the author determined his thesis topic in November 2011.

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INTRODUCTION

Freeways play one of the most important roles in the current transportation system because they can carry a very large portion of traffic and provide high speed operation. Freeways provide important access to the public for their daily lives and routes for trucks for commercial activities.

Interchanges are important parts of the freeway system. An interchange is a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways or highways on different levels [1]. Based on the function, there are two kinds of interchanges: service interchanges and system interchanges. A service interchange connects freeways with surface highways or streets. The service interchange controls access to the local streets and always uses ramps to connect the two components. The system interchange interconnects two freeways; it is intended to provide safe and high speed traffic movement transfer operations between two freeways.

Interchanges achieve three objectives in the freeway system. First, interchanges provide a method to finish the traffic transformation between local streets and freeways or two freeways that at-grade intersections cannot achieve. Second, interchanges are good ways to reduce conflict points and improve the safety of the traffic movements, and they also can add extra capacity to the system. Third, interchanges improve the efficiency of traffic operations and reduce the delays at intersections. System interchanges do not use traffic signals so they can save lots of travel time.

Nowadays, interchanges have become the critical points in many designs. They determine the delay, speed, and capacity; have higher collision rates; and cost more than roadway segments. They are influenced by lots of aspects. Designers always need to take into account the right-of-way (ROW), increasing average daily traffic or peak hour traffic, driver expectations, wrong way potential, and the surrounding environment. Especially in developing cities, the available land becomes more and more precious and expensive. In addition to geometry, safety, and efficiency, the environment also becomes an important topic when companies or departments want to develop an area. The various restrictions make the design of interchanges complex and difficult. Some failed designs result in environment pollution and heavy congestion.

Since the first modern interchange in the United States was constructed and opened in 1928, engineers have developed and used numerous designs to effectively and safely manage traffic movements at interchanges [2]. These included three-leg interchanges, diamonds, partial cloverleafs, cloverleafs, directionals (with or without loop ramps), and multi-leg interchanges [3]. However, none of the existing interchanges satisfy all the requirements and restrictions at all places. As a result, transportation experts and designers have tried to provide and test new kinds of interchanges, such as single point interchanges, diverging diamond interchanges, and continuous flow interchanges.

Figure 1 shows a typical cloverleaf interchange. It is a very common but old interchange style. It uses loop ramps to achieve all left-turning movements. Cloverleaf interchanges were common prior to the 1970s at system interchanges as well as at rural or suburban service interchanges. Experience gained with the cloverleaf showed relatively low capacity due to the four weaving sections between loop ramps and high collision rates as well [3]. Besides capacity and safety issues, it has many disadvantages: long paths for loop users, weaving issues, signing, safety issues due to multiple exit points, and large right-of-way requirements. Some cloverleaf interchanges contain collector-distributor roads (C-D roads), but these also have significant traffic weaving issues.

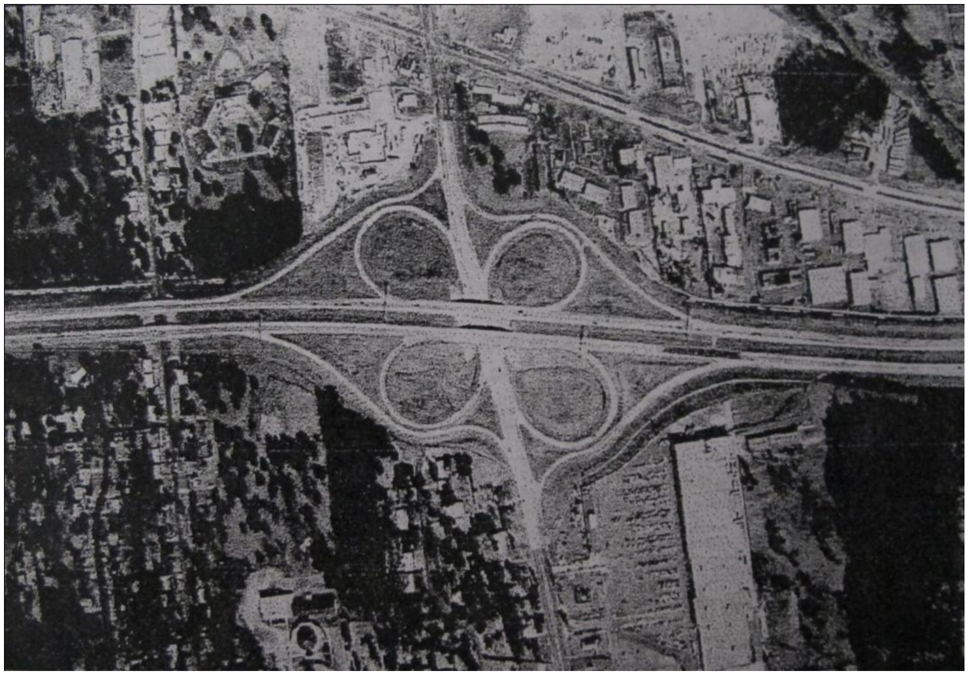

Figure 1 Typical Cloverleaf Interchange [3]

Building upon the traditional cloverleaf interchange, Mr. Antonio Loro has created a new system interchange design, the free-flow parclo interchange. The main advantages of free-flow parclo interchange are that it: [4]

- Contains no weaving sections,
- Has right-hand side entrances and exits only,
- Has two loop ramps, and
- Requires as few as two bridges, which is fewer than any known alternative weaving-free system interchange configurations with right-hand entrances and exits only.

Loro asserts that the free-flow parclo interchange should be strongly considered when: [4]

- There is a need for a weaving-free interchange due to new freeway construction or due to the poor performance of an existing cloverleaf interchange because of weaving problems or low design speed in the loops, and

- Budgetary, environment, or other limitations preclude the use of conventional system interchange configurations that require more, longer, or higher structures, e.g., the four-level directional or modified cloverleaf configurations such as the ‘clover-stack’ and the ‘clover-turbine’.

The basic illustration of the free-flow parclo is shown in Figure 2.

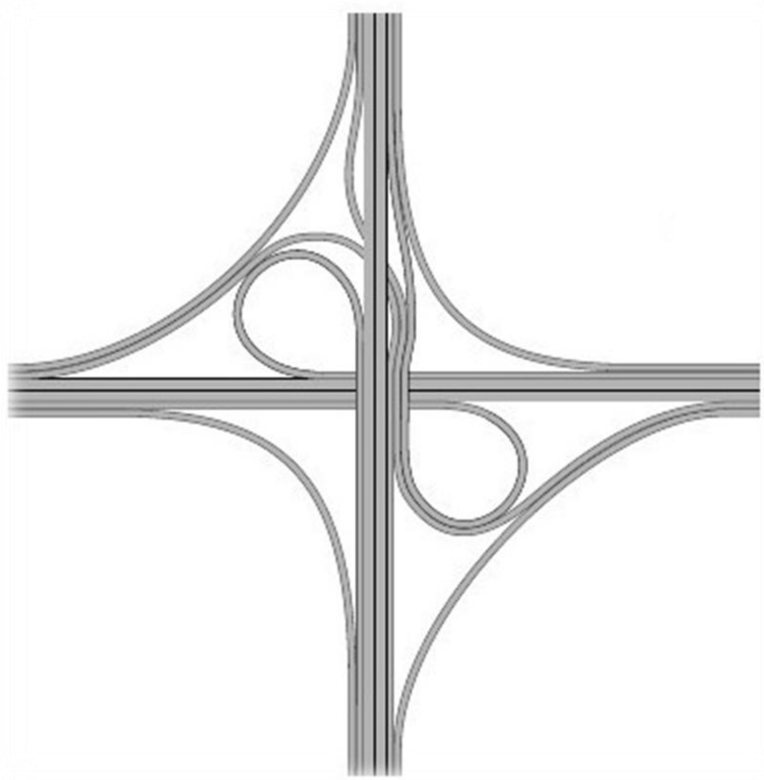

Figure 2 Basic Geometric of Free-Flow Parclo Interchange [4]

There is at least one previously existing weaving-free interchange design that requires only two bridges; however, it uses left-hand exits and entrances and requires that the mainlines curve and diverge [4]. The left-hand exits and entrances violate driver expectations and cause safety issues. Other known designs that are weaving-free with right-hand exits and entrances need at least three bridges, such as the clovermill interchange and the continuous flow interchange. So, the free-flow parclo interchange would seem to have strong advantages in cost and safety.

Unfortunately, the free-flow parclo has not yet been built. The objective of this paper is therefore to introduce the free-flow parclo interchange and provide a geometric design for the free-flow parclo mainly based on *A Policy On Geometric Design of Highways and Streets* [1]. After the geometric design, the paper provides comparisons of geometry, cost, and right-of-way between the free-flow parclo and the all-directional four-level interchange as well as the cloverleaf interchange. The main software that I used to estimate the cost and required right-of-way is AutoCAD. All the basic design elements and parameters are based in the *A Policy On Geometric Design of Highways and Streets* [1]. The cost and right-of-way are determined after finishing the geometry, since the heights and spans of bridges, shapes and radii of ramps, requirement of retaining wall are all decided in the geometric design.

In addition to the geometric design, designers and researchers need to build models and conduct simulations to analyze the interchange capacity, collision estimates, environment effects, etc. These models require different software, such as VISSIM, and traffic data. While very necessary before a new design is built, this effort was limited to geometry, cost, and right-of-way. If the new design proves promising in these areas, future research should take capacity, collision estimates, environmental effects, and other impacts into account.

LITERATURE REVIEW

The objective of the literature review is to identify the relevant interchange design elements and the best comparison interchanges for the new free-flow parclo interchange.

Interchange Spacing

Interchange spacing has a sizeable influence on the whole freeway system. The concept of interchange spacing affects the new free-flow parclo design because the more ROW a design consumes, the shorter the spacing to the next interchange. Proper interchange spacing can improve the mobility and efficiency of the whole traffic system. However, it is hard to attain a proper spacing between interchanges because the requirements of traffic entrances and exits. If the interchanges are too close to each other, they will influence the traffic operation of the adjacent ones. The traffic streams from adjacent interchanges perhaps can weave across each other, causing delays and collisions. Interchanges that are too close also make signing difficult, forcing drivers to divert too much attention to reading too many signs and causing driver confusion. Closely spaced interchanges encourage short trips on the freeways and reduce the mobility function of the facility [5].

Interchange spacing also affects traffic safety. Bared and Zhang developed valid fatal/injury crash prediction models that show the relationship between crashes and interchange spacing. These models quantify the sensitivity of crash rates to interchange spacing for fatal and injury crashes. A major value of the model is the ability to evaluate the impact of inserting new interchanges in existing urban freeway interchange spacing [6]. Their basic data come from 7 urban freeways in California and 10 urban areas in the State of Washington.

Route Continuity and Lane Continuity

Route continuity refers to the provision of a directional path along and throughout the length of a designated route [1]. It is an important aspect to maintain and improve traffic mobility and travel speed. Route continuity helps meet driver expectations, and reduces lane-changing movements. It needs to use simple signs to help drivers finish the through movement and avoid driver confusion with a continuous through route.

Proper and efficient route design has lots of benefits. It can improve the level of service, ensure the travel speed, avoid driver confusion and ensure the safety, even save some freeway system maintain cost. In a certain segment of a freeway route, it should have a consistent number of lanes to ensure the traffic movements can be operated smoothly. This is the lane continuity [1]. If there are weaving or capacity issues, we can add auxiliary lanes to the route, but they are always designed to the right side of the route. The start and termination of auxiliary lanes also need to be calculated carefully. The purposes of the lane continuity is similar to those of route continuity, it helps the drivers avoid confusion and lane-changing movement, and improves the safety and mobility.

Ramps Types and Consistent Ramp Pattern

Figure 3 shows some basic type of ramps. Ramps can be divided into three kinds: direct ramp, indirect ramp, and loop ramp. Direct ramps are widely used to achieve right turn movements in interchanges with high design speeds and low costs. Indirect ramps are often used for left turn movements. However, an indirect ramp requires a high cost and may use a large right-of-way. A loop ramp is a very common type of ramp in a system interchange to achieve left turn movements. Loop ramps need large rights-of-way and it is rare to have a loop ramp with a high design speed.

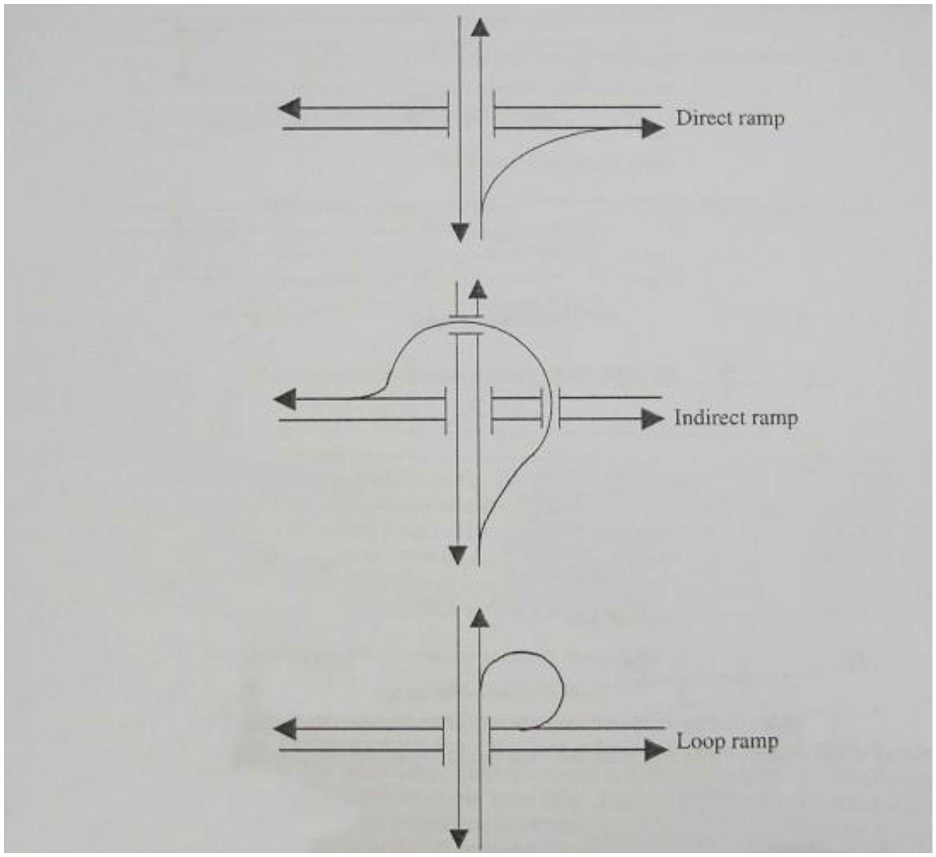

Figure 3 Types of Ramps [5]

Ramp design must account for speed changes and transitions to and from the interchanging facilities. Service interchanges typically require transitioning to a stop condition and providing adequate storage for queued vehicles. System interchange ramp configurations often require special attention to grade separations as well as ramp and freeway levels [7]. Drivers expect high speeds on ramps at a system interchange.

Indirect ramps are mostly used in high-volume conditions. Loop ramp designs require applying speed transition principles for decelerating and accelerating traffic. These three-dimensional considerations can affect horizontal ramp placement to attain desired grades [7].

At interchanges, drivers always expect a consistent ramp pattern for both merging and diverging movements. The consistent ramp pattern also keeps drivers from facing too much unexpected information. Drivers always expect all right side ramps, the off-ramp prior to the crossroad, and the on-ramp after the crossroad.

Some interchanges that have left-hand ramps have been built in United States, but these unconventional designs usually have issues. There have been many studies and projects that show the drawbacks of the left-hand exits and entrances. A very early study was done in 1963 which focused on the difference in collision rates between right-hand ramps and left-hand ramps. Table 1 shows the study result. It is obvious that left-hand ramps had a much higher collision rate.

Table 1 Collision Rates in California [8]

Ramp Type	On	Off	On+Off
Left Hand Ramps	0.93 (Col/MV)	2.19 (Col/MV)	1.91 (Col/MV)
Average	0.59 (Col/MV)	0.95 (Col/MV)	0.79 (Col/MV)

Col/MV = Collision/ Million Vehicles

Garber and Fontaine stated that system interchanges usually operate best when there are right-hand exits and one or more direct connectors [9]. They also concluded that left-side ramps have consistently higher collision rates than other ramp types [9].

Human factors also have its important affect on freeway safety. Hall's study showed that left-hand ramps had a higher potential to produce collisions than the right-hand ramps [10]. The reason he cited was that drivers were unfamiliar with the left-hand exits and entrances, and their normal expectations led to wrong decisions.

A recent safety study on this topic was done by Moon. He focused on the effect of left-hand ramps on collisions compared to right-hand ramps. Comparisons of collision rates for right-hand and left-hand ramps were made using collision estimation models to estimate the safety effects. Traffic, geometry, and environment data were obtained in North Carolina. In addition, collision data were available from the Highway Safety Information Services (HSIS). [11] The final estimated model is below; ramp ADT was considered first, followed by main AADT, position, type, difference between the design speeds of main freeways and ramps, speed-change lane length, and area. Based on the b_1 value, it is obvious that the left-hand ramp has a much higher total collision number than the right-hand ramp.

$$y = 0.682 \times (\text{Ramp ADT}/10000)^{0.8925} \times [\text{Main AADT}/10000 \times e^{-0.1139*(\text{Main AADT}/10000)}]$$
$$\times (0.0450 \times \text{difference design speed difference design speed} + e^{-0.2806*\text{difference design speed}})$$
$$\times [(\text{Length}/1000) \times e^{-1.523 \times (\text{Length}/1000)}] \times b_1 \times b_2 \quad [11]$$

where

y = total collision number for one year;

b_1 = 1 if right-hand ramp, or 3.872 if left-hand ramp; and

b_2 = 1 if off-ramp, or 3.106 if on-ramp

Ramp Widths and Ramp Acceleration/Deceleration Lengths

The ramp traveled-way width for a turning roadway includes the traveled-way width plus the shoulder width or equivalent clearance outside the edges of the traveled way [1]. It is influenced by the ramp radius, traffic volume, traffic type, and types of curb and shoulder. The shoulder can provide a necessary space for emergency stopping, to minimize the effect of breakdowns, and to aid drivers who may be confused [1]. The width of the traveled way is also important. Designers should take the movements of large size vehicles, such as trucks, into account. Sufficient widths and proper radii of ramps can ensure freeway safety and improve speed and mobility.

To ensure safe and efficient traffic flow on urban freeway and provide proper interchange spacing, it is necessary to optimize the lengths of acceleration and deceleration lanes on urban freeways. Based on the vehicles' running characteristics, acceleration lanes are typically divided into three sections, namely acceleration section, waiting merging section, and width transition section. The deceleration lane is typically divided into three sections, too, i.e. width transition section, the first deceleration section, and the second deceleration section [12].

Acceleration and deceleration lanes provide the space and time for drivers to make the merging and diverging movements. They are also signals to alert drivers to begin their movements in time. They help drivers avoid sudden lane-changing and speed-changing, and provide smooth and friendly ways to exits or entrances. They provide some benefits to reduce collisions in the gore section at the same time. Advanced lane-changing movements ensure that drivers travel in the right lane and avoid weaving in a short space and time. Proper acceleration and deceleration lanes make their contributions to increasing capacity and improving safety and efficiency.

The lengths of acceleration and deceleration lanes have a major impact on safety at interchanges. Shorter acceleration and deceleration lanes have higher probability of collisions. Urban interchanges have much higher collision rates than rural interchanges (214 collisions/100 million vehicles vs. 109 collisions/100 million vehicles). This may be partially due to inadequate acceleration lanes in urban areas due to the limited right of way [13].

Sometimes there isn't enough right-of-way or budget for long acceleration and deceleration lanes. However, even a short deceleration lane could reduce the number of collisions significantly [14].

Weaving Sections

Weaving sections are created where an entrance ramp is followed by an exit ramp within a short distance, where the ramps are connected by an auxiliary lane, and where the conflicting traffic streams are not controlled by stop signs or traffic signals [5].

Safety becomes an issue because it is hard to control the traffic movements throughout the weaving sections. The weaving section should have enough length and proper acceleration and deceleration lanes. The safety study of the relationship between weaving section length and crashes by Bonneson and Pratt indicated that longer acceleration and deceleration lengths lead to fewer crashes [15]. Enough length also provides the space for guide signs. It helps drivers accept the important information and have enough time to make decisions.

Weaving sections also restrict freeway capacity. Chapter 12 of the *Highway Capacity Manual* introduces and provides a methodology to analysis the capacity of weaving sections [16]. For example, in the middle section of typical cloverleaf interchange, weaving movements have low speed and efficiency, which has become a big drawback.

Given the undesirable effects of weaving sections, some designers apply collector-distributor (C-D) roads in new designs to more the weaving areas from mainline roadways. Designers also develop some interchanges that contain no weaving sections, such as the free-flow parclo, to improve system efficiency and safety. However, interchanges without weaving sections likely cost more than conventional ones, because they create new structures and connections.

Signing and Marking

Travel on freeways is almost always at a high speeds. The interchange and environment also could be complex and unfamiliar to drivers. To ensure safety, efficiency, and correct decisions during the freeway travel, necessary and proper signing and marking are important.

Human factors are important remarkable in signing and marking designs. There are five main concepts that come into play in interchange sign placement: overload, spreading, primacy, repetition, and redundancy [5]. The amount of information and their importance on a guide sign is a key limiting factor for maintaining the legibility of signs on higher speed freeways [17]. We must make sure the drivers do not have to accept too much information at one time. Too much information can divert their attention and result in poor decisions. The minimum distance between two signs is 800 feet. We also need to make drivers will not miss important information that helps them choose correct paths and speeds. The number of signs and the amount of information in one sign are good targets that need to be studied. Hawkins recommended that sometimes designers need to put more guide signs and markings throughout one freeway segment, since the amount of information that can be contained in one sign is limited, especially when the traffic speed is high [18]. More signs and markings mean they will require a longer length; how to find the balance between the two is a challenge.

Signs and markings need to be direct, simple and clear. Designers should avoid making drivers waste time on thinking about the meaning of a sign or marking or provide repetitive information too many times, because that means longer reaction time and sight distance. It also push drivers make wrong decisions. This is very important when the interchange is complex and unfamiliar to the drivers. It can reduce the wrong way potential and improve efficiency and safety.

Overpass or Underpass

Whether to place the crossroad on an overpass or an underpass is another important design item at an interchange and affects the free-flow parclo design. The first factor that needs to be taken into account is the topography. The design should fit the existing topography. It can make the interchange building become much easier and save lots of budget on the earth work and structures. The designer should not only think about the crossing highways, but also the related structures. The whole views of the interchange and the target area are important. We need treat the interchange as a whole structure. Except the crossing highways, the loops, ramps, and bridges should fit the topography too.

If the topography doesn't favor one upon another, the advantages of different styles are secondary criteria.

A crossroad over the freeway provides [5]:

- A single structure, probably smaller than for the freeway going over the crossroad;
- Off-ramps that go uphill and on-ramps that go downhill, allowing gravity to aid deceleration and acceleration;
- Good visibility on the freeway to the crossroad, providing an early alert to existing drivers; and
- Less noise impact from the freeway.

The choice between overpass and underpass also has its influence on future developments. It affects the cost of widening roadways, adding new levels, the location of new structures and so on.

Similar Designs

Except the free-flow parclo, there are some other interchanges that have straight mainlines, no weaving sections, and use right-side exits and entrances. These include the turbine, windmill, clover-turbine, continuous flow interchange, clovermill, braided cloverleaf, nano, parclo with two flyovers, and four-level.

The free flow parclo interchange is a development based on the cloverleaf interchange, and it has two loops. Though the cloverleaf is an old design and does not avoid the weaving area, it is very common and still being built in many countries, such as China. So the cloverleaf interchange is a good comparison target for the free-flow parclo interchange. Nowadays, cloverleaf interchanges are usually built with collector-distributor roads to mitigate the weaving issue at the mainline. The weaving issue happens in the sections between two adjoining loop ramps. It will result in a huge reduction in travel speed and the traffic service when the traffic weaving volume in the special area exceeds 1,000 vph (vehicle per hour) [1]. A C-D road is a good way to remove the weaving section from the freeway main lanes to improve the system mobility. Figure 4 shows a cloverleaf interchange with C-D roads.

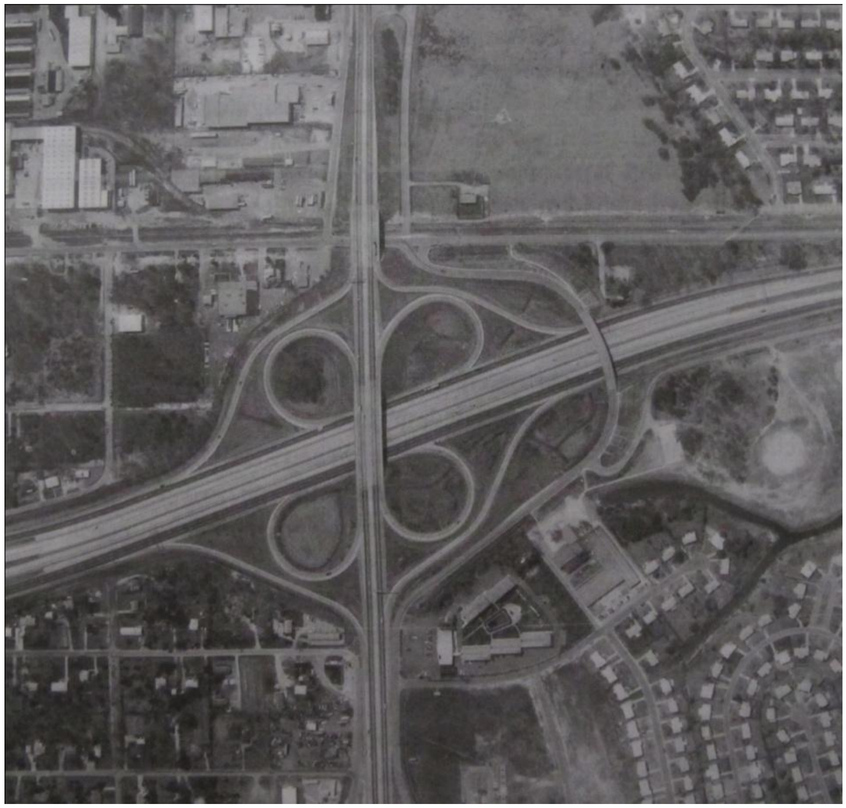

Figure 4 Typical Cloverleaf Interchange with C-D Roads [1]

The cloverleaf interchange only needs one bridge for the whole system. This is an impressive advantage. It makes the structural cost of the cloverleaf stand out among all the system interchanges. The ramp pattern meets the driver expectations only with C-D roads. All the left-turning movements are achieved by loop ramps, and there is no strange or unfamiliar structure to drivers. Signing and marking is easier than other designs since the configuration of the cloverleaf is very common.

Though the advantages that the cloverleaf interchange has are considerable, they cannot compete with the disadvantages of this old design when we think about the design from an integrated view. The four loops of cloverleaf require a very large right-of-way, which means that the cloverleaf only can be built in a rural or suburban area. A cloverleaf will require that a lot of land is removed from the tax rolls forever.

The travel distance and travel time on the loop, as compared with that of a direct left turn at grade, increase rapidly with an increase in design speed. On a loop designed for 50km/h (80 m radius) [30 mph (250-ft radius)], the extra travel distance is approximately 500 m [1,500 ft]. For a 10 km/h [5 mph] increase in design speed, extra travel distance increases 50 percent; the right-of-way area needed increases by about 130 percent [1]. For an increase of 10 km/h [5 mph] in loop design speed, travel time increases 20 to 30 percent or approximately 7s [1].

Trucks are another big issue for interchange operations. If designers want to save money and right-of-way by using small radius loops, it will become harder to operate trucks in the area with high efficiency and speed. The trucks have a huge influence on the traffic operation; slow trucks can result in a significant reduction on the efficiency and mobility of the whole system.

Except the weaving and right-of-way issue, the loop capacity is another restriction for the cloverleaf interchange. A loop rarely operates with more than a single line of vehicles, regardless of roadway width, and the loop ramp always has a lower design speed than the direct ramp [1] With rapid increase of traffic volume, the limited capacity of the one-lane loop would not be able to meet the traffic demand. If designers want to apply a two-lane loop, the design will become much more complex and expensive. The two-lane loop will produce new weaving issues. Two-lane loops also require larger rights-of-way, which increase the budget.

The population and traffic volume are increasing rapidly nowadays, which make congestion a difficult problem that designers need to face, especially in urban areas. For example, congestion on the Beijing freeways every day can easily exceed 5 hours. All the drivers complain about this situation, but it is really hard to eliminate congestion since the constraints come from the limited right-of-way and other surrounding environments. The right-of-way is the biggest factor that designers need to take into account for the urban area interchanges. Property costs are becoming higher and higher in dense urban areas, especially in developing countries such as China and India. Designers must develop an interchange that can provide high capacity in the constrained right of way. The design speed for the interchange also cannot be too low.

The stack interchange is the reigning champion of the urban system interchanges; we also call it the four-level interchange. It is very popular in the United States. Many four-level interchanges have been built in many states. Figure 5 shows a typical four-level interchange. Table 3 shows the locations of some four-level interchanges. It requires much smaller right-of-way than the cloverleaf interchange since it avoids using loop ramps. However, it needs higher and longer bridges than a cloverleaf and requires retaining walls, so the cost of the four-level interchange is huge.

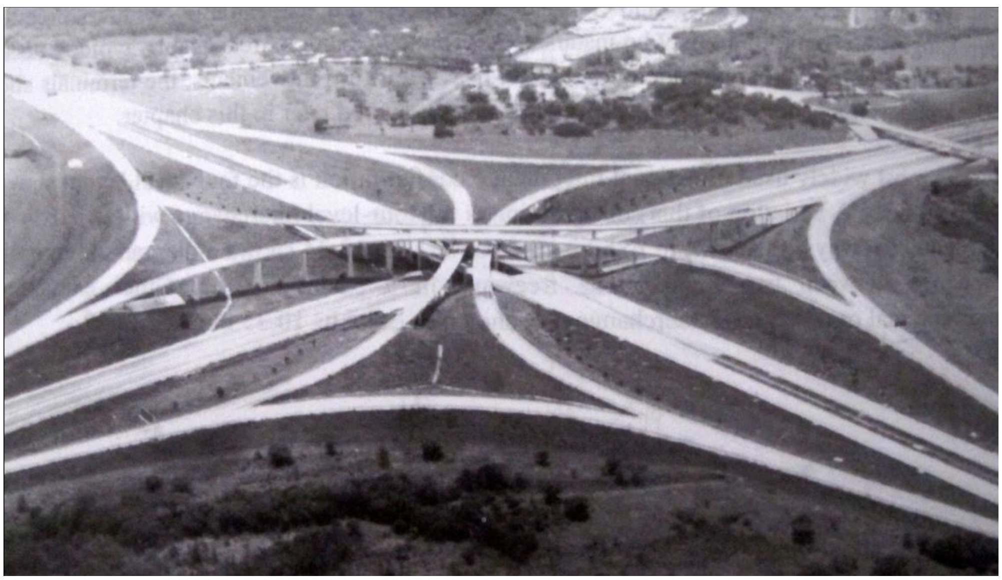

Figure 5 Four-level Interchange [5]

The four-level interchange has advantages and disadvantages compared to other system interchanges. The four-level interchange can achieve continuous traffic flow without loops and weaving areas, and the turning movements can be designed to have relatively high speeds. The four-level interchange can therefore be more efficient for high traffic volumes. The elimination of the weaving area also improves the efficiency and safety. As shown in

Table 3, the number of ramp lanes in the four-level interchange can be very flexible. This means the ramp capacity does not have to be an issue for the interchange any more, and this style interchange can be designed various ways to suit different situations. The strongest advantage is right-of-way; the four levels mean the traffic transfer can be operated in a limited space with acceptable efficiency and mobility.

The cost of the four-level interchange is the first large negative issue. The number of bridges is greater than other interchanges. The length and height of the bridge are large too. The cost for structures for this design is probably higher than all the other system interchanges discussed in this section. Though the right-of-way and property cost of the four-level interchange is low, the structural cost makes the total budget for a four-level interchange high. Since there is a big change in elevation, the four-level interchange also requires retaining walls. This is another big part of the cost. Another negative is the ramp grades. To achieve the traffic movements, the ramps must finish the movement in a short horizontal range but large vertical distance. So the grades of the ramp are steep and unfriendly to drivers.

There are other system interchange designs described in the literature, but they have more important limitations that prevent them from being serious general competitors to the free-flow parclo interchange. For example, the windmill interchange is a very rare design, and the clover-trubine interchange requires very large right-of-way.

Table 2 Four-level Interchange Locations [19]

	All-Directional Four-level Interchanges				# Ramp Lanes
	City	State	Freeway	Freeway	
1	Cleveland	OH	I-490	I-77	1
2	Shreveport	LA	LA 3132	I-49	1
3	Baton Rouge	LA	US 61/190	I-110	1
4	Dallas	TX	President George Bush Turnpike	Dallas North Tollway	1
5	San Antonio	TX	I-410/US 281	I-37/US 181	1
6	San Antonio	TX	I-10/US 90/US 87	I-35/US 81	1
7	San Antonio	TX	I-10/US 90/US 87	I-37/US 281	1
8	Baltimore	MD	I-695	I-70	1
9	Nashville	TN	I-440	I-65	1
10	Queens, NY	NY	I-295	Grand Central Parkway	1
11	Birmingham	AL	I-20	I-459	1 and 2
12	Birmingham	AL	I-65	I-459	1 and 2
13	Dallas	TX	I-45/US 75	I-30/US 67	1 and 2
14	Houston	TX	I-610	US 75	1 and 2
15	Houston	TX	I-610	US 59	1 and 2
16	Houston	TX	I-610	TX 288	1 and 2
17	Houston	TX	I-610	I-10/US 90/TX 73	1 and 2
18	Houston	TX	I-610	I-10/US 90/TX 73	1 and 2

Table 2 Continued

19	Denver	CO	CO 470	I-25/US 87	1 and 2
20	Seattle	WA	I-90	I-405	1 and 2
21	Phoenix	AZ	I-10	AZ 202	1 and 2
22	Phoenix	AZ	I-17	AZ 101	1 and 2
23	San Diego	CA	I-8	I-805	1 and 2
24	Los Angeles	CA	US 101	CA 110	1 and 2
25	Detroit	MI	I-75	I-696	1 and 2
26	Detroit	MI	I-96	MI-39	1 and 2
27	Cleveland	OH	I-90/I-490	I-90/I-71	1 and 2
28	Independence	OH	I-77	I-480	1 and 2
29	Albany	NY	I-90	i-787	1 and 2
30	Albany	NY	I-90	US 9	1 and 2
31	Ontario	CA	I-15	I-10	2
32	Pomona	CA	CA 57	I-10	2
33	Atlanta	GA	I-85/State 403	GA 407	1,2 and 3

Summary

This chapter shows the most important and relevant design elements that designers should take into account when thinking about system interchange designs. The elements that need to be considered include ramps types, ramp widths, acceleration/deceleration lengths, and overpass or underpass. This chapter showed the research on the safety of left-side ramps. The research has revealed that left-side ramps have consistently higher collision rates than right-side ramps because drivers were less familiar with the left-hand entrances and exits, and their normal expectations led to wrong decisions. The chapter showed that weaving sections often produce safety issues, restrict the freeway capacity, and reduces mobility and efficiency. Finally, this chapter reviewed the current system interchange designs, including the cloverleaf interchange with C-D roads and the four-level interchange. These two interchange designs are considered to be the most comparable with the free-flow parclo interchange. The free flow parclo interchange is a development based on the cloverleaf interchange since it has two loops. The four-level interchange is the reigning champion of the urban system interchanges. Many four-level interchanges have been built in the United States; they require small rights-of-way and high costs.

FREE-FLOW PARCLO INTERCHANGE GEOMETRIC DESIGN

The objective of this paper is to provide a geometric design for the free-flow parclo interchange mainly based on *A Policy On Geometric Design of Highways and Streets*.[1] After the geometric design, I will estimate the cost and right-of-way of the free-flow parclo interchange and compare them with the all-directional four-level interchange as well as the cloverleaf interchange. This section describes the geometric design of the free-flow parclo and its competitors, including value selections and important design decisions. To minimize the rights-of-way required, minimum design values were welcomed. However, the geometry produced by minimum values may have negative influence on driving safety. All the values were therefore chosen to achieve a balance between right-of-way and interchange performance.

I chose 70 mph as the mainline design speed since this value is normal in the United States. I chose ramp design speeds of 30, 40, and 50 mph because these represent a feasible range for new system interchange designs in the US and other countries with similar freeway systems. Most loop ramps on system interchanges in the US have at least 30 mph design speeds. However, ramp design speeds above 50 mph would lead to ridiculously large rights-of-way for most urban and suburban areas.

The basic design parameters are shown in Tables 4, 5 and 6. Calculations for different design speeds are in Appendix.

Table 3 Basic Design Parameters for the Free-flow Parclo Interchange

Roadway	Mainline	Ramp
Design Speed, mph	70	30, 40, or 50
Lane Width, ft	12	12
Median Width, ft	10	10
Left Shoulder Width, ft	4	4
Right Shoulder Width, ft	8	8
Clear Zone Slope	1/4	1/4
Clear Zone Width, ft	30	30
Through Lanes	3	1

Table 4 Design Parameters for Free-flow Parclo Interchange Horizontal Alignment

Roadway	Mainline	Ramp
Minimum Radii, ft	None	30 mph – 231
		40 mph – 485
		50 mph – 833
Minimum Acceleration Lane Length, ft	None	30 mph – 1350
		40 mph – 1000
		50 mph – 580
Minimum Deceleration Lane length, ft	None	1500
Maximum Superelevation Rate, %	None	6

Table 5 Design Parameters for the Free-flow Parclo Interchange Vertical Alignment

Roadway	Mainline	Ramp
Crest K Factor	None	30 mph – 19
		40 mph – 44
		50 mph – 84
Sag K Factor	None	30 mph – 37
		40 mph – 64
		50 mph – 96
Maximum Grade, %	None	4
Vertical Clearance, ft	16	16

The range of maximum superelevation rate in the United State is from 4% to 12%. The maximum rates of superelevation are controlled by four factors: climate conditions; terrain conditions; type of area; and frequency of slow-moving vehicles whose operation might be affected by high superelevation rates [1]. Though large superelevation rates are helpful for high speed traveling, it is rare to use them in high volume interchanges. This free-flow parclo interchange can be built in different states and countries, so ice and snow climate must be taken into account. For ice and snow conditions, the coefficient of friction decreases a lot, and a maximum superelevation rate of 8% is used to ensure safer driving and vehicle stopping. Low superelevation rates are also friendlier to turning trucks, making negotiation of the curves easier and safer. The low rates also have less affect on slow speed vehicles. Judging from all the factors above, a 6% maximum superelevation rate was my choice for this design.

To improve the safety and drivers' comfort level, spiral curves were used in the free-flow parclo interchange design. Roadways with high speeds and sharp curvature almost always benefit from longer transition roadways. Drivers naturally follow a spiral path to make a turning movement while staying in a specific lane. Spiral curves are helpful for this design; they provide safer and more comfortable paths between the runoffs and curves, as well as between two curves. A proper transition curve length also provides a suitable location for the superelevation runoff [1]. The application of spiral curves also has its own restrictions. First is the minimum lateral offset between the tangent and circular curve, ρ_{min}. The recommended value for ρ_{min} is 0.66 ft [1]. One should use a spiral curve instead of a simple curve when the lateral offset is greater than ρ_{min}, which was the case for every curve in all designs developed during this effort. Though most of the curves have spirals, there are three sections of the indirect ramps that use simple curves, as will be explained later.

Next is the maximum lateral offset between the tangent and circular curve, ρ_{max}. The ρ_{max}, 3.3 ft [1], is consistent with the maximum lateral shift that occurs as a result of the natural steering behavior of most drivers. It also provides a reasonable balance between spiral length and the curve radius [1]. The lateral offset is a factor to determine the length of spiral.

To be cost-conscious, minimum radii are welcomed to save the right-of-way. For 50 mph design speed curves, the lateral offset of the 833 ft minimum radius is in the range. It means I can use the minimum radius for all the 50 mph curves. However, for 30 mph and 40 mph design speed ramps, the lateral offsets of the minimum radii curves are greater than the ρ_{max}. In such instances, I must use larger radii to decrease the lateral offsets. In the end, I chose 300 ft as the radius for 30 mph design speed curves and 510 ft as the radius for 40 mph curves to ensure the lateral offsets are less than the ρ_{max}. By using these two radii, the lateral offsets drop into the feasible range, and they are very close to the maximum value, while using radii as small as possible to save right-of-way.

The sum of left shoulder width and right shoulder width should not exceed 12 ft [1], so I choose 4 ft and 8 ft as the widths for left shoulder and right shoulder respectively. For a barrier, I used a minimum width of 2 ft. Therefore, the median width will be 10 ft.

With a 30-foot clear zone and a 1:4 slope, the vertical distance between the edge of lane and the slopestake line is 5.5 ft as Figure 6 shows. If the vertical change between two roadways closer than 30 feet apart exceeded 5.5 ft, retaining walls were needed and the cost will increase. A proper slope gradient can improve safety and avoid overturning collisions.

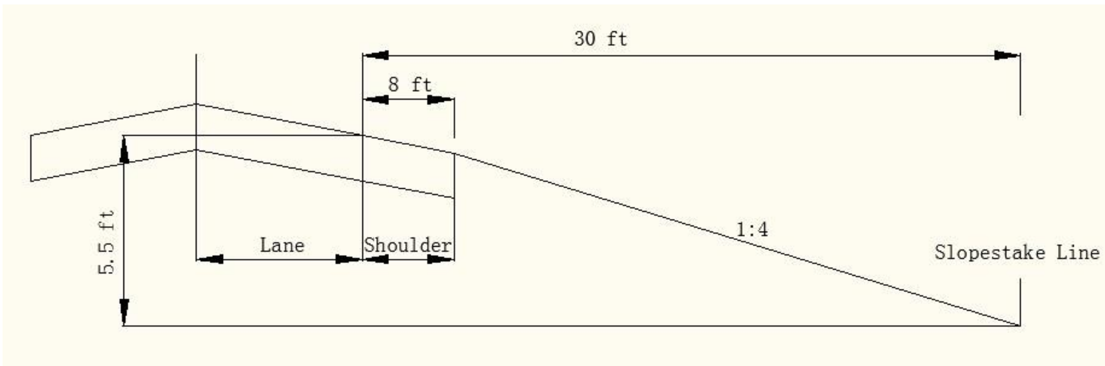

Figure 6 Slope Gradient and Measurements

For entrance ramp terminals, I chose the parallel type design as is standard practice in North Carolina. Parallel-type entrances can provide more time and space to enable the merging vehicles to accelerate to a speed near the mainline vehicles. The taper at the downstream end of a parallel-type acceleration lane should be a suitable length to guide the vehicle gradually onto the through lane of the freeway. For the 70 mph design speed mainline, the recommended taper length is 300 ft [1].

For exit ramp terminals, I chose a taper type design as is standard practice in North Carolina. The taper-type exit fits the direct path preferred by most drivers, permitting them to follow an easy path within the diverging area [1]. Drivers only need to perform one steering movement before they enter the ramp.

Figure 7 shows the key parts of the free-flow parclo interchange design, which are the two indirect ramps. They have a profound effect on the interchange right-of-way and overall layout. They also determine the span and path of the ramp bridge which can greatly affect the total cost. In Figure 7, the indirect ramp that carries southbound left-turning traffic is shaded to aid viewing.

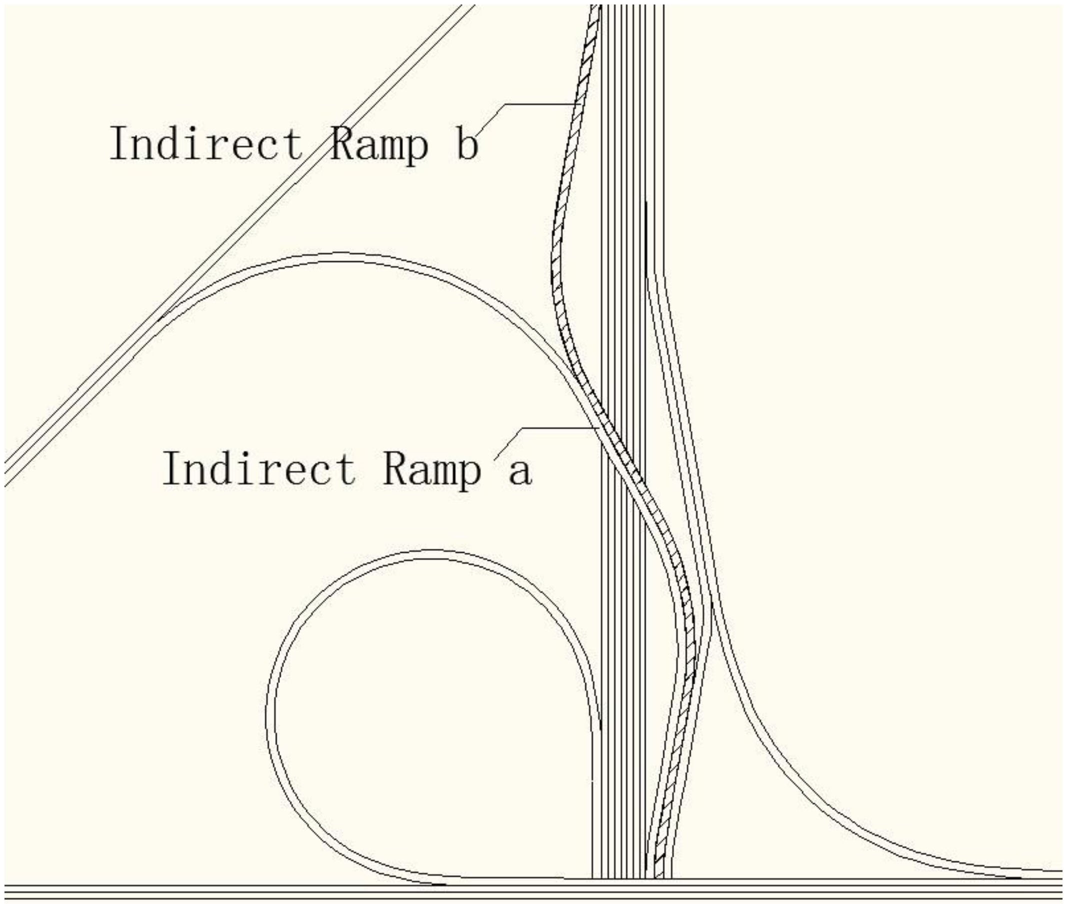

Figure 7 Indirect Ramps in the Free-flow Parclo Interchange

Figure 8 shows the free-flow parclo interchange design divided into three key sections. In section I, there are three adjacent ramps which have the same deflection angle. For 40 mph and 50 mph design speed indirect ramps, I placed the runoff and tangent runout (TRO) parts of the curves under the bridge to save right-of-way. These ramps were long enough to achieve the vertical change from under the east-west freeway in section I to over the north-south freeway in section II. However, for the 30 mph design speed indirect ramps, the paths of these ramps were not long enough to make the vertical change if I put the runoff and TRO parts under the bridge, since these curves use much shorter radii. A design goal for the indirect ramps in section II was to provide a straight bridge which had the best possible angle to the freeway. If the angle between the bridge and freeway is closer to the 90 degrees the span of the bridge is shorter. On the other hand, the bridge angle affects the paths of the indirect ramps, especially the curves in section III. If the bridge angle was 90 degrees, the indirect ramp a placed in section III can have a small deflection angle and will be more friendly for driving. The required right-of-way of this curve decreases at the same time. However, the indirect ramp b curve in section III will become very sharp and require a large right-of-way. So it is necessary to compromise, and it appears that the best choice is a bridge angle close to 45 degrees. Another possibility was to make the two indirect ramps divide before the end of the bridge to make the curves in section II smaller and gentler. However, in that case, I would need to make a split on the bridge or even build a new bridge. That would produce a significant increase in the cost which is not reasonable.

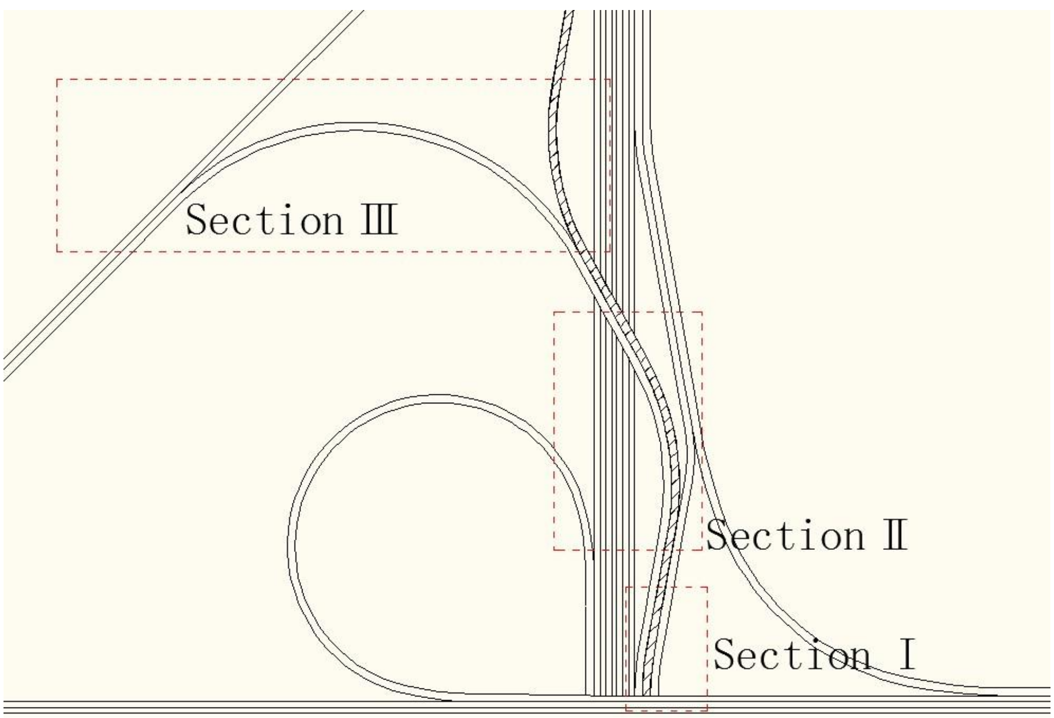

Figure 8 Important Sections of the Indirect Ramps

The deflection angles of the indirect ramps in section I was another important design choice. To determine the deflection angles of the curves in section I, I assumed that the angle of the ramp bridge was 45 degrees and used different deflection angles to check the required right-of-way and the path lengths. Figure 9 shows the ramp changes and the right-of-way requirements based on different deflection angles of the curves in section I. According to Figure 9, with an increase of the curve deflection angle, the path length and right-of-way will increase greatly. The length of path 4 in Figure 9 is 2.1 times longer than path 1. The required right-of-way of path 4 is 12.4 times larger than path 1. The deflection angle of the section I curves also should not be too small, since they need to provide enough space for the following curves. I used a 10-degree deflection angle for the section I curves. Since the deflection angle is small and the spiral angles would have exceeded 10 degrees, I used simple curves here to save right-of-way. This choice should not have an apparent influence on traffic movements.

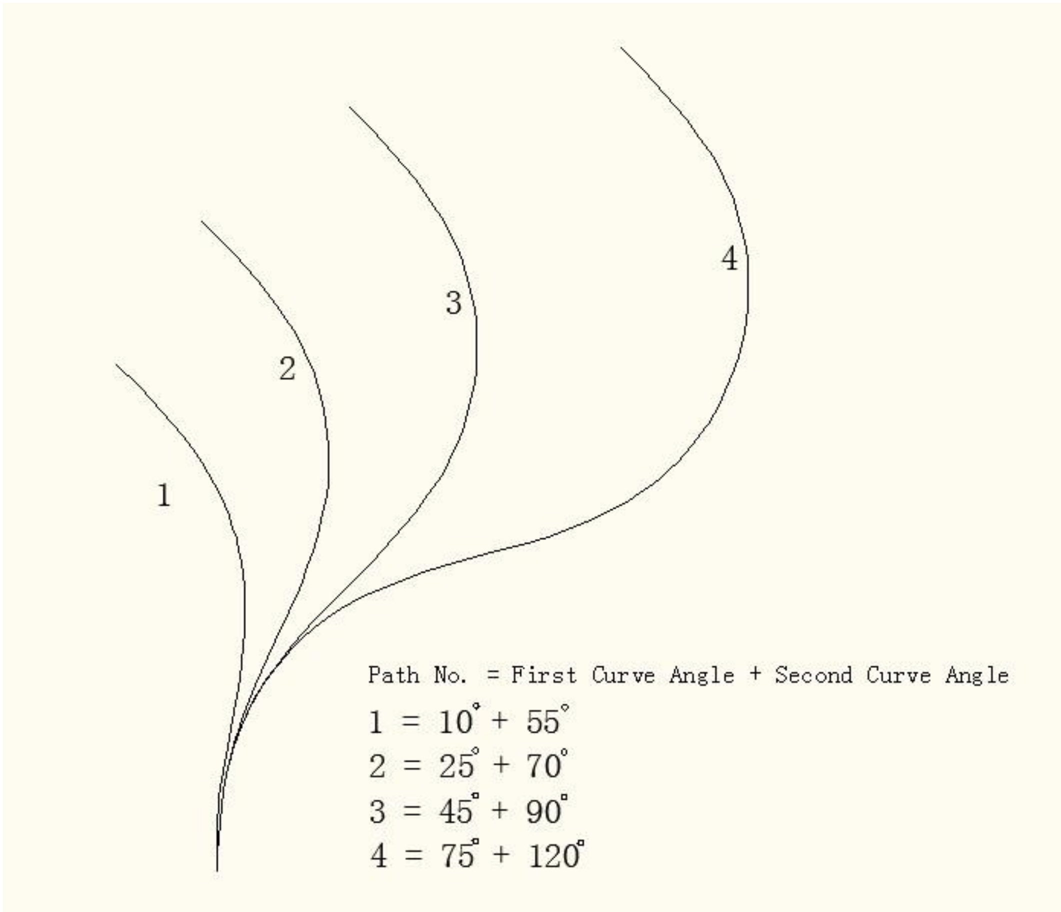

Figure 9 Path Length and Right-of-way Affect of the Section I curves

For the curves in section II, in addition to saving right-of-way, I needed to ensure that the bridge was straight. Curving bridges cost much more than straight bridges. For spiral curves, the runoffs are curving, so I would not use these parts to build the bridge. To get spiral curves to fit, I increased the path lengths between the Section I curves and section II curves. However, the situation changes when I used simple curves. The important item to note is that 2/3 of the runoffs and all of the TROs of the simple curves are straight. So the bridge can contain that portion of the runoff and the TRO. This instance also happens in section III. To save right-of-way and make the best curves possible, I used simple curves for the indirect ramps in sections I, II and III. I also tried to use two continuous spiral curves for the indirect ramps in sections I and II, but that design could not achieve the straight bridge in a smaller right-of-way than that of simple curve design.

Figure 10 shows the comparison of the indirect ramp with a simple curve and with a spiral curve. The spiral curve ramp requires a longer distance and a larger right-of-way. Even more important is that the spiral curve ramp needs a curving bridge while the simple curve ramp does not.

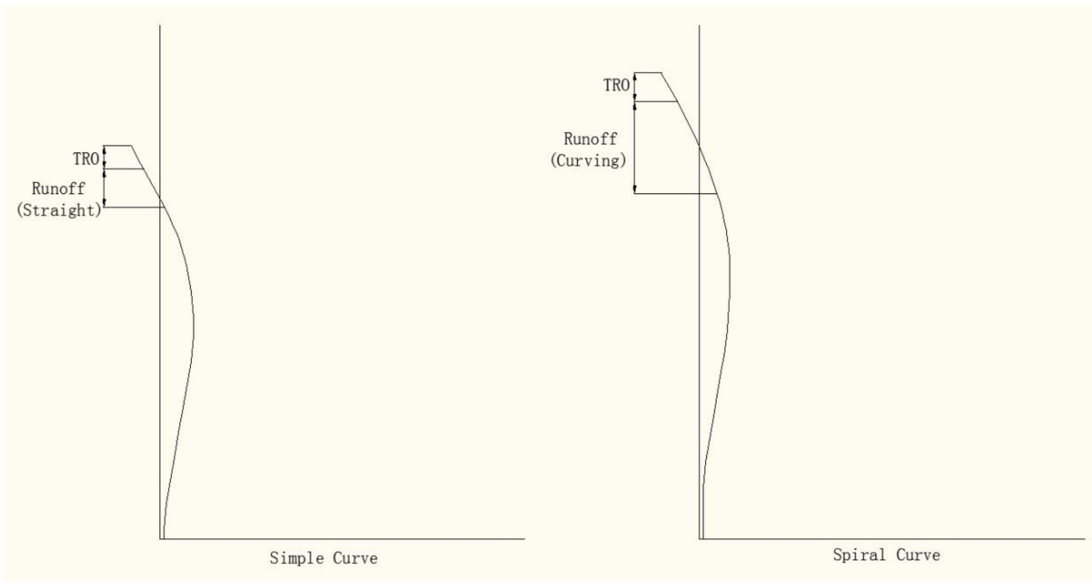

Figure 10 Comparisons of Simple Curve Ramp and Spiral Curve Ramp

Figure 11 shows the quadrant numbers of the free-flow parclo interchange design. The ramps in every quadrant have their own characteristics.

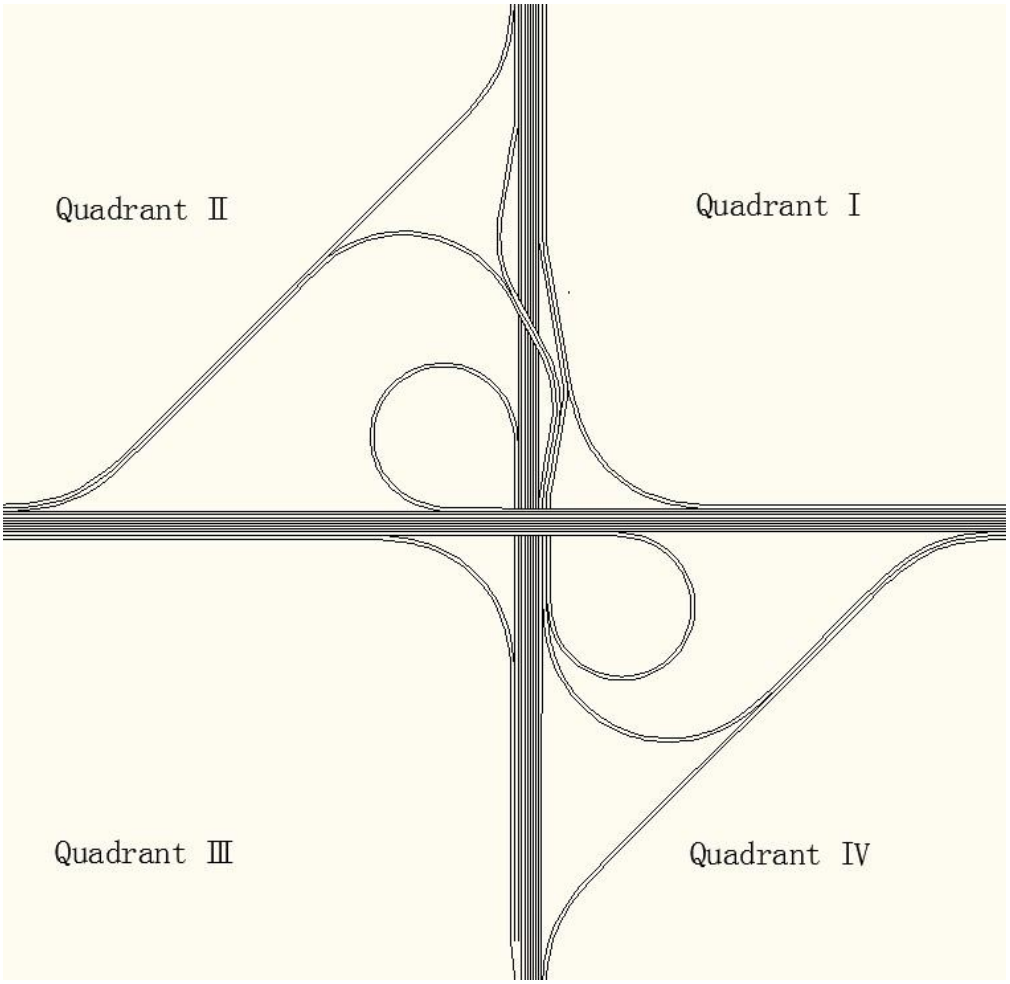

Figure 11 Quadrant Numbers of the Free-flow Parclo Interchange

There are four direct ramps in the free-flow parclo interchange to serve the right turns. In quadrant III, the only ramp is the direct ramp. I used a spiral curve with 90-degree deflection angle for that ramp. In the other quadrants, since there are loop ramps and indirect ramps, it is impossible to build direct ramps with 90-degree deflection angle curves with small radii. I therefore divided the direct ramps in quadrants I, II, and IV into two parts, each with a spiral curve with a 45-degree deflection angle. Figure 12 shows the direct ramp in quadrant IV for example. The two spiral curves are connected by a tangent. By using this kind of direct ramp, I saved lots of right-of-way and ensured that the curves are built with appropriate radii (510 ft for the 40 mph design speed curves and 833 ft for the 50 mph design speed curves, respectively).

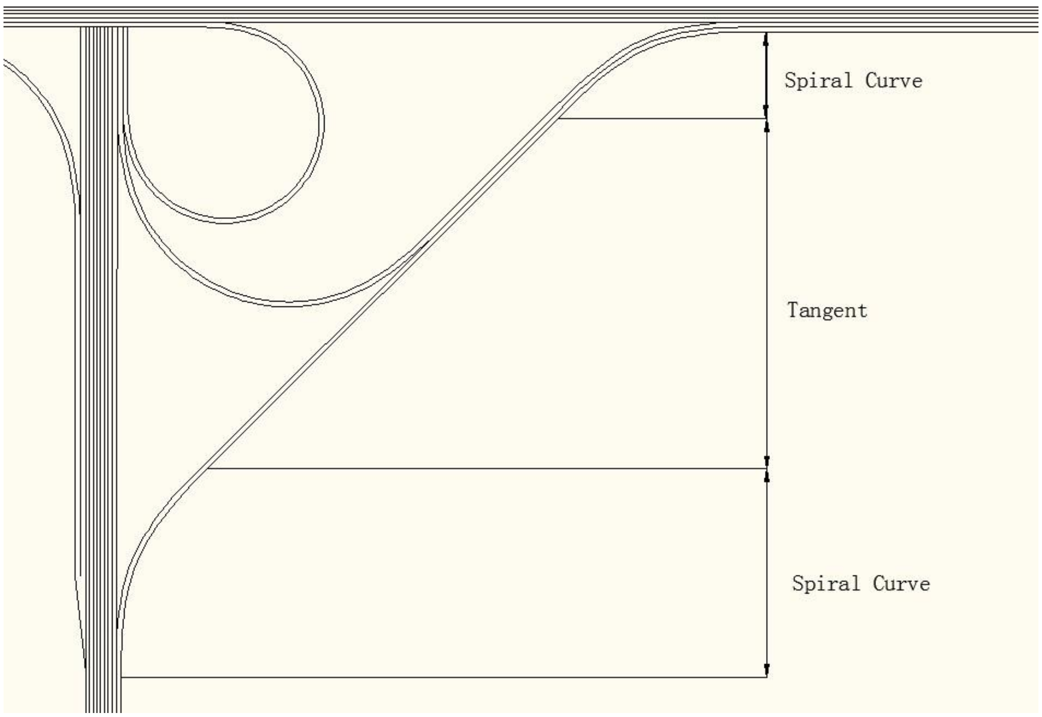

Figure 12 Direct Ramp in Quadrant IV (30 mph and 40 mph Design Speed Designs)

As mentioned earlier, the most important parts in the free-flow parclo interchange are the two indirect ramps. They have significant influence on the required right-of-way and interchange pattern. I used three different design speeds for the indirect ramps, including 30 mph, 40 mph, and 50 mph. Figures 13, 14, and 15 show the free-flow parclo interchanges produced with the three design speeds. I used a specific square that can contain all the three interchanges to highlight the differences among the three interchanges. All the squares in Figures 13, 14, and 15 are in the same size, with each side being 4665 ft long. With 40 mph indirect ramps in the free-flow parclo interchange, the loop ramp in quadrant II can be designed with a 40 mph design speed curve. With 50 mph indirect ramps in the free-flow parclo interchange, the two loop curves in quadrant II can be designed as 40 mph design speed curves too. These changes will not influence the interchange right-of-way.

For the 50 mph design speed free-flow parclo interchange, the two indirect ramps use very large radii and require very large rights-of-way. The large indirect ramps also affect the direct ramps. To save right-of-way, I added several curves in quadrant II and IV for both indirect ramps and direct ramps as Figure 15 shows. These extra curves only helped in the 50 mph design speed free-flow parclo interchange.

The maximum grade for the vertical design was 4%. Since the vertical change is 23 ft, the minimum path length to achieve the vertical change is 575 ft; this length does not contain the vertical curves. There was enough room to design all the vertical curves. For the ramps that were longer than the minimum 575 ft, there were two measures to deal with them. One was to use a lower grade while another was to use the maximum grade for only parts of the paths. As an example, the beginning and ending parts of the loop ramp in quadrant II were designed to be flat, using the remainder of the ramp length to accomplish the vertical change. The remainder is longer than 575 ft, so the grade is smaller than 4%.

For the loop ramp in quadrant IV, the lateral clearance between the indirect ramp and the direct ramp can be small, especially with the 30 mph design speed ramps. If the indirect ramp and direct ramp stay at the different elevations while the lateral clearance is limited, retaining walls are needed, which will cost a lot. To avoid building retaining walls and save the cost, I chose appropriate grades to make the adjacent ramps stay at the same elevation. The minimum distance between the ramps is from the middle of the loop curve to the indirect ramp. This minimum space contains the right shoulder of the loop ramp, the barrier between the two ramps, and the left shoulder of the indirect ramp, or 14 ft altogether.

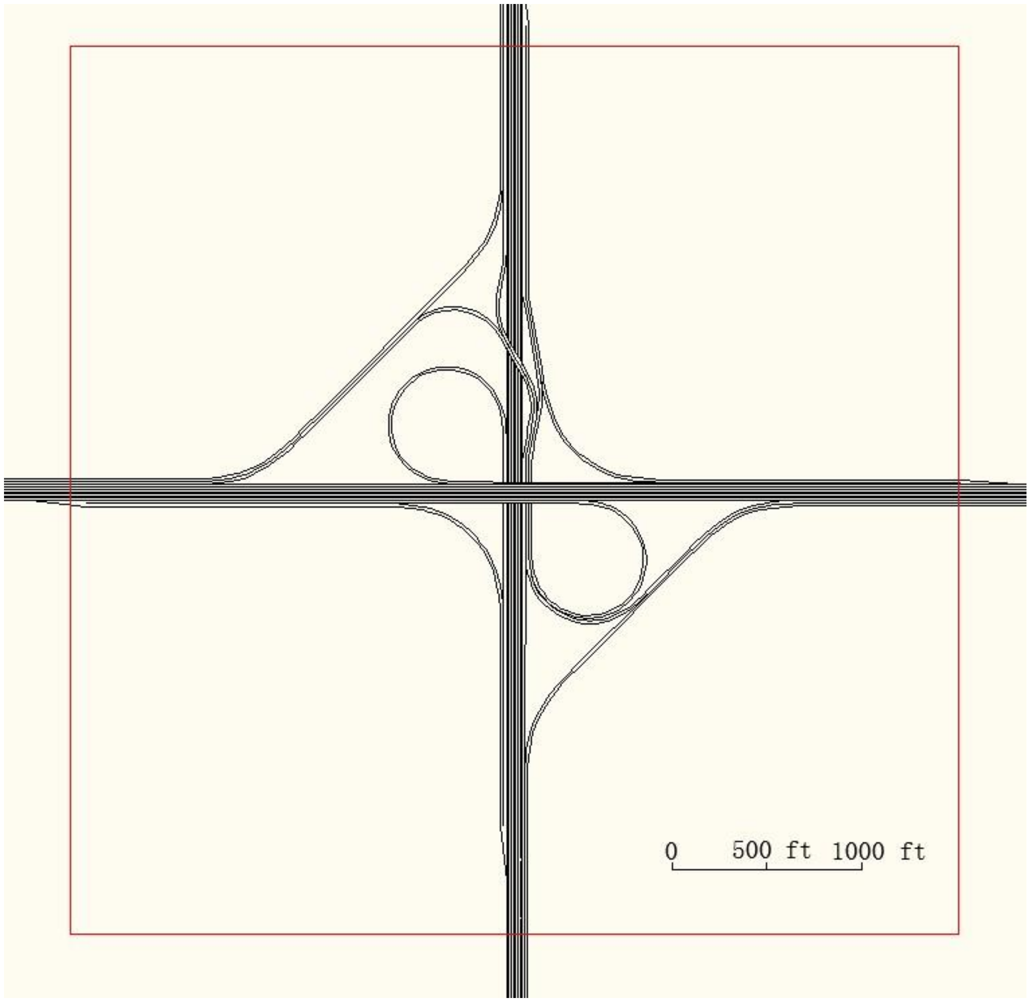

Figure 13 Free-flow Parclo Interchange (30 mph Indirect Ramps)

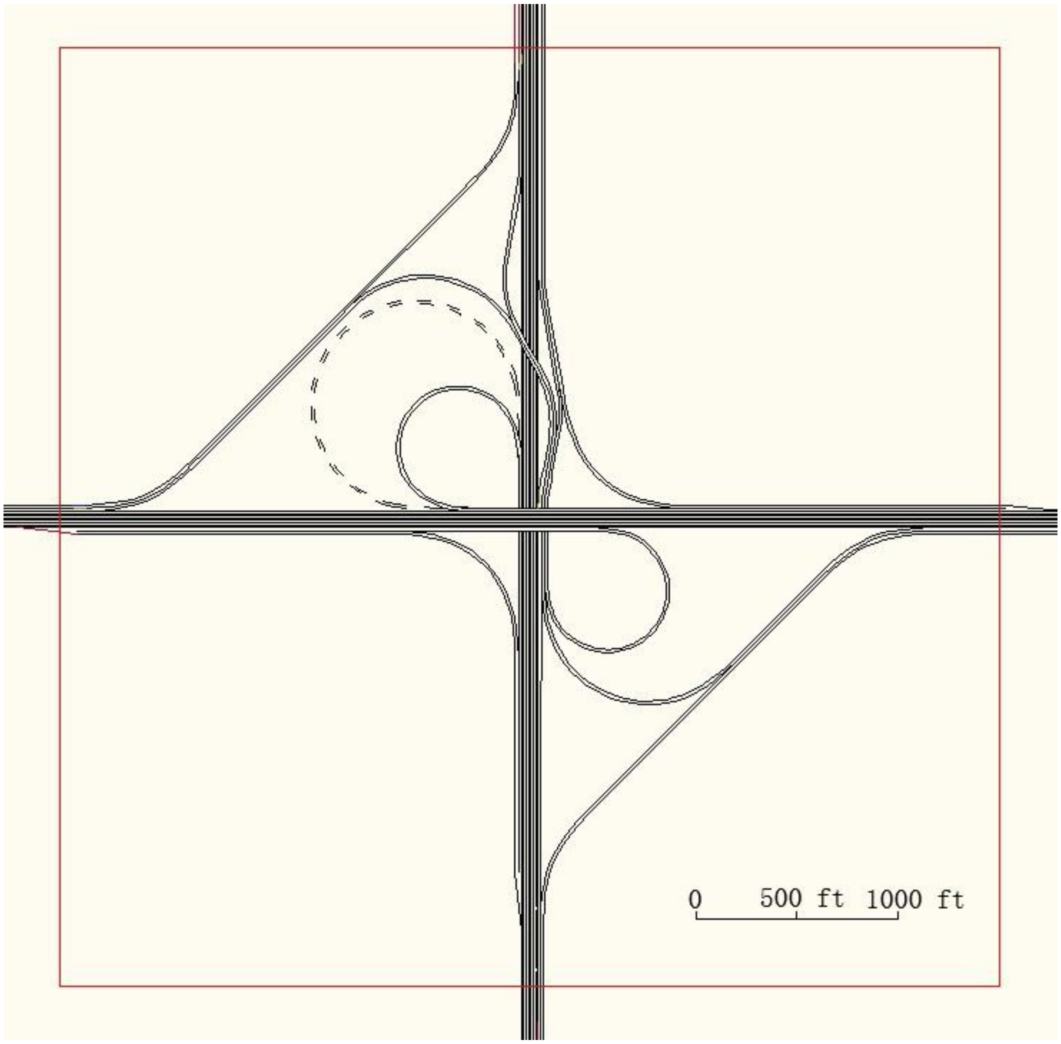

Figure 14 Free-flow Parclo Interchange (40 mph Indirect Ramps)

(Dashed line is the optional 40 mph design speed loop ramp)

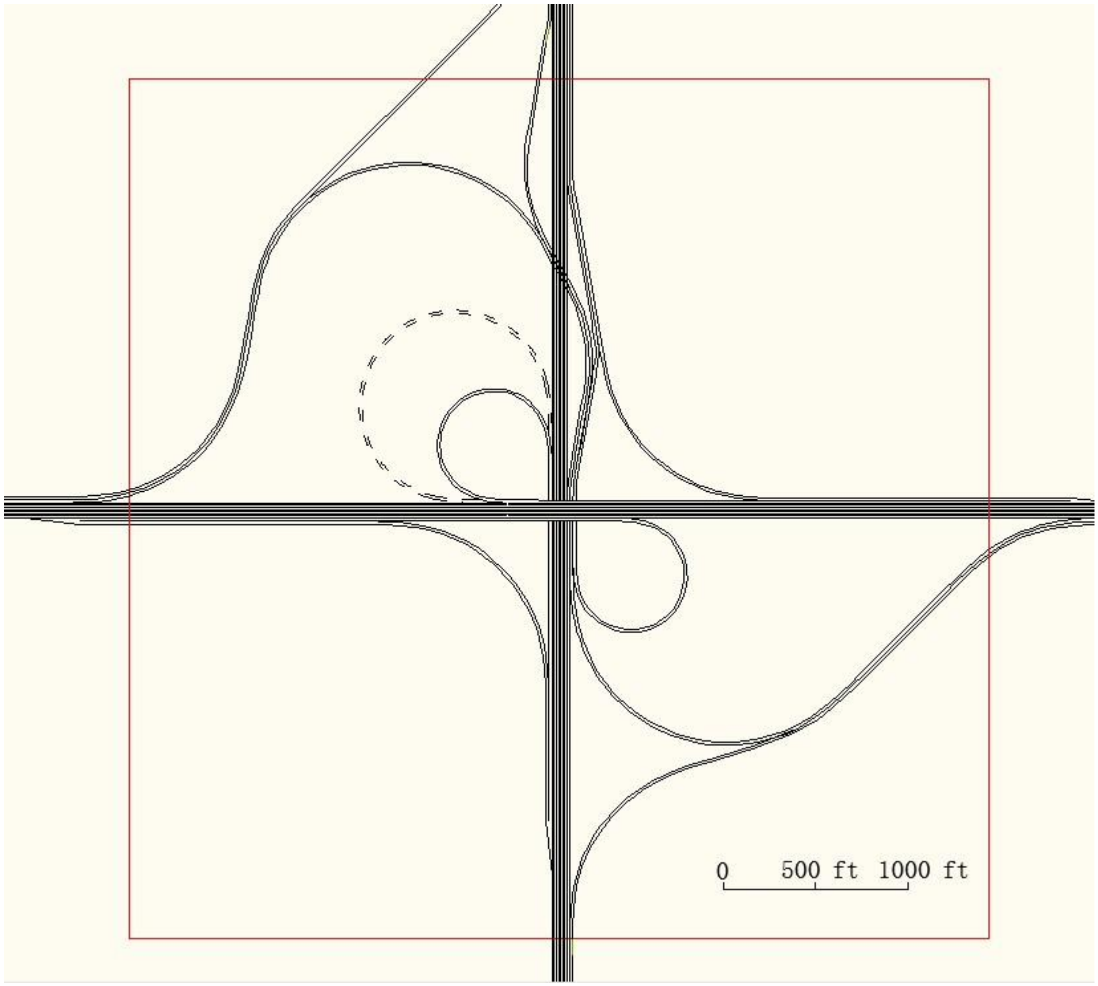

Figure 15 Free-flow Parclo Interchange (50 mph Indirect Ramps)

(Dashed line is the 40 mph design speed loop ramp)

CLOVERLEAF INTERCHANGE WITH C-D ROADS AND FOUR-LEVEL INTERCHANGE GEOMETRIC DESIGN

For the cloverleaf interchange with C-D roads, all the values meet the 2011 Greenbook [1] recommendations, and the most design parameters are the same as those for the free-flow parclo interchange. However, since there is a C-D road system, there are some differences. The basic design parameters are shown in Tables 7, 8, and 9.

Table 6 Basic Design Parameters for Cloverleaf Interchange with C-D Roads

Roadway	Mainline	Ramp	C-D Roads
Design Speed, mph	70	30, 40, or 50	60
Lane Width, ft	12	12	12
Median Width, ft	10	10	None
Left Shoulder Width, ft	4	4	4
Right Shoulder Width, ft	8	8	8
Clear Zone Slope	¼	¼	¼
Clear Zone Width, ft	30	30	30
Through Lanes	3	1	2

Table 7 Design Parameters for Cloverleaf Interchange with C-D Roads Horizontal Alignment

Roadway	Mainline	Ramp	C-D Roads
Minimum Radii, ft	None	30 mph – 231	None
		40 mph – 485	
		50 mph – 833	
Minimum Acceleration Lane Length, ft	None	30 mph – 1350	None
		40 mph – 1000	
		50 mph – 580	
Minimum Deceleration Lane Length, ft	None	1500 ft	None
Maximum Superelevation Rate, %	None	6	None

Table 8 Design Parameters for Cloverleaf Interchange with C-D Roads Vertical Alignment

Roadway	Mainline	Ramp	C-D Roads
Crest K Factor	None	30 mph - 19	None
		40 mph - 44	
		50 mph - 84	
Sag K Factor	None	30 mph - 37	None
		40 mph - 64	
		50 mph - 96	
Maximum Grade, %	None	4	None
Vertical Clearance, ft	16	16	16

The minimum lane arrangement for a C-D system in the middle of the weaving section is a two-lane C-D road, two-lane main road in one direction, two-lane main road in the other direction, and a two-lane C-D road [1]. In this design, I use three-lane main road instead of a two-lane main road to ensure the fairness of the comparisons between interchanges.

The design speeds of C-D roads are typically less than the mainlines, and the usual reduction is 10 mph. I therefore used 60 mph as the design speed for the C-D roads.

The median between the mainline and the C-D roads was 14 ft, including the right shoulder of the mainline, a 2-ft wide barrier, and the left shoulder of the C-D roads.

Because the terminals of the C-D roads are designed and treated as ramp terminals, the length of the transfer roads should meet the ramp spacing criteria in the Greenbook. The minimum space for this case is 800 feet [1]. Because of the cloverleaf interchange pattern, there is not enough space for the required acceleration and deceleration lanes to and from the loop ramps.

The design process for the direct ramp horizontal design and the vertical design were the same as that used for the free-flow parclo interchange design to avoid retaining walls, save the right-of-way, and reduce cost.

The three different cloverleaf interchange with C-D roads patterns are shown in Figures 16, 17, and 18. The loop ramps used 30 mph or 40 mph as design speeds, while the direct ramps used 40 mph or 50 mph. I still used a specific square that can contain all the three interchanges to highlight out the differences among the three interchanges. All the squares in Figure 16, 17, and 18 are in the same size, with each side being 4665 ft long.

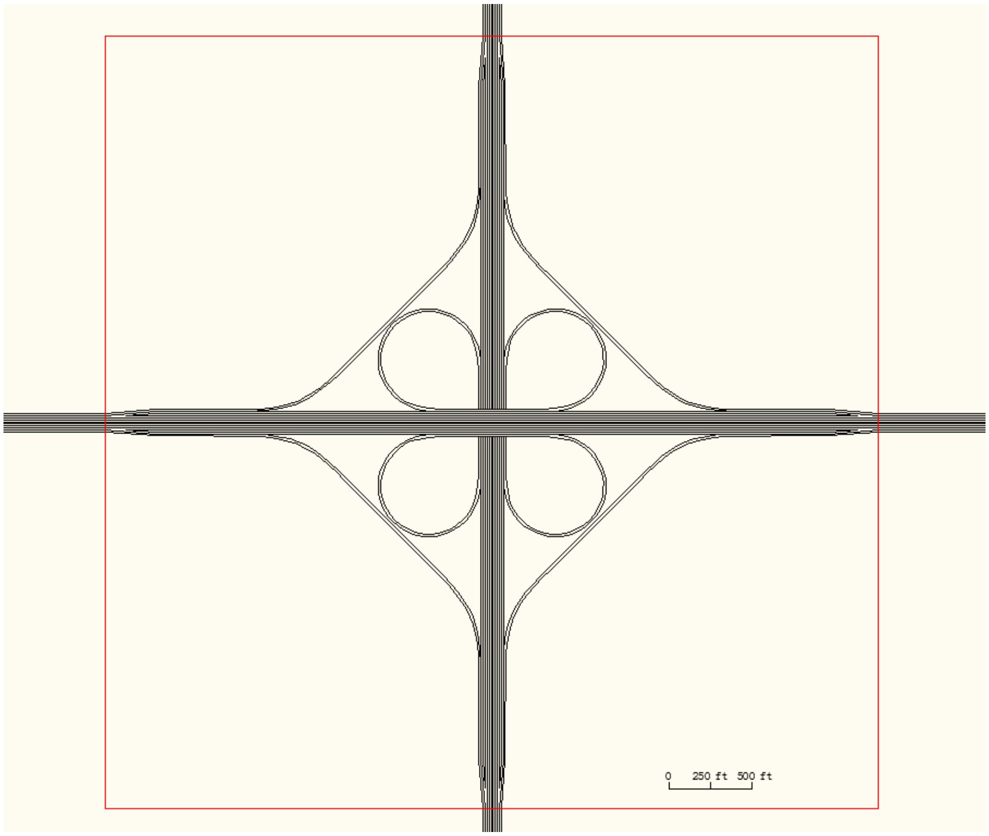

Figure 16 Cloverleaf Interchange with C-D Roads

(30 mph Loop Ramps and 40 mph Direct Ramps)

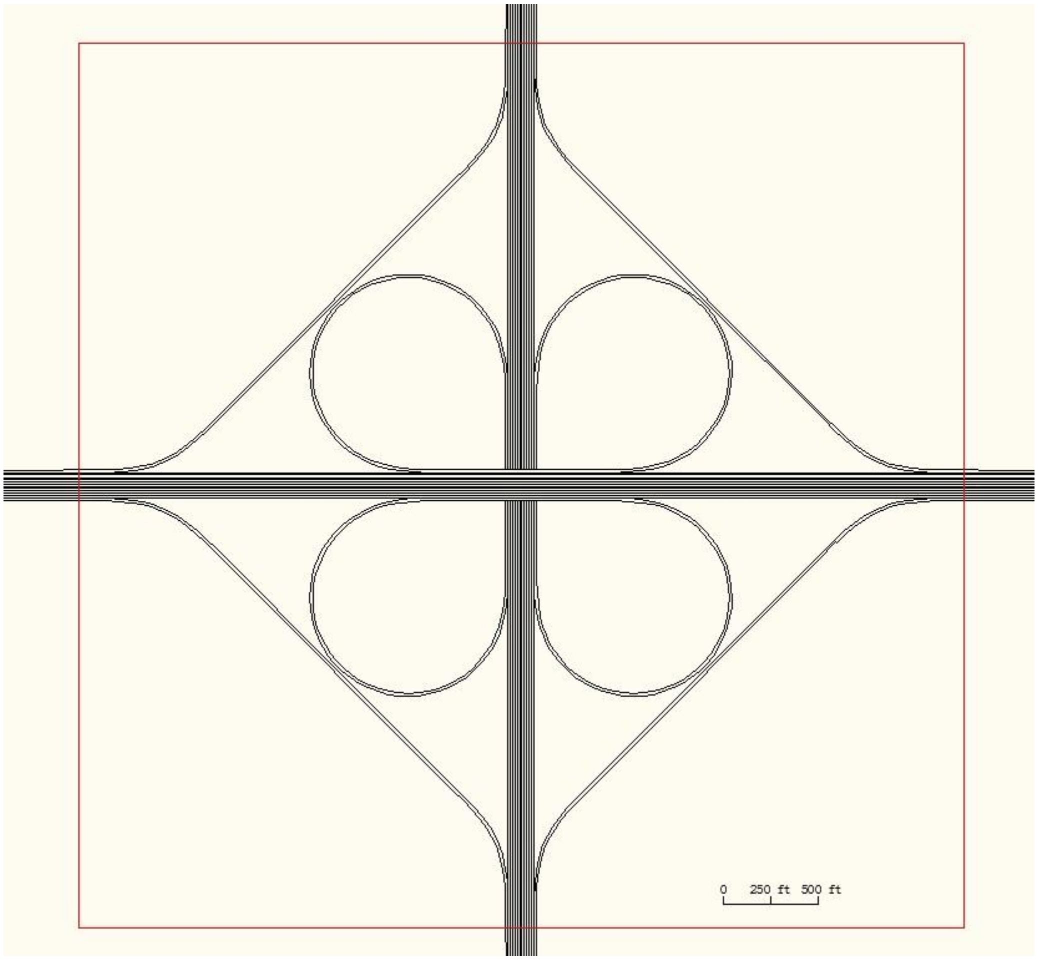

Figure 17 Cloverleaf Interchange with C-D Roads

(40 mph Loop Ramps and 40 mph Direct Ramps)

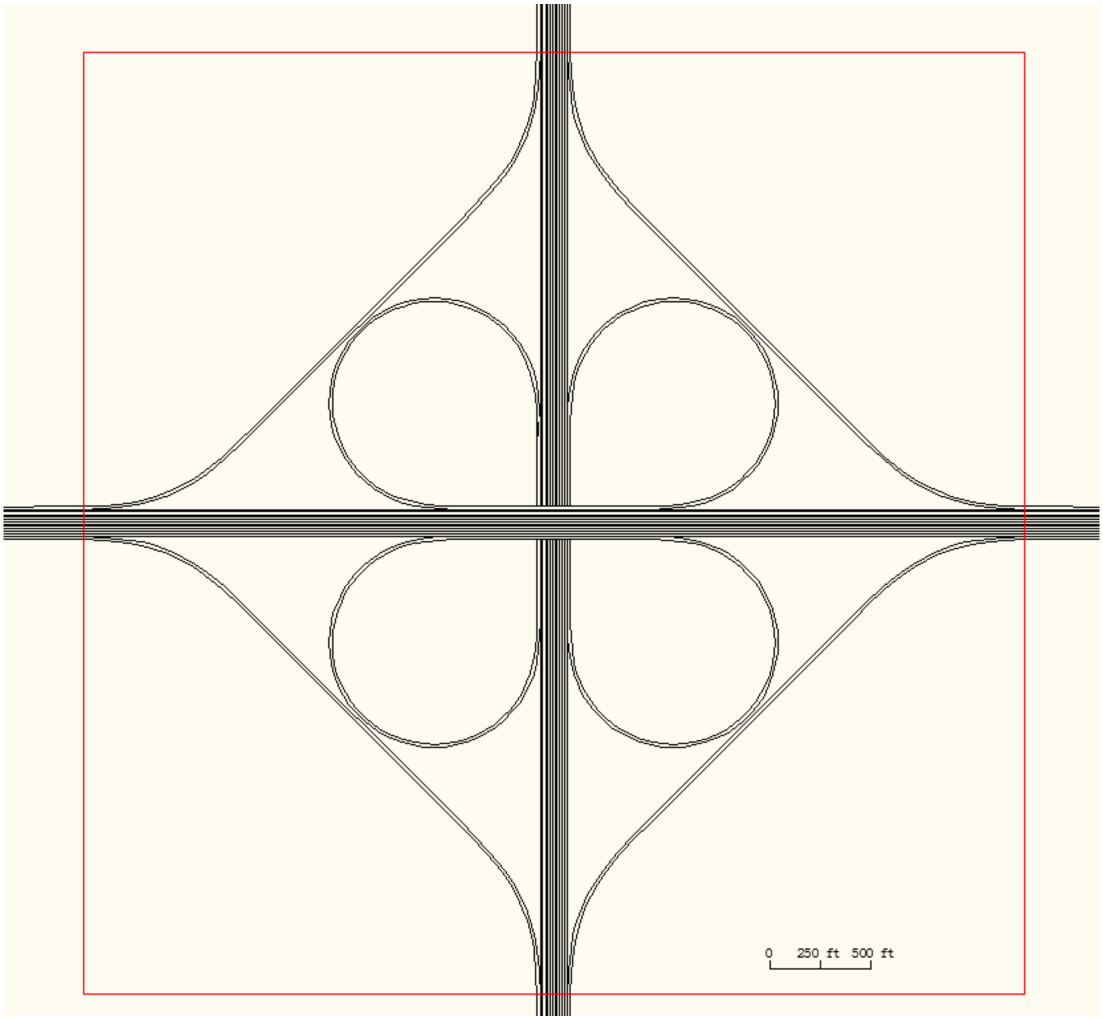

Figure 18 Cloverleaf Interchange with C-D Roads

(40 mph Loop Ramps and 50 mph Direct Ramps)

For the four-level interchange, all the basic design parmeters are the same as for the free-flow parclo interchange design.

An important design choice for the four-level interchange is which levels the mainlines and ramps should occupy. In the existing four-level interchanges as shown in Table 3 previously, there are lots of different combinations [19]. In this effort, I placed the mainlines on the two lowest levels and the ramps on the two highest levels to minimize the cost. Mainlines are much wider than the ramps, so with the same span and height, the ramp structure is much cheaper that way.

Another design choice for the four-level interchange is the lateral clearance between the two ramps on the same level. There is not a specific standard for this lateral spacing available in the literature, so I checked the lateral clearance of the existing four-level interchanges listed in Table 3. Those clearances ranged from 10 feet to 350 feet. To stay within that range, I decided to use 50 feet for the 30 mph design speed interchange, 80 feet for the 40 mph design speed, and 160 feet for the 50 mph design speed. In the four-level interchange design, I used the minimum radii for the ramps to save right-of-way.

For the two ramps that connect level 1 and level 4, the vertical change is 69 feet and the maximum grade is 4%, so they need long roadways to achieve that vertical change. To provide enough space, I used ramps with five horizontal curves. Ramp with three horizontal curves and a middle curve with an obtuse angle could not provide long enough roadways to make the vertical change.

Figures 19, 20 and 21 show the four-level interchange designs at the three different design speeds. As shown earlier for the cloverleaf interchanges, I used a specific square to highlight the differences. The each side of the square in Figures 19, 20, and 21 is 2315 ft long.

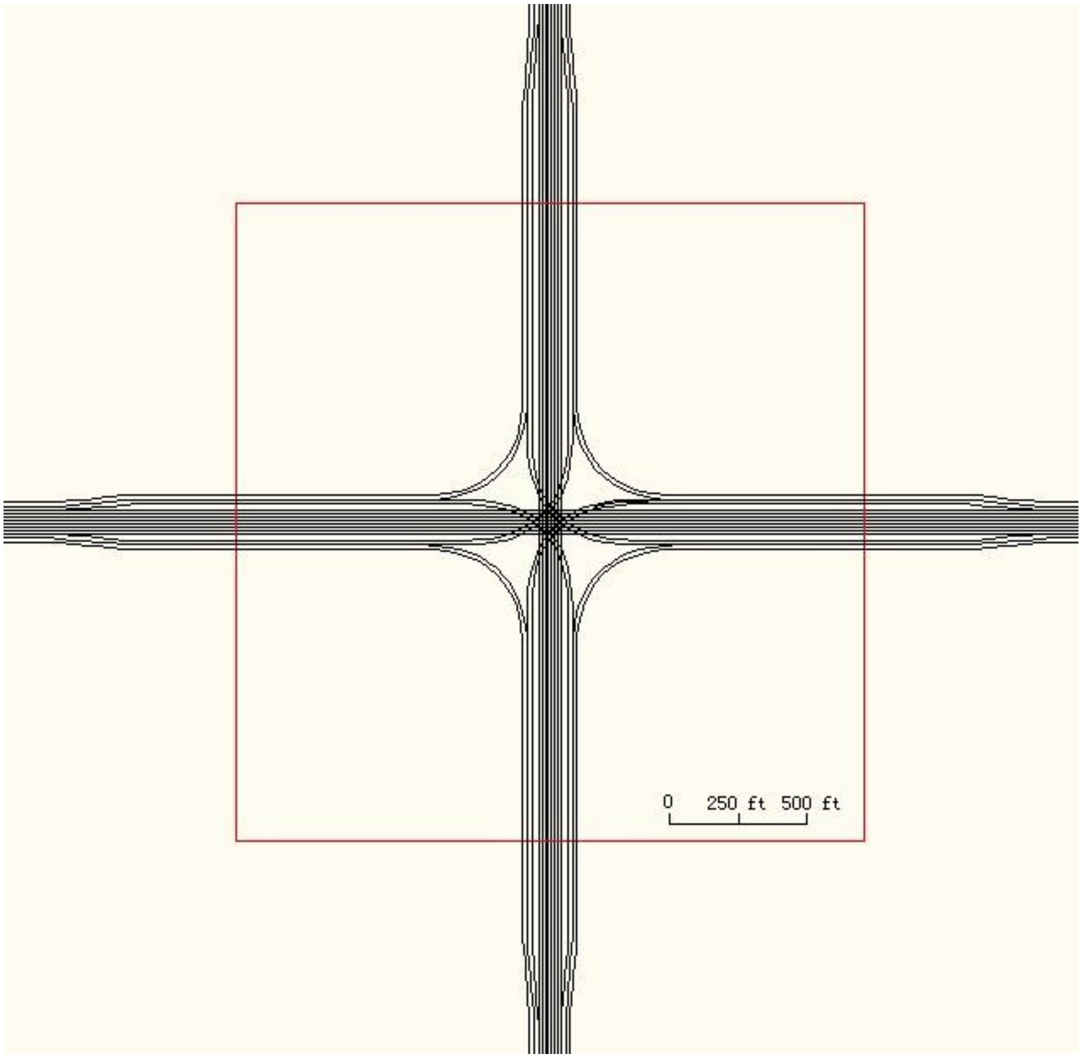

Figure 19 Four-level Interchange (30 mph Ramps)

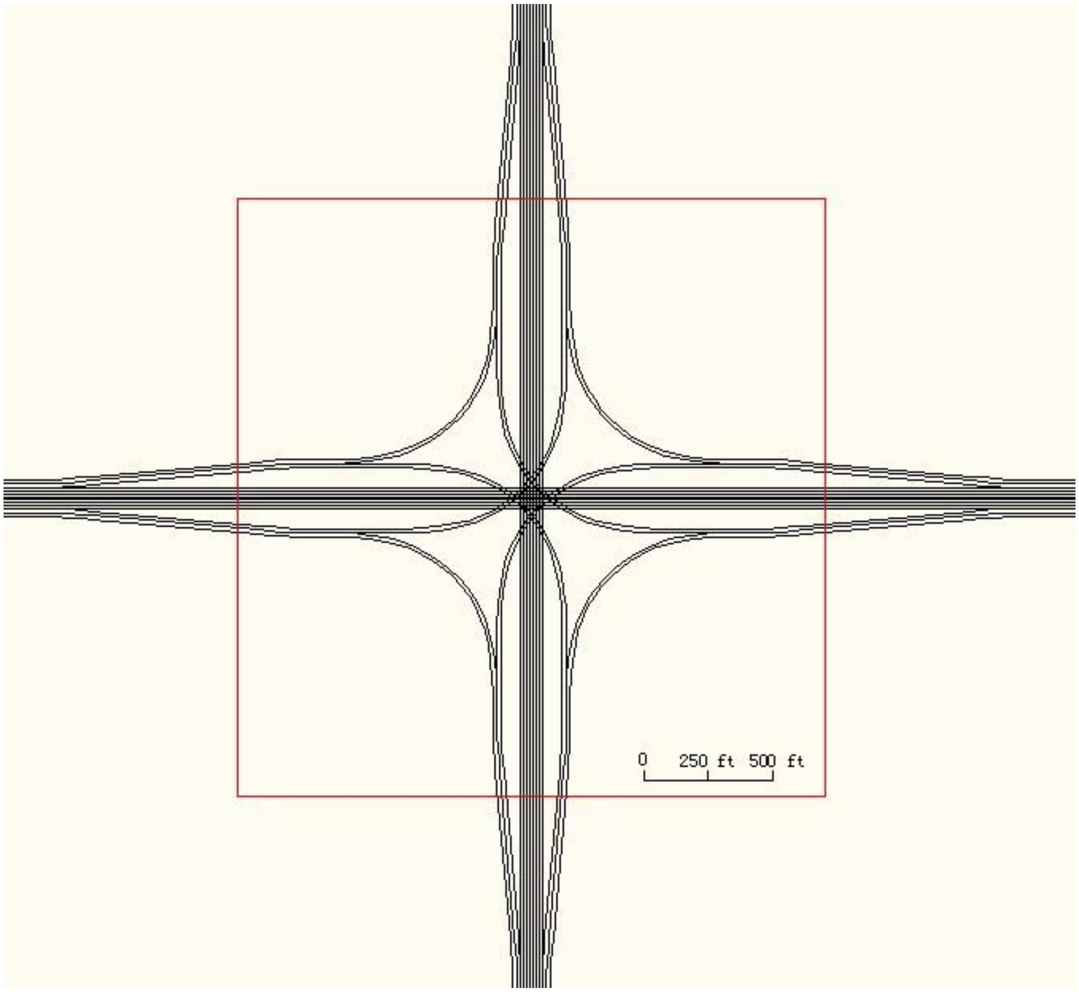

Figure 20 Four-level Interchange (40 mph Ramps)

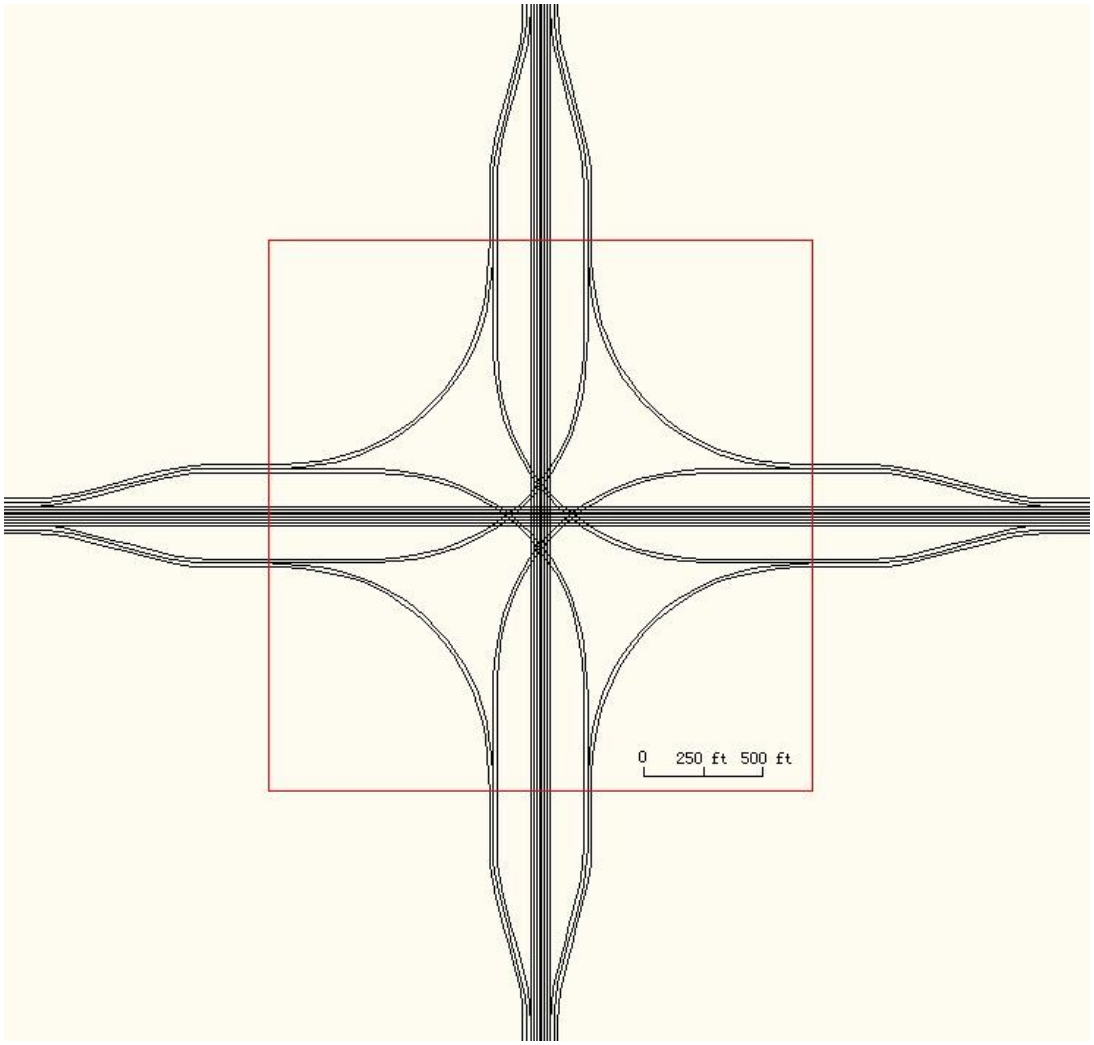

Figure 21 Four-level Interchange (50 mph Ramps)

RIGHT-OF-WAY ESTIMATE METHODOLOGY AND COMPARISON

The right-of-way limit in the designs tested in this research is considered to be the line at which the 4:1 slopestake gradient reaches level ground. There are three main parts of the right-of-way quantity: the mainlines, the area inside the ramps, and the area outside the ramps to the slopestake line. The dashed line in Figure 22 is the slopestake line.

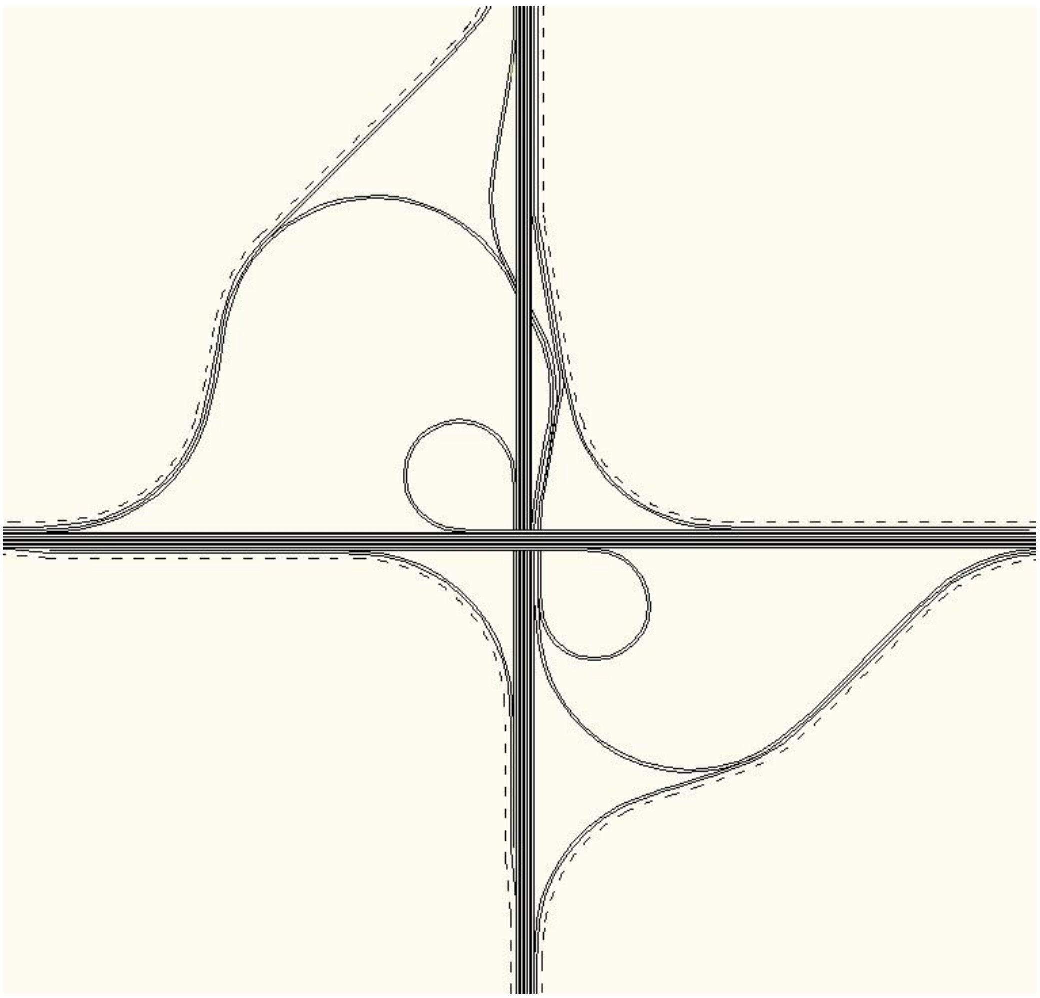

Figure 22 Example of Slopestake Line

To avoid bias, all the interchanges of the same style are contained in a specific rectangle, and I did the right-of-way calculation in that rectangle. The long side is 10180 ft and the short side is 8340 ft. The right-of-way calculation results and comparison are shown in Table 10. Please note that the loop ramps of the 50 mph design speed cloverleaf interchange with C-D roads use 40 mph design speed, and the loop ramps of the 50 mph design speed free-flow parclo interchange use the 30 mph design speed.

Table 9 Right-of-Way Calculation Results (Acre)

Indirect Ramp Design Speed, mph	Direct Ramp Design Speed, mph	Loop Ramp Design Speed, mph		Free-Flow Parclo	Cloverleaf with C-D Roads	Four-level
		Free-Flow Parclo Quadrant IV	Others			
30	40	30	30	114	138	75
40	40	30	40	154	229	96
50	50	30	40	245	242	130

As expected, the four-level interchanges require the least right-of-way for the same design speed. For the 30 mph and 40 mph design speed interchanges, the free-flow parclo interchanges require less right-of-way than the cloverleaf interchanges with C-D roads, since the roadways in the quadrant I and III of the free-flow parclo interchange need less space. However, for the 50 mph design speed interchange, the free-flow parclo interchange roadways in quadrant II and IV require large rights-of-way. Because of this, the free-flow parclo interchange required a larger right-of-way than the cloverleaf interchange with C-D roads. However, the difference in right-of-way is only 3 acres. Figure 23 compares the 50 mph design speed free-flow parclo interchange and cloverleaf interchange with C-D roads at the same scale.

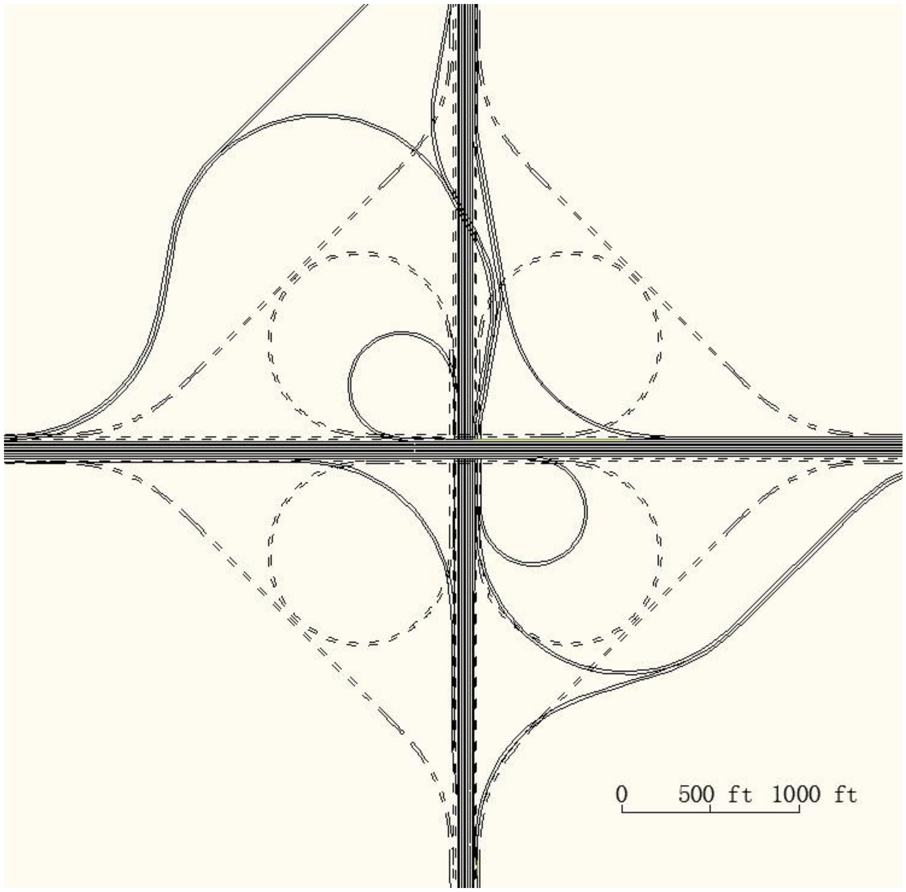

Figure 23 50 mph Design Speed Free-flow Parclo Interchange and Cloverleaf Interchange with C-D Roads Comparison

COST ESTIMATE METHODOLOGY AND COMPARISON

According to Harris's thesis [19], the earth-working cost is only a small part of the total cost of a typical system interchange project. Therefore, I did not take the earth-working cost into account in this work and the total cost had three parts: ramp pavement cost, structure cost, and retaining wall cost.

For the ramp pavement cost, I used lane miles as the main indicator. Since the cost per linear unit of pavement in every state DOT is different, the number of lane miles is an objective measure. It is easy for different departments to make judgments on pavement cost based on lane miles.

The structure cost is very important for a system interchange. There are two bridges in the free-flow parclo interchange: one is the level 2 mainline over level 1 mainline bridge, and the other is the ramp over mainline bridge. In the cloverleaf interchange with C-D roads, the only bridge is the level 2 mainline and C-D over level 1 mainline and C-D bridge. There are three kinds of bridges in the four-level interchange: level 2 mainline over level 1 mainline, level 3 ramp bridge, and level 4 ramp bridge. According to Harris's thesis [19], bridges of heights less than or equal to 23 feet (level 2) are typically assumed in early project scoping in North Carolina to cost $120 per square foot, bridges between 23 and 60 feet (level 3) are assumed to cost $160 per square foot, and bridges at or taller than 60 feet (level 4) are assumed to cost $200 per square foot. The cost per unit is based on a NCDOT 2006 cost document. [19]

Retaining walls only exist in the four-level interchange. For the free-flow parclo interchange and cloverleaf interchange with C-D roads, I avoided building retaining walls and saved that structure cost by choosing appropriate grades to make the adjacent ramps stay at the same elevation. In the four-level interchange design I assumed that the level 3 ramp retaining walls ended at 46 feet of elevation and the level 4 ramp retaining walls ended at 69 feet of elevation.

Table 11 is the ramp pavement lane miles estimation. The cloverleaf interchange with C-D roads has the highest number of lane miles since there are four loop ramps. The free-flow parclo interchange is in the middle, since there are two loop ramps in this design. The four-level interchange has the smallest number of lane-miles since all the ramps are directional. The lane miles become larger with an increase of the design speed. Please notice when I calculated the ramp pavement lane miles of the free-flow parclo interchanges, I used the loop ramps that were as large as possible. For the cloverleaf interchanges with C-D roads, I also took the C-D roads into account.

Table 12 shows the free-flow parclo interchange and cloverleaf interchange with C-D roads structure size estimation. The free-flow parclo interchange and cloverleaf interchange with C-D roads only have 23-ft bridges. The bridge areas of free-flow parclo interchange and cloverleaf interchange with C-D roads are very close. For the free-flow parclo interchange, the bridge area becomes a little larger with an increase in the design speed. For the cloverleaf interchange with C-D roads, the bridge area stays the same for the different design speeds.

Table 13 is the four-level interchange structure size estimation. The areas for the 23-ft tall bridge are the same for the three different design speeds. For the 46-ft and 69-ft bridges, the bridge areas increase with increases of design speed.

Table 14 is the structure cost estimation between designs. The cloverleaf interchange with C-D roads cost the least since it only has one 23-ft bridge. The free-flow parclo costs more than the cloverleaf interchange with C-D roads, but the increase was very small. As expected, the four-level interchange cost the most because it has 46-ft and 69-ft bridges, and because the spans of the bridges were much longer too.

Figure 24 is the retaining walls estimation. The retaining wall areas grew with the increases in the design speed.

Table 10 Ramp Pavement Lane Miles Estimation

Indirect Ramp Speed, mph	Direct Ramp Speed, mph	Loop Ramp Design Speed, mph		Free-Flow Parclo	Cloverleaf with C-D Roads	Four-level
		Free-Flow Parclo Quadrant IV	Others			
30	40	30	30	8.71	13.43	7.86
40	40	30	40	9.12	17.48	7.92
50	50	30	40	11.07	18.21	8.63

Table 11 Free-flow Parclo Interchange and Cloverleaf Interchange with C-D Roads Structure Estimation (Square Feet)

Indirect Ramp Speed, mph	Direct Ramp Speed, mph	Loop Ramp Design Speed, mph		Free-Flow Parclo	Cloverleaf with C-D Roads
		Free-Flow Parclo Quadrant IV	Others		
30	40	30	30	33,700	33,100
40	40	30	40	34,000	33,100
50	50	30	40	36,500	33,100

Table 12 Four-level Interchange Structure Estimation (Square Feet)

Height, ft	30 mph Indirect Ramp	40 mph Indirect Ramp	50 mph Indirect Ramp
23	9,600	9,600	9,600
46	20,400	24,800	40,100
69	20,400	24,800	40,100

Table 13 Structure Cost Estimation (2006 Dollars)

Indirect Ramp Speed, mph	Direct Ramp Speed, mph	Loop Ramp Design Speed, mph		Free-Flow Parclo	Cloverleaf with C-D Roads	Four-level
		Free-Flow Parclo Quadrant IV	Others			
30	40	30	30	4,050,000	3,970,000	8,510,000
40	40	30	40	4,090,000	3,970,000	10,100,000
50	50	30	40	4,380,000	3,970,000	15,600,000

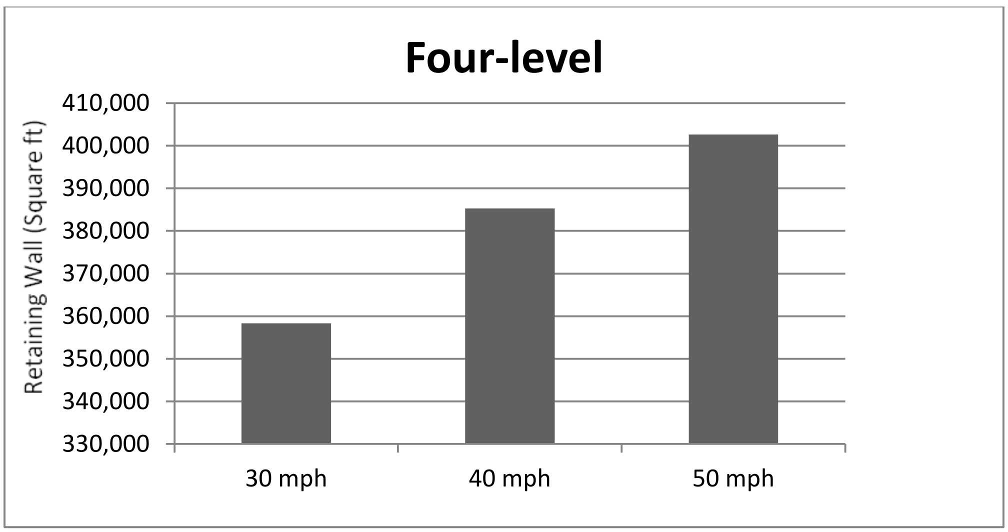

Figure 24 Four-level Interchange Retaining Wall Estimation (Square Feet)

Another important result is the distance from the center of the interchange to the end of the last taper. This distance affects interchange spacing and signing. Table 15 shows the comparison of the distance from the center of the interchange change to the end of the last taper of the three kinds of interchanges. Four-level interchanges do not have the loop ramps and require the least rights-of-way, so the distances of every design speeds are not large. For the 30 mph and 40 mph design speeds interchanges, the distances of the free-flow parclo interchanges are smaller than the cloverleaf interchanges with C-D roads. However, for the 50 mph design speed interchange, the free-flow parclo interchange roadways in the quadrant II have very large radii and require much more right-of-way. So the distance of the 50 mph design speed free-flow parclo is the largest.

Table 14 Distances from the Center of the Interchange to the End of the Last Taper Comparison (Feet)

Indirect Ramp Speed, mph	Direct Ramp Speed, mph	Loop Ramp Design Speed, mph		Free-flow Parclo	Cloverleaf with C-D roads	Four-level
		Free-Flow Parclo Quadrant IV	Others			
30	40	30	30	2053	2332	2224
40	40	30	40	2573	3057	2237
50	50	30	40	3848	3222	2578

CONCLUSIONS

The purpose of this paper was to design a free-flow parclo interchange and compare the required right-of-way and structure cost to the cloverleaf interchange with C-D roads and to the four-level interchange. All the design parameters were based on *A Policy On Geometric Design of Highways and Streets*. [1] I used 30mph, 40 mph, and 50 mph as design speeds for the ramps and 70 mph design speed for the mainlines. By using different design speed for the ramps, I could distinguish the differences between the interchanges tested in more detail. I used straight bridges to reduce the cost. I also avoided using retaining walls for free-flow parclo interchange and cloverleaf interchange with C-D roads. I chose proper deflection angles for the indirect ramps and using proper shapes for the direct ramps to save rights-of-way.

The required right-of-way and ramp pavement lengths for the free-flow parclo interchanges with 30 mph and 40 mph design speed were in the middle of the three different interchanges tested. Meanwhile, the structure costs for the free-flow parclo interchanges were much less than for the four-level interchanges, and the free-flow parclo interchanges avoided using retaining walls in contrast to the four-level interchanges. Putting this together, it appears that the free-flow parclo interchange may have a niche in suburban areas where right-of-way is too expensive for a cloverleaf but there is no need for the high cost of the four-level. The free-flow parclo should also be considered to replace a cloverleaf interchange with C-D roads that is struggling with operational or safety problems due to the weaving areas.

The flexibility is another advantage of the free-flow parclo interchange. It requires very small right-of-way in two quadrants, and large right-of-way in other two quadrants. This means that if there are ROW constraints in one or two of the quadrants near a proposed new interchange, we may be able to place the small right-of-way quadrants of the free-flow parclo in the tough areas to adapt to the constraints and reduce the cost and environmental impacts.

However, the benefits of the free-flow parclo design may not be great at higher ramp design speeds. The required right-of-way for the 50 mph free-flow parclo interchange was the largest one in the comparison. Designers may be able to find ways to reduce the required right-of-way for the higher speed free-flow parclo, such as using a curving bridge or divided bridges.

Though safety and capacity research were not within the scope of this paper, the free-flow parclo interchange still has some obvious advantages in these areas. First of all, it has right-hand side entrances and exits only, which meets driver expectations. It contains no weaving sections. For additional ramp capacity it is easy to widen the ramps of the free-flow parclo interchange from one lane to two lanes, as opposed to the cloverleaf interchange with C-D roads where the weaving sections make ramp widening difficult.

The free-flow parclo interchange can be considered as a variation of the basic parclo interchange. Since it has good traffic operations and safety potential and appears cost-effective in some niches, AASHTO should consider adding it in the next edition of the Green Book.

RECOMMENDATIONS FOR FUTURE RESEARCH

This research only took a few aspects of the design of a free-flow parclo into account. There is much work need to be done before transportation agencies accept the free-flow parclo interchange as a feasible choice for a freeway-to-freeway interchange. Based on the viability and potential benefits of the free-flow parclo interchange, it appears worthwhile to do more research and detailed studies on the other aspects of this new style interchange.

First of all, future research should compare the free-flow parclo interchange with other interchanges. The four-level interchange is a good choice to do the comparison, but there are other kinds of interchanges that can be compared, such as turbine, windmill, clover-turbine, continuous flow interchange, clovermill and so on. These existing interchanges also allow for straight mainlines, avoid weaving sections, and use right-hand side entrances and exits only. These characteristic are same as the free-flow parclo interchange. These modifications of the cloverleaf interchange provide high capacity, but the number, height, and length of the bridges required vary widely. Some of these interchanges may be interesting competitors to the free-flow parclo interchange. For example, the continuous flow interchange is similar with the free-flow parclo, but it requires different indirect ramps and at least three bridges; and the clovermill interchange replaces two of the cloverleaf's loop ramp with windmill-type ramps, it requires as few as three bridges.

Designers also can use different design standards and strategies to complete new geometric designs. For example, to minimize structure costs, I used straight bridges, but the required right-of-way in quadrant II increased due to this choice. Designers can try to use a curving bridge to reduce the right-of-way, though the cost will increase. A curving bridge will likely require less right-of-way than the straight bridge design. If designer can find a balance between these two factors, it will be a nice goal. Designers also can try to use divided bridges for the indirect ramps.

Multi-lane ramps are another good topic to explore with the free-flow parclo interchange. Though the multi-lane loop ramps may have safety issues, it can improve the capacity and efficiency of the interchange. Designers can try to apply the multi-lane ramp in the free-flow parclo interchange and conduct a safety analysis to find the balance between safety and capacity.

The free-flow parclo interchange has the potential to be considered as a service interchange as well as a system interchange, and designers could explore this possibility. In some suburban areas, a free-flow parclo service interchange can be a good choice that may have a small affect on the existing properties. Some design changes and traffic devices should be added if changing the free-flow parclo from a system to a service interchange.

Safety and capacity research is necessary for a new style of interchange. Researchers can build models and use simulation to check the interchange performance under certain circumstances. They can compare the free-flow parclo interchange with other interchanges, especially the interchanges that have weaving areas and left-hand side entrances and exits. They can apply known safety models to estimate collision rates and compare those for the free-flow parclo to other designs.

Since this research was not in the structure design area, it did not develop detailed specifications for any of the bridges. In addition, this research only considered the bridges, retaining walls, and ramp pavement for the cost comparison. More detailed cost estimation is welcomed for the free-flow parclo interchange. There are still a lot of aspects that should be considered, such as earthwork, signing and marking, drainage, and barriers.

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APPENDICES

Appendix A

Roadway Calculation 30 mph Ramp Design Speed

Simple Curve

Minimum Radius = 231 ft, from Green Book Table 3-7

Choose Radius = 300 ft

Deflection Angle (D) = 10 degrees

Superelevation Rate (e) = 5.74%, $e < e_{max}$ = 6.00%

Runoff Length (L_r) = 104 ft, from Green Book Table 3-17b

Tangent Runout Length (TRO) = L_r * NC/e = 36 ft, NC = Normal Crown in % = 2%

Length of Curve (L) = D*R/57.2958 = 52 ft

T = R*tan(D/2) = 26 ft

Spiral Curve

Minimum Radius = 231 ft, from Green Book Table 3-7

Choose Radius = 300 ft

Superelevation Rate (e) = 5.74%, $e < e_{max}$ = 6.00%

Length of Spiral (L_s) = $3.15*V^3/(R*C)$ = 142 ft, C typically = 2

Tangent Runout Length (TRO) = L_s * NC/e = 49 ft, NC = Normal Crown in % = 2%

Find:

$\Theta_s = 28.6479*L_s/R_c$ = 13.56 degrees

$Y_s = L_s^2/(6*R_c)$ = 11 ft

$X_s = L_s – Y_s^2/(2*L_s)$ =141 ft

$\rho = Ys – Rc*(1\text{-}\cos\Theta_s)$ = 2.8 ft, ρmin = 0.66 ft < ρ <ρmax = 3.3 ft

$k = X_s – R_C*\sin\Theta_s$ = 71 ft

Appendix B

Roadway Calculation 40 mph Ramp Design Speed

Simple Curve

Minimum Radius = 485 ft, from Green Book Table 3-7

Choose Radius = 510 ft

Deflection Angle (D) = 10 degrees

Superelevation Rate (e) = 5.96%, $e < e_{max} = 6.00\%$

Runoff Length (Lr) = 123 ft, from Green Book Table 3-17b

Tangent Runout Length (TRO) = Lr * NC/e = 41 ft, NC = Normal Crown in % = 2%

Length of Curve (L) = D*R/57.2958 = 89 ft

T = R*tan(D/2) = 45 ft

Spiral Curve

Minimum Radius = 485 ft, from Green Book Table 3-7

Choose Radius = 510 ft

Superelevation Rate (e) = 5.96%, $e < e_{max} = 6.00\%$

Length of Spiral (Ls) = 3.15*V3/(R*C) = 198 ft, C typically = 2

Tangent Runout Length (TRO) = Ls * NC/e = 66 ft, NC = Normal Crown in % = 2%

Find:

Θs = 28.6479*Ls/Rc = 11.10 degrees

Ys = Ls2/(6*Rc) = 13 ft

Xs = Ls – Ys2/(2*Ls) = 197 ft

ρ = Ys – Rc*(1-cosΘs) = 3.2 ft, ρmin = 0.66 ft < ρ <ρmax = 3.3 ft

k = Xs – RC*sinΘs = 99 ft

Appendix C

Roadway Calculation 50 mph Ramp Design Speed

Simple Curve

Minimum Radius = 833 ft, from Green Book Table 3-7

Choose Radius = 833 ft

Deflection Angle (D) = 10 degrees

Superelevation Rate (e) = 6.00%, e = emax = 6.00%

Runoff Length (Lr) = 144 ft, from Green Book Table 3-17b

Tangent Runout Length (TRO) = Lr * NC/e = 48 ft, NC = Normal Crown in % = 2%

Length of Curve (L) = D*R/57.2958 = 145 ft

T = R*tan(D/2) = 73 ft

Spiral Curve

Minimum Radius = 833 ft, from Green Book Table 3-7

Choose Radius = 833 ft

Superelevation Rate (e) = 6%, e < emax = 6.00%

Length of Spiral (Ls) = 3.15*V3/(R*C) = 236 ft, C typically = 2

Tangent Runout Length (TRO) = Ls * NC/e = 79 ft, NC = Normal Crown in % = 2%

Find:

Θs = 28.6479*Ls/Rc = 8.13 degrees

Ys = Ls2/(6*Rc) = 11 ft

Xs = Ls – Ys2/(2*Ls) = 236 ft

ρ = Ys – Rc*(1-cosΘs) = 2.8 ft, ρmin = 0.66 ft < ρ < ρmax = 3.3 ft

k = Xs – RC*sinΘs = 118 ft