International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:8, No:11, 2014

An Analysis of New Service Interchange Designs

Joseph E. Hummer

***Abstract*—**An efficient freeway system will be essential to the development of Africa, and interchanges are a key to that efficiency. Around the world, many interchanges between freeways and surface streets, called service interchanges, are of the diamond configuration, and interchanges using roundabouts or loop ramps are also popular. However, many diamond interchanges have serious operational problems, interchanges with roundabouts fail at high demand levels, and loops use lots of expensive land. Newer service interchange designs provide other options. The most popular new interchange design in the US at the moment is the double crossover diamond (DCD), also known as the diverging diamond. The DCD has enormous potential, but also has several significant limitations.

The objectives of this paper are to review new service interchange options and to highlight some of the main features of those alternatives. The paper tests four conventional and seven unconventional designs using seven measures related to efficiency, cost, and safety.

The results show that there is no superior design in all measures investigated. The DCD is better than most designs tested on most measures examined. However, the DCD was only superior to all other designs for bridge width. The DCD performed relatively poorly for capacity and for serving pedestrians. Based on the results, African freeway designers are encouraged to investigate the full range of alternatives that could work at the spot of interest. Diamonds and DCDs have their niches, but some of the other designs investigated could be optimum at some spots.

***Keywords*—**Alternative, design, diverging diamond, freeway, interchange.

I. INTRODUCTION

AN efficient freeway system will be essential to the development of Africa, and interchanges are a key to that efficiency. Around the world, many freeway-to-surface street (i.e., service) interchanges have serious operational and safety problems. Especially serious are interchanges where the traffic volumes have grown up to become higher than the capacity of the interchange. In such cases, queues may build up on the surface street to block other intersections, or queues may build up on the off-ramps to block freeway lanes. Safety problems arise due to spillback or due to drivers experiencing undue delay thereby making poor decisions in gap acceptance or lane changing.

Diamond interchanges are the most popular service interchange design worldwide but they are particularly inefficient. If the two ramp terminals of the diamond are signalized, it is difficult to coordinate the signals well to allow progression for through traffic on the surface street in both directions. Because the diamond relies on vehicle storage between the ramp terminals it is susceptible to spillback.

Many highway agencies have changed the nature of their interchanges by adding one to four loop ramps (creating a partial or full cloverleaf interchange). However, loop ramps with a reasonable design speed require large amounts of expensive right-of-way (ROW), and may create unsafe and inefficient weaving areas. Agencies have also constructed flyover structures to carry left turns or through traffic on a third level over the existing interchange. This is an extremely expensive and disruptive option, and often leaves an operational and safety problem on the surface street level. Another popular option is to install roundabouts at the diamond interchange ramp terminals. This works well for safety and travel efficiency at low demand levels, but at high demand levels the roundabouts tend to become congested and fail. All in all, conventional service interchange designs are fraught with potential pitfalls.

Unconventional solutions provide a menu of other options that highway agencies can explore to overcome the pitfalls associated with conventional solutions. Unconventional intersections and interchanges typically involve rerouting one or more movements—often left turns—to reduce the number of conflict points remaining in the middle of the intersection or interchange. This allows a reduction in signal phases, less lost time, fewer opportunities for crashes, and a host of other potential benefits. Unconventional intersections designs probably originated with the jughandle intersection in New Jersey, USA in the 1950's, followed by the median u-turn intersection in Michigan, USA in the 1960's. Interest in unconventional designs surged in the US beginning in the early 1990's as traffic demands and project costs soared while project funding grew tighter. Roundabout interchanges and single-point diamond interchanges became so popular through the 1990's that today they are considered conventional.

The most prominent unconventional service interchange design with no loops and no weaving at the moment is the double crossover diamond (DCD), also known as the diverging diamond. The DCD contains two places where the through directions of the surface street cross each other. If, for example, the surface street runs north-south as Fig. 1 shows, from the south there would first be a crossover where the northbound traffic would move to the left of the southbound traffic, then the bridge over the freeway, then the second crossover where the northbound traffic would move back to the right of the southbound traffic. This temporary reversal of the usual US "keep right" custom allows left turns to and from the freeway to occur with simple merges and diverges.

Joseph E. Hummer is Professor and Chair, Department of Civil and Environmental Engineering, Wayne State University, 5050 Anthony Wayne Drive, Detroit, Michigan 48202 USA (Tel. 313-577-3790, e-mail joseph.hummer@wayne.edu).

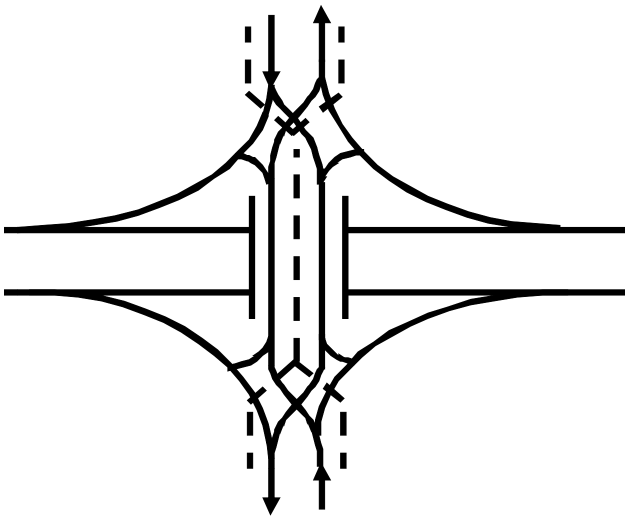

Fig. 1 DCD schematic (a dashed line indicates a pedestrian path)

The DCD has enormous potential in places where a diamond, partial cloverleaf, or roundabout interchange would not work. The through movement crossovers are controlled by two-phase signals, in contrast to the two three-phase signals a diamond requires. Because of the efficient signals and the fact that there is no need to store queued left-turning vehicles on the bridge as in a diamond, the bridge can remain narrow thereby reducing costs. A DCD should be efficient compared to a diamond, particularly at locations with heavy left turn demands. Needing only a little extra room for the curves of the through roadways, the DCD should typically use barely more ROW than a diamond.

The first three DCD interchanges were installed in France in the 1960s and 1970s [1]. Fig. 2 shows the first DCD in the US, which opened in Missouri in 2009. There are now about 20 DCD interchanges open in the US.

Fig. 2 First DCD in the US in Springfield, Missouri [1]

A. Previous Literature on DCD

The DCD has only a short history in the US. Nonetheless, the literature on it could help agencies in choosing one. Chlewicki was the first American to publish the idea of the DCD [2]. Chlewicki presented the results of an experiment comparing a diamond, a DCD in which the left turns from the freeway merged with the surface street, and a DCD in which the junction between the left turns from the freeway and the surface street was controlled by a signal. The experiment used the demands from an interchange with heavy left turns, and employed the Synchro traffic model. The results showed that the DCD was far superior in operations to the conventional diamond, producing, for example, the following average delays:

- Conventional diamond, 80 seconds per vehicle,
- DCD with merges, 27 seconds per vehicle, and
- DCD with signals, 26 seconds per vehicle.

Bared et al. [3] and Edara et al. [4] conducted more extensive evaluations of the DCD than Chlewicki but arrived at a similarly rosy conclusion. The authors used the microscopic simulation program VISSIM to examine four-lane and six-lane surface streets handling five levels of traffic demand. They timed signals using trial-and-error methods for the DCD and the program PASSER-III for the diamond they used for comparison. They also simulated pedestrian flows. Their results showed that the DCD was far better at the higher levels of demand than the diamond. The pedestrian delay results showed that the DCD processed them fairly well. Edara et al. [4] also found that the DCD installations in France had very good safety records, producing far fewer serious crashes than would be expected at typical US diamonds. The authors recommended further study of the DCD, especially the safety implications.

In 2007 the US Federal Highway Administration (FHWA) published the results from an evaluation of driver behavior on a DCD with a complete set of signs, a DCD with a reduced set of signs, and a comparable diamond using a driving simulator [5]. Each of the 74 test subjects—33 of whom were older than 65 years—navigated each interchange six times. The measures of effectiveness included wrong way and other erratic maneuvers, red light violations, and speeds. The results showed that the DCD with full signing or the DCD with reduced signing had fewer driver errors, fewer red light violations, and lower mean speeds than the diamond. The researchers concluded that any concern about wrong way movements at a DCD is "not warranted" and that the DCD will deliver safety benefits over a diamond where it is adopted.

The FHWA's Alternative Intersections/Interchanges: Informational Report (AIIR, [1]) presented a chapter on the DCD with the best available information about many important aspects of the design. The report summarized the previous knowledge on operations at a DCD and presented results from new VISSIM runs comparing the DCD to a diamond. The new results were similar to previous results, as the DCD produced lower travel times and associated measures, especially at higher volumes and with larger left turn volumes. The AIIR chapter concludes with a statement that the DCD would be most applicable at junctions with:

- Heavy volumes of left turns onto freeway ramps;
- Moderate and unbalanced through volumes on bridge approaches on the arterial road;
- Moderate to very heavy off-ramp left turn volumes; and
- Limited bridge deck width availability.

Missouri has been the most aggressive US state in pursuit of DCD installation, looking at one in as early as 2005 and finally opening the first in the US in 2009. Anecdotal reports from Missouri are that the first few DCDs built there are performing well. The DCD may have saved the Missouri DOT about $8 million in comparison to a rebuilt diamond [6]. Queue lengths, which had been one to two miles long occasionally with the old interchange dropped to minimal lengths with the DCD. Drivers seem to have adapted quickly, and even the large numbers of trucks through the interchange seem to navigate easily. A large evaluation of the early DCDs in the US has been funded by the FHWA and results should be published soon.

Ohio investigated DCD installation as early as 2004. Other states have examined or built the design, including Utah, New York, Oregon, Kentucky, Tennessee, New Mexico, Maryland, and Michigan. In all cases known to the author, the DCD fared well in comparison to a standard diamond in project-level evaluations. For example, Ohio engineers compared an upgraded diamond to a DCD [7]. Even though the upgraded diamond would cost $14 million while the DCD would cost $8 million, the DCD would produce better levels of service. In a more challenging comparison, consultants in Michigan examined a DCD, a diamond with roundabout ramp terminals, and a two-loop partial cloverleaf [8]. All three designs had comparable costs, the DCD needed no exceptions to the design standards while the others did, and the DCD had comparable levels of service to the partial cloverleaf.

B. DCD Limitations

The DCD is not the perfect interchange form, however, and does have at least three obvious limitations. First, the capacity of a DCD is limited by the two crossover intersections. If the surface street through movements is large enough, the DCD will break down before other interchanges. Second, it is not possible to establish good signal progression in both directions between the signals at the two crossover intersections. If the through demands on the surface street are relatively equal in both directions, one or both directions will have progression bands considerably shorter than the green times. Finally, due to the curvature for the through movements leading into the crossover intersections the DCD restricts nearby driveways to a greater extent than a diamond or some other interchanges. More experience with DCDs may reveal other weaknesses in the design, but for now it is obvious that the scope for DCD application should be limited.

C. Other Service Interchanges

Within the service interchange category, with no loops and no roundabouts, the competitors to the DCD include several diamond interchange variations. The range, shown in Fig. 3, includes spread diamonds with 400 meters or so between ramp terminals to tight diamonds with only 70 meters or so between ramp terminals. Standard diamonds have about 200 meters between ramp terminals. The spread diamond offers more storage space between signals, while the tight diamond offers signal control that essentially mimics a single four-phase signal. Single-point diamonds offer the advantage of a single signal with just three phases. The large bridge needed to accommodate the single-point makes it much more expensive than the other diamond variations and the DCD though.

In recent years, alternative methods of treating left-turning movements and simplifying signal phasing have been developed besides the DCD to provide high capacity treatments compared to traditional diamonds. In most cases, turning movements are displaced from ramp terminal intersections, creating two-phase signals. In this paper the author analyzed six unconventional interchanges of this form, including:

- Median u-turn (MUT),
- MUT with slip ramps,
- Superstreet,
- Displaced left turn (DLT),
- Contraflow left, and
- Three-point.

(a) Spread diamond

(b) Tight diamond

(c) Single-point diamond

Fig. 3 Common diamond interchange variations [9]

II. Purpose of This Paper

The objective of this paper is to analyze the alternatives to a diamond interchange so that designers of new service interchanges can have some idea about which alternatives make sense in a particular location before embarking upon detailed simulations. The scope of the paper is limited. The paper considered service interchanges with no loop ramps or roundabouts. The paper did not consider interchanges with more than two levels (i.e., no flyover ramps) due to their higher costs and impacts. The paper was limited to cases with no vehicles or pedestrians crossing the surface street (i.e., no frontage roads or ramp-to-ramp movements); this is likely the most common design context for new interchanges. Also, the paper mainly considered interchange sites with four-lane surface streets since this is such as important niche.

III. Measures Considered

To compare the competitor designs, the paper employed seven measures. Two were related to travel efficiency, two were related to installation cost, and three were related to safety.

A. Travel Efficiency Measures

The first measure employed related to travel efficiency was capacity. In particular, for a sample of service interchanges with four-lane (and one six-lane site, number 2) surface streets in the Raleigh, North Carolina, USA area, we calculated the highest sum of critical lane volumes at any point in each of the designs. The sum of the critical lane volume is a terrific measure of capacity for intersections and interchanges; in fact, US FHWA recently released a calculation tool for this measure to evaluate unconventional designs [10]. For intersections with two-phase signals a critical sum of about 1600 vph is at capacity; for intersections with three-phase signals a critical sum of about 1500 vph is at capacity. Table I shows the peak hour turning movements (the most recent counts available) from the six interchanges tested for this paper. For sites 4 and 5 some of the lower-volume movements were not counted, so the author assumed 200 vph for those movements. The sample provides a variety of turning patterns that give the competitors a worthy test. Sites 1 and 4 had some high ramp volumes, sites 2 and 3 had some high through movement volumes, and sites 5 and 6 had more moderate and balanced volumes. To keep the test fair all designs employed two through lanes in each direction on the surface street and one-lane exclusive left turn and right turn bays.

The second measure we employed related to travel efficiency was quality of progression. As noted above, poor progression between the two signals at many diamonds causes delay, leads to potential spillback problems, and means wider and longer bridges are needed to store queued vehicles. The quality of progression should vary widely between interchange designs.

Note that this paper did not compute delay, level of service (LOS), or travel time for the competitor designs. Going beyond the capacity and progression measures to delay, LOS, or travel time would require making a host of other assumptions about how the designs would be applied to our set of test interchanges that would be subjective and liable to criticism. Designers finding one or more of these competitor designs to be an intriguing possibility at a site can employ a traffic operations model to produce their own delay, LOS, or travel time estimates while making their own customized assumptions.

TABLE I
Peak Hour Turning Movements Tested (in VPH)

Direction	Site 1, I-540 @ Falls of Neuse	Site 2, I-40 @ South Saunders	Site 3, I-440 @ New Bern	Site 4, I-440 @ Glenwood	Site 5, I-440 @ Hillsborough	Site 6, I-440 @ Western
EBL	1142	54	200	1028	57	280
EBR	219	90	383	112	152	600
WBL	66	479	200	200	233	650
WBR	136	214	200	1781	186	370
NBL	303	532	809	200	376	590
NBT	1214	1353	2844	1320	1063	1270
NBR	258	82	200	200	477	750
SBL	223	114	454	200	242	360
SBT	877	2447	1403	955	732	1200
SBR	431	455	568	200	62	440

The freeway runs east-west in each case

B. Cost Measures

The two cost-related measures considered in this paper were the amount of ROW and the size of the bridges. There should be little debate that those are the two major factors related to the installation cost of an interchange retrofit. They are also closely related to the environmental impacts one should expect upon installing an interchange.

When considering ROW, remember that designs that require more ROW also restrict distances to nearby interchanges and/or access points. Note when considering bridge size that none of the bridges in this category of interchange are on a third level (no flyovers).

C. Safety Measures

This paper considered three measures related to safety, including the number of unusual maneuvers required of drivers, the number of vehicular conflict points on or near the surface street, and the ease by which pedestrians can cross the interchange (walking along the surface street). Unfortunately, in the case of most of the new alternatives there are not enough historic collision records available to study safety directly, so these indirect measures must suffice.

Unusual maneuvers include cases when drivers must first turn right to eventually go left and cases when drivers travel in a contraflow position. These cases should cause concerns for designers that drivers will become confused and hesitate, swerve, or go the wrong way.

There is wide agreement that the number of conflict points at a junction is generally related to safety; for example, the AIIR uses this measure to evaluate new designs [1].

The pedestrian measure is based upon the number of road or ramp crossings and the number of those crossing at which the vehicular traffic is free-flowing.

IV. Details on the Alternate Designs

As mentioned above, this paper examined six unconventional interchanges as well as the DCD. In this section of the paper we describe the operation and design of those six forms. The paper also examined standard diamond, tight diamond, spread diamond, and single-point diamond designs.

Fig. 4 (a) shows a MUT interchange. Like the MUT intersection, MUT interchanges were in operation in Michigan, USA by the 1960's. This form requires left-turning vehicles from the surface street to make a right turn, cross over u-turn bridge, and travel back across the surface street before entering the freeway. Left turns from the freeway onto the cross street are made as in a diamond. The main extra costs are for the two u-turn bridges, but the design is well-tested in Michigan [11], is operationally efficient with some demand combinations, and is friendly to pedestrians.

Fig. 4 (b) shows a variation of the MUT that may also have good potential. There is at least one in place, in Wisconsin, USA. The slip ramps for traffic from the u-turn crossovers mean that those vehicles do not have to go back across the surface street, making this design highly efficient. If the two extra bridges do not drive the cost too high, and there is room along the freeway for the u-turn crossovers and slip ramps, this design could be worth a look.

If the interchange site in question has room along the surface street for u-turn crossovers, a superstreet interchange as created by the author and as shown in Fig. 4 (c) may be an efficient design. A left turn from the freeway to the surface street is made by first turning right and then making a u-turn at a median crossover. A superstreet interchange has six two-phase signals—one at each median crossover and one at each off-ramp terminal--but they should be efficient because they are independent by direction and therefore allow perfect progression in both directions at any speed and any signal spacing.

As described in the AIIR [1] and as shown in Fig. 4 (d), a good alternative design is a displaced left turn (DLT) diamond. It uses attributes of "continuous flow intersections" to create counter-flow travel lanes and free-flowing left turns from the surface street. It has four traffic signals, but each has only two phases and the two outlying secondary signals are easy to coordinate with the main two signals. It should not need a bridge much wider than a diamond. The AIIR notes that this design is not patented in the US.

A close kin to the DLT is the contraflow left design, as Fig. 4 (e) shows. It has existed at several interchanges in Florida, USA for many years, and has recently become more popular [12]. Whereas the DLT moves the left-turning traffic from the cross street to the left of the opposing through traffic, the contraflow design just moves those left-turning vehicles to the left of the opposing left-turning vehicles. This shift helps travel efficiency without adding the two extra signals introduced by the DLT, and it should be a relatively inexpensive competitor.

The final unconventional interchange competitor tested was the three-point interchange, as shown in Fig. 4 (f). In this design, which was installed in Missouri, USA [13], the left turns from the freeway meet in the middle of the bridge as in a single-point, but the left turns from the surface street are served at two-phase signals some distance downstream of the bridge. These secondary signals are easy to coordinate with the main signal. Since there are two fewer movements occurring at the bridge, the bridge may be smaller than at a single-point, which may make this design competitive.

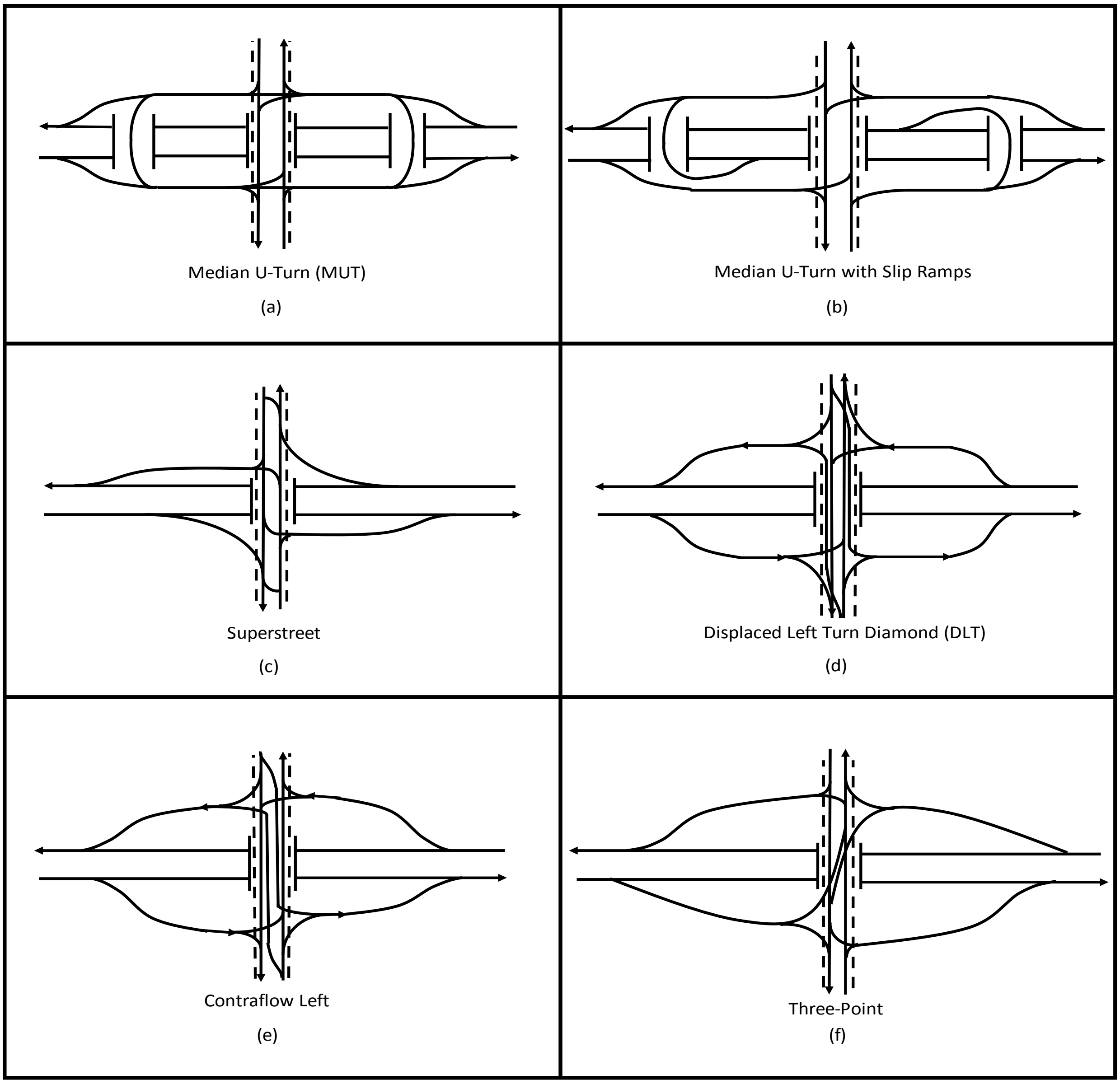

Fig. 4 Schematics showing six competitor designs (a dashed line indicates a pedestrian path)

V. RESULTS

Table II shows a summary of the capacity results for the designs tested while Table III provides a summary of the measures other than capacity. In Table III the author rates the competitor designs relative to the standard diamond, on a scale from "much better than the standard diamond" to "much worse than the standard diamond", and provides some of the bases for the ratings. The paragraphs below provide details on the performance of each competitor evaluated.

International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:8, No:11, 2014

TABLE II
SUMMARY OF CAPACITY RESULTS

Interchange	Critical sum, vphpl					
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
DCD	1900	2410	2630	2360	1200	1860
Tight diamond	2120	2290	2660	2960	1110	2020
Spread diamond	2120	2290	2660	2960	1110	2020
Single-point	1970	2240	2080	2960	1010	1840
Median u-turn	1750	1760	2330	2960	940	1520
MUT with slip ramps	1750	1550	1800	2960	790	1520
Superstreet	2030	2050	2380	2160	1010	1700
Displaced left turn	1750	1990	1980	2960	860	1520
Contraflow left turn	1970	2240	2260	2960	980	1840
Three-point	1900	1810	2280	2960	960	1580

Cell(s) with lowest critical sum for each site are shaded

TABLE III
SUMMARY OF RESULTS FOR OTHER MEASURES

Interchange	Quality of progression	Right of way	Bridge size	Unusual maneuvers	Conflict points	Crossing pedestrians
Standard diamond	(2 @ 3φ)	(200 m along the cross street)	(5-lane)	(Quite intuitive for motorists)	(16)	(2 rd, 0 ff)
Tight diamond	~ (1 @ 4φ)	++	- (6-lane)	-	~ (16)	~ (2 rd, 0 ff)
Spread diamond	- (2 @ 3φ)	--	++ (4-lane)	+	~ (16)	~ (2 rd, 0 ff)
Single-point	+ (1 @ 3φ)	~	-- (5-lane & 4 ramps)	-	-- (20)	-- (4 rd, 2 ff)
DCD	+ (2 @ 2φ)	~	++ (4-lane)	--	+ (14)	-- (4 rd, 2 ff)
Median u-turn	+ (2 @ 2φ)	~	-- (3 bridges with 6 total lanes)	--	-- (22)	~ (2 rd, 0 ff)
MUT with slip ramps	+ (2 @ 2φ)	-	-- (3 bridges with 6 total lanes)	-	+ (12)	- (2 rd, 1 ff)
Superstreet	++ (3 @ 2φ)	+	- (6-lane)	-	+ (14)	~ (2 rd, 0 ff)
Displaced left turn	+ (3 @ 2φ)	~	- (6-lane)	-	- (18)	- (3 rd, 1 ff)
Contraflow left turn	~ (2 @ 3φ)	~	- (6-lane)	-	-- (20)	~ (2 rd, 0 ff)
Three-Point	+ (2 @ 2φ)	-	- (4-lane & 2 ramps)	~	+ (14)	- (3 rd, 1 ff)

Key: ++ means much better than the standard diamond, + means somewhat better, ~ means roughly the same, - means somewhat worse, and -- means much worse. In the "quality of progression" column, "(2 @ 2φ)" means, for example, that each direction of surface street through traffic must pass two signals, each with two phases. In the "crossing pedestrians" column, "(4 rd, 2 ff)" means, for example, that pedestrians traversing the interchange must cross roadways, two of which have free-flowing traffic.

For capacity, the tight diamond critical sums were lower than the standard diamond in three cases and higher twice. The best feature of the tight diamond is that it should require much less ROW than the standard diamond. However, it will require a wider bridge than the standard diamond and may cause a little driver confusion due to the short distance between signals on the bridge.

The capacity of a spread diamond is equivalent to the capacity of a standard diamond based on critical sums. The best feature of the spread diamond is the small bridge. However, it will require more ROW than the standard diamond, and will also restrict access points along the surface street. It also does not lend itself well to two-way progression due to the signal spacing.

For capacity, as might be expected the single-point fared better than the standard diamond at five of the six test sites and was the same at the sixth site. It should produce better coordination than the standard diamond; if the right turns from the freeway to the surface street require signals, they are easy to coordinate with the main signal. The single-point interchange has several significant drawbacks, though, including that it will need a much larger bridge than at a standard diamond because it is five lanes wide and must accommodate the ramp terminals as well; will likely cause some driver confusion for the left turns on the bridge due to the wide expanse; has four more conflict points than the standard diamond; and will be much more difficult for crossing pedestrians.

The DCD critical sums were lower than the standard diamond in four cases and higher twice. The DCD did not fare as well when through volumes were relatively higher than left turn volumes, as might be expected. The best feature of a

DCD is the smaller bridge required. Two-way progression is easier through a DCD, and it has fewer conflict points than a standard diamond. The biggest drawback at a DCD is the unusual driver maneuvering required. The DCD is also more difficult for crossing pedestrians.

The MUT had the best capacity of all interchanges tested at two of the sites, and was better than the standard diamond for capacity at five of the six interchanges tested. Other highlights for the MUT included that it is better than the standard diamond for progression and is excellent for crossing pedestrians like the standard diamond. However, the MUT requires three bridges with a total width larger than a standard diamond, requires a very unusual driving maneuver that has the potential to confuse drivers, and has more conflict points than any interchange studied.

The MUT with slip ramps was the best design tested for capacity, besting the field (and the DCD) at five of the six interchanges tested. It was also the best interchange examined for the number of conflict points, and should allow better signal progression than the standard diamond. Its biggest drawback was that it requires three bridges with a total width larger than a standard diamond. Other drawbacks included that it should require more ROW than the standard diamond, particularly along the freeway to create room for the u-turn crossovers and slip ramps; requires drivers to make unusual maneuvers, and requires pedestrians to cross a free-flowing ramp.

The superstreet interchange was better than the standard diamond for capacity at all six interchanges tested, and was the best in the field at site 4 with heavy ramp volumes. Another highlight is that surface street through traffic in each direction must move past three two-phase signals, but since each signal only controls one direction of through traffic the design has the unique feature of "perfect progression" (the widest possible green band) in both directions at any speed and any signal spacing, which is much better than the progression provided by the standard diamond. It should require slightly less ROW than the standard diamond, has fewer conflict points than the standard diamond, and should provide the same excellent service to pedestrians as the standard diamond. The only relatively minor drawbacks to the superstreet interchange are the larger bridge required and the potential for more driver confusion than at a standard diamond since it requires left turns from the freeway to first turn right, then make a u-turn at a crossover.

Like the MUT, the DLT was better than the standard diamond for capacity at five of the six interchanges tested, and was tied for the top spot in capacity with the MUT designs at two interchanges. It also should provide better surface street signal progression than the standard diamond. However, it has several drawbacks compared to the standard diamond, including a wider bridge, some unusual driving maneuvers, two more conflict points, and more difficult pedestrian crossings.

The contraflow left was better than the standard diamond for capacity at five of the interchanges tested and provides the same excellent service to crossing pedestrians as the standard diamond. However, in comparison to the standard diamond it requires a larger bridge, requires left-turning traffic to make an unusual maneuver, and has more conflict points.

For capacity, the three-point was better than the standard diamond at five of the interchanges tested and equivalent at another. It is better than the standard diamond for signal progression and had fewer conflict points. However, the three-point interchange will require a larger bridge and more ROW, and will be more difficult for crossing pedestrians than the standard diamond.

VI. Conclusions

The results show that there is no superior design in all measures in the interchange category investigated. The standard diamond, the most common service interchange design at this time, has some good features like excellent service for crossing pedestrians, but has generally poor capacity and signal progression. The DCD, currently the popular choice as a diamond replacement, is a fine design, and is as good as or better than most other designs on most measures examined. However, bridge width was the only measure for which the DCD was not beaten by some other design. On the other hand, the DCD performed relatively poorly for capacity and for serving pedestrians. Each of the other designs had their good features and poor features. Generally, the MUT with slip ramps was best for capacity and conflict points, the tight diamond was best for ROW, the spread diamond was best for unusual maneuvers, and the MUT was best for pedestrians. The single-point, DLT, contraflow left and three-point all had some positive attributes as well. The superstreet design had the best signal progression, was generally good for capacity, and had the fewest negative attributes of all interchanges tested.

VII. Recommendations

Based on the results from this paper, designers of new service interchanges with four-lane surface streets should investigate the full range of alternatives that could work at the particular spot. Simple diamonds and DCDs have their niches, but some of the other designs investigated here look like they could be optimum at some spots. The superstreet interchange in particular appears to have good potential. Designers looking at a particular spot can use the information presented here to quickly reduce the alternatives to a short list of those that could work well, then employ a traffic simulation model to investigate travel efficiency measures in detail and employ a set of scale drawings to investigate cost measures in detail. Designers owe it to their clients and to future generations of motorists to not disregard viable alternatives without some investigation.

The results presented here strongly suggest that more research is needed to learn more about some of these unconventional designs. Similar to the recent research on the DCD sponsored by the US FHWA, to be released soon, agencies should fund research on the travel efficiency of the new designs using traffic models and on the unusual maneuvers required by some the new designs using driver simulations. The superstreet, median u-turn with slip ramps, and three-point designs all have uniquely positive features that make them worth further study.

ACKNOWLEDGMENT

The author thanks the City of Raleigh, North Carolina, USA for the traffic count data used in the paper. Ms. Sarah Ott provided terrific help with the calculations and sketches used in the paper.

REFERENCES

[1] Hughes, W., R. Jagannathan, D. Sengupta, and J. Hummer, Alternative Intersections/ Interchanges: Informational Report, FHWA-HRT-09-060, Washington, DC, April 2010.
[2] Chlewicki, G. L., "New Interchange and Intersection Designs: The Synchronized Split-Phasing Intersection and the Diverging Diamond Interchange," 2nd Urban Street Symposium, TRB, Anaheim, CA, 2003.
[3] Bared, J.G., P.K. Edara, and R. Jagannathan, "Design and Operational Performance of Double Crossover Intersection and Diverging Diamond Interchange," Transportation Research Record 1912, 2005.
[4] Edara, P. K., J. G. Bared, and R. Jagannathan, "Diverging Diamond Interchange and Double Crossover Intersection - Vehicle and Pedestrian Performance," 3rd International Symposium on Highway Geometric Design, Chicago, IL, June 2005.
[5] FHWA, "Drivers' Evaluation of the Diverging Diamond Interchange," Tech Brief, FHWA-HRT-07-048, McLean, VA, 2007.
[6] "Diverging Diamond Interchange," brochure produced by the Missouri Department of Transportation, Springfield District, 2008.
[7] Young, J. and N. English, "Diverging Diamond Interchange," presentation to the Ohio Transportation Engineering Conference (OTEC), Columbus, 2007.
[8] Orchard, Hiltz, and McCliment, Inc., "Diverging Diamond Interchange," Livonia, MI, 2008.
[9] Aerial photos from www.bing.com.
[10] Asokan, et al., "Alternative Intersections Selection Tool-AIST," Paper 10-2146, presented at the 89th Annual Meeting of the TRB, Washington, DC, 2009.
[11] Dorothy, P.W., T.L. Maleck, and K.K. Miller, "The Operational Aspects of the Michigan Urban Diamond Interchange," Transportation Research Record 1612, 1998.
[12] Reid, J.D., Unconventional Arterial Intersection Design, Management and Operations Strategies, Parsons Brinckerhoff Quade and Douglas, Inc., New York, NY, September 2003.
[13] Crawford, Murphy, and Tilly, Inc., "Interstate 55-MO Route 141 Corridor Study, Arnold, Missouri," Prepared for Missouri DOT, St. Louis, March 22, 1999.