Interchange and Grade-Separated Intersection Designs that Promote Arterial Progression

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For publication in Proceedings, Urban Street Symposium, Raleigh, NC, May 2017

Topics: Alternative intersection designs, design effects on operations and safety

Key words: Signal progression, arterial, interchange, superstreet, contraflow

Word count: 4750 text + 11 figures or tables = 7500 words total

ABSTRACT
Signal progression on the arterial(s) involved is clearly on the list of factors that designers of interchanges and grade-separated intersections must consider, but judging by what gets built it does not rate highly. Designers continue to choose configurations that offer no chance for good two-way progression, including diamonds and parclo A's. Meanwhile, designs that could provide good two-way progression are available. The objective of this paper is to highlight progression-friendly intersection, grade-separated intersection, and interchange designs.

Some grade-separated intersections are capable of good progression in both directions of both arterials, some can progress traffic in both directions on one arterial, and some cannot provide two-way progression on either arterial. The echelon, built at least once in the US, can provide great progression on both arterials. Alternative designs such as the two-level signalized and the half superstreet half single-point have been published that also promote great four-way progression. Designers can also use contraflow principles to promote great progression in all directions.

The older interchange that provides superior two-way progression potential, and many other good features, is the parclo B. The FRE alternative design published in 2010 offers great progression potential and other strong features. Two designs called the synchronized and the Milwaukee B, not published or built previously to the author's knowledge, also are capable of great two-way progression and have other excellent features.

INTRODUCTION

Many urban and suburban corridors in the US have poor signal progression. One common reason for those struggles is that the signals have too many phases which do not leave time for the through movements. Another common reason is that the signals are spaced poorly at places that do not allow good two-way progression at any feasible cycle lengths or travel speeds. An underlying reason for both of these reasons is that nobody designed for progression. In many cases, intersections were sited and signals were installed individually, with little or no regard for surrounding signals. Particularly with signals installed as part of a traffic impact analysis, if an individual signal was estimated to produce a reasonable intersection-level quality of service the light was turned on with no thought to the progression that was possible along the arterial. Arterial progression in many cases is the exclusive duty of signal timing professionals—engineers and technicians who enter the picture long after planners and designers and try to make the best of the combination of signals and phasing they are handed.

Fortunately, we do not have to settle for the usual way of doing business described above. When we have the chance to build or rebuild a junction or a corridor, we have tools to design for progression along a corridor. There are intersection, grade-separated intersection (intersections with bridges), and interchange designs that promote good progression both ways in a corridor or in all four directions in the case of the meeting of two arterials. These designs work by reducing the number of phases, from four basic (not counting overlaps) phases to three or two. The designs also work by using half-signals, which are signals that only impact one direction of the arterial. Full signals, which impact both directions of the arterial, must be spaced within narrow limits to allow good two-way progression, but half signals can be spaced at any distance without concerns about the progression bands being impacted. Designs that reduce the number of phases and use half-signals promote good progression can be very easy to time.

The objective of this paper is to show intersection, grade-separated intersection, and interchange designs that promote good two-way or four-way progression. Many of these designs have other benefits besides progression, but we will concentrate on progression in this paper. Some of these designs have been used for years and are widespread, some have only been installed in a few places, some have only been published, and one is being published for the first time in this paper. Hopefully if planners and engineers know that there are designs available and that it is possible to design for progression they will begin to do so, or at least look up and down the street before powering up a new four-phase full signal.

SPACING GUIDELINES

As mentioned above, full signals only allow progression in both directions on an arterial at certain spacings. There are four main constraints. First, signals spaced closely together can be timed so the through green phases at both signals begin at the same time. This simultaneous plan usually works well with full signals spaced below about 500 to 1000 feet. Second and third, full signals can be timed for two-way progression if the through green phase of one signal begins just as the through green phase of the second signal ends. This alternate plan usually works well with full signals spaced from around 2000 feet apart to about 3500 feet apart. Fourth, signals progression is not possible if signals are spaced too far apart, because traffic flows gradually return to a random state some distance downstream from a signal. That distance is thought to range from one-half mile at slow speeds to maybe one mile with faster speeds. Table 1 puts all four constraints together for various cycle lengths and speeds, showing the “sweet spots” and “dead zones” for two-way progression. Table 1 is based on the standard equation for progression band efficiency (1) and an efficiency of 40 percent of the cycle. For example, at a speed of 25 mph and a cycle length of 60 seconds progression (at 40 percent efficiency) using a simultaneous system is possible if the spacing is below 220 feet and is possible using an alternate system if the signal spacing is between 880 and 1320 feet, but at spacings between 220 and 880 feet and again above 1320 feet good two-way progression is not possible. Note that at some combinations of higher speeds and/or longer cycles the random flow limit is lower than the upper or lower limit on alternate progression, indicating that those alternate progression limits are no longer relevant.

When retrofitting an existing corridor, there is often a cost involved in converting an existing full signal to some design that uses half-signals or fewer phases. In these cases, designers may want to consider staying with a full signal if it is well-spaced to promote two-way progression and it is functioning well in other respects. In that light, readers may wish to consider the designs in this paper as especially well-suited for places where a full signal would be poorly-spaced for progression.

INTERSECTIONS

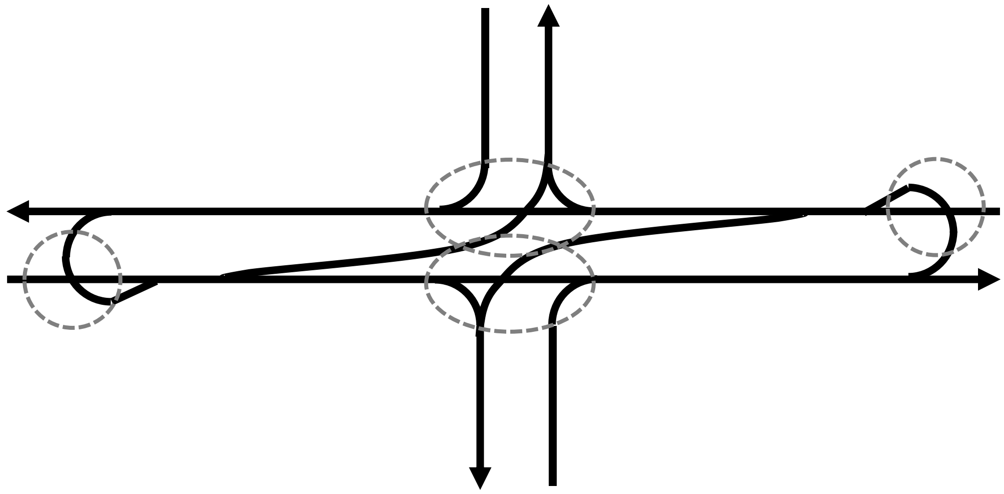
Designs that Use Half-Signals

There is no known design that provides excellent four-way progression for the at-grade intersection of two two-way streets without regard to the signal spacing on the streets. In other words, the two designs in this category use half-signals to promote progression on one street but do nothing for progression on the other street.

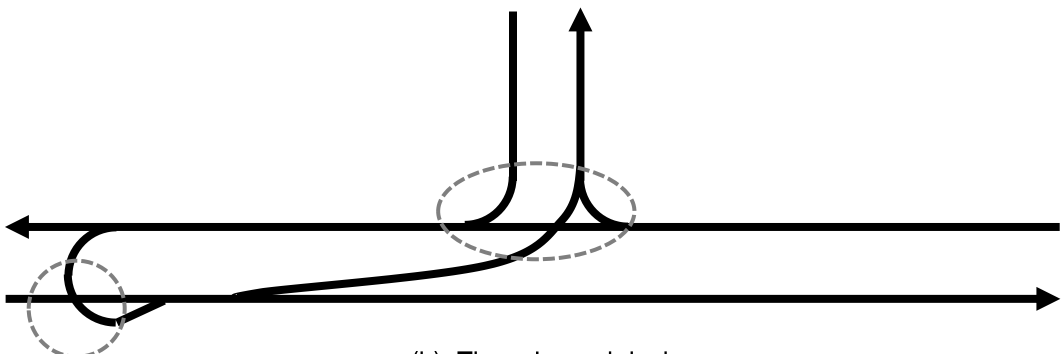
The main intersection design that promotes good arterial progression with half-signals is the superstreet, also known as the synchronized street, the restricted crossing u-turn (RCUT), the j-turn, and the reduced conflict intersection. Figure 1 shows the most popular four-legged superstreet design, a three-legged design, and a design for lower-demand locations. In Figure 1 and all subsequent figures showing designs, a dashed gray circle indicates a signal location. A superstreet redirects minor street left turn and through movements to u-turn crossovers; the lower-demand design in Figure 1 also redirects the major street left turns. Since their development in the 1980s (2) superstreets have been installed in hundreds of locations across at least 11 states. Superstreets bring documented safety, efficiency, and pedestrian benefits (3). Since superstreets break up a standard intersection with one full signal into a larger intersection with four half-signals, they provide great two-way progression at any signal spacing.

Table 1. Full signal spacing limits for progression.

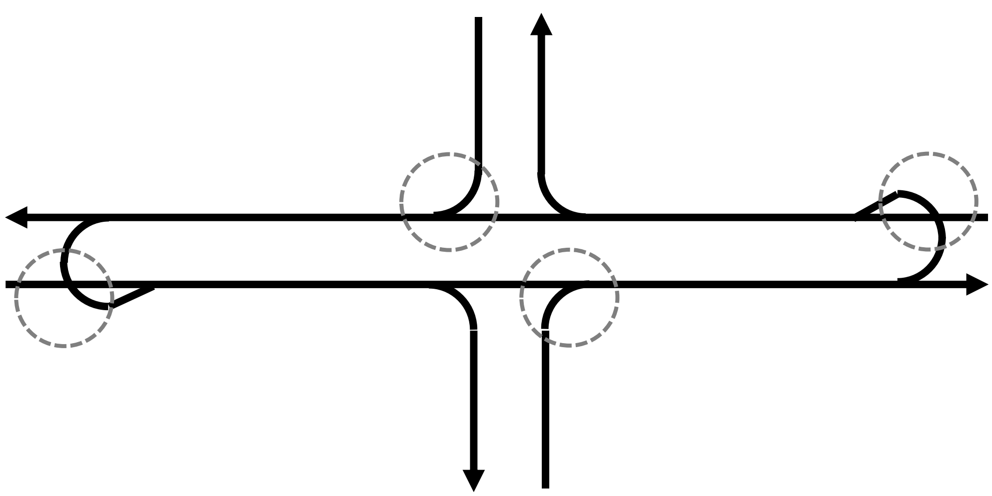
Speed, mph	Cycle, sec	Upper limit for simultaneous progression, ft	Lower limit for alternate progression, ft	Upper limit for alternate progression, ft	Lower limit for random flow, ft
25	60	220	880	1320	2640
30	60	264	1056	1584	2640
35	60	308	1232	1848	3960
40	60	352	1408	2112	3960
45	60	396	1584	2376	5280
50	60	440	1760	2640	5280
55	60	484	1936	2904	5280
25	80	293	1173	1760	2640
30	80	352	1408	2112	2640
35	80	411	1643	2464	3960
40	80	469	1877	2816	3960
45	80	528	2112	3168	5280
50	80	587	2347	3520	5280
55	80	645	2581	3872	5280
25	100	367	1467	2200	2640
30	100	440	1760	2640	2640
35	100	513	2053	3080	3960
40	100	587	2347	3520	3960
45	100	660	2640	3960	5280
50	100	733	2933	4400	5280
55	100	807	3227	4840	5280
25	120	440	1760	2640	2640
30	120	528	2112	3168	2640
35	120	616	2464	3696	3960
40	120	704	2816	4224	3960
45	120	792	3168	4752	5280
50	120	880	3520	5280	5280
55	120	968	3872	5808	5280
25	150	550	2200	3300	2640
30	150	660	2640	3960	2640
35	150	770	3080	4620	3960
40	150	880	3520	5280	3960
45	150	990	3960	5940	5280
50	150	1100	4400	6600	5280
55	150	1210	4840	7260	5280
25	200	733	2933	4400	2640
30	200	880	3520	5280	2640
35	200	1027	4107	6160	3960
40	200	1173	4693	7040	3960
45	200	1320	5280	7920	5280
50	200	1467	5867	8800	5280
55	200	1613	6453	9680	5280



(a) Most popular four-legged design.



(b) Three-legged design.



(c) Lower-demand four-legged design without direct major street left turns.

Figure 1. Superstreet designs.

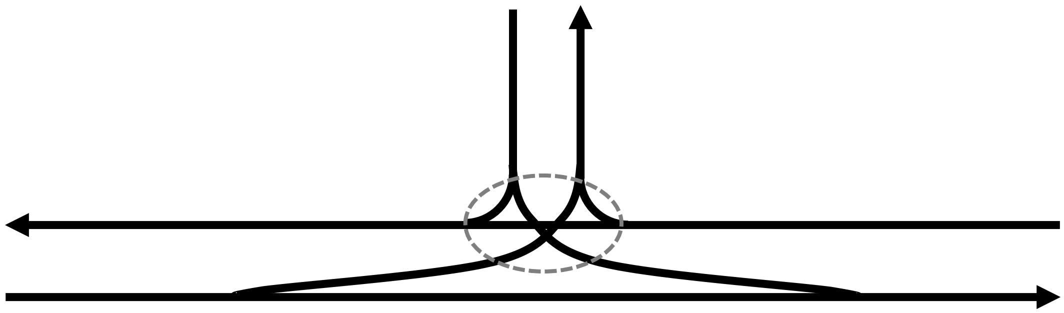
The other known at-grade intersection design that promotes progression by using only half-signals is the continuous green T. Figure 2 shows one type that has a left merge and one type that has a second signal instead of the left merge. The continuous green T has been the subject of recent research (4) and has been installed at many sites in several states. The main constraint on this design is that it only applies to three-legged intersections.

Designs that Reduce Signal Phases

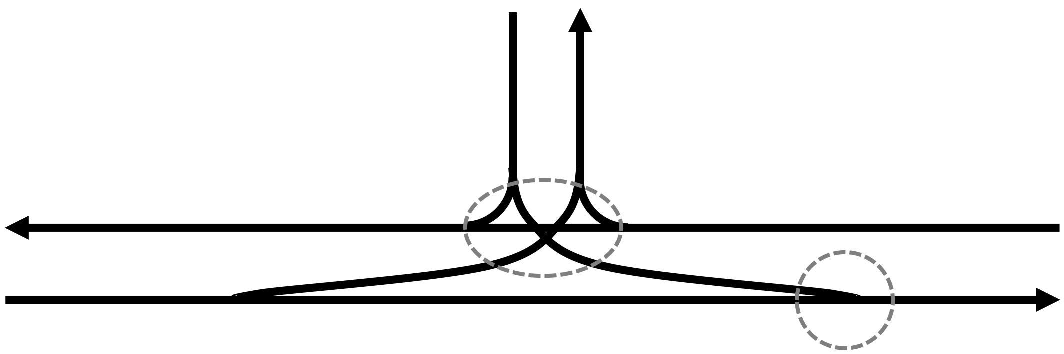
Two prominent at-grade intersection designs promote progression by reducing the number of basic signal phases to three or two. These designs still have full signals, which means that their progression potential is not nearly as good as the superstreet and continuous green T that only use half-signals. The spacing guidelines described above still apply to these designs. Nonetheless, the designs in this category provide better progression potential than a standard signal with four basic phases because they are able to provide more green time to the through movements, all else being equal.

The continuous flow intersection (CFI), also known as a displaced left turn, is intended for the intersection of two major arterials. It provides the highest capacity per lane of any known intersection design because it moves left turns at the main intersection at the same time as the through movements. Figure 3 shows a CFI that reroutes all four left turns, a CFI that reroutes two of the four left turns at an intersection with four approaches, and two versions of three-legged CFIs. The four-legged CFI that reroutes two of the four left turns gets the signal down to three basic phases, while the other designs shown in Figure 3 only require two basic phases. A CFI uses a half-signal where a left turn crosses the opposing through movement, but those signals are easy to progress with the main signal. CFIs have been well-researched (5).

The median u-turn (MUT), also called a Michigan left turn or a thru-turn, is also intended for the intersection of two major arterials. A MUT reroutes all four left turns to u-turn crossovers. Figure 3 shows a MUT with two u-turn crossovers. A three-legged MUT is the same as the three-legged superstreet shown in part b of Figure 1. At most MUTs the crossovers are signalized, but the crossover signals are two-phase half-signals that are easy to coordinate with the full main signal. If all four left turns are rerouted to u-turn crossovers the main signal has just two phases. MUTs are extensive in Michigan and a few have been built in Utah and other states (6). FHWA has provided extensive information on MUT design and operation (6), including documentation on the safety benefits of a MUT compared to a conventional intersection.

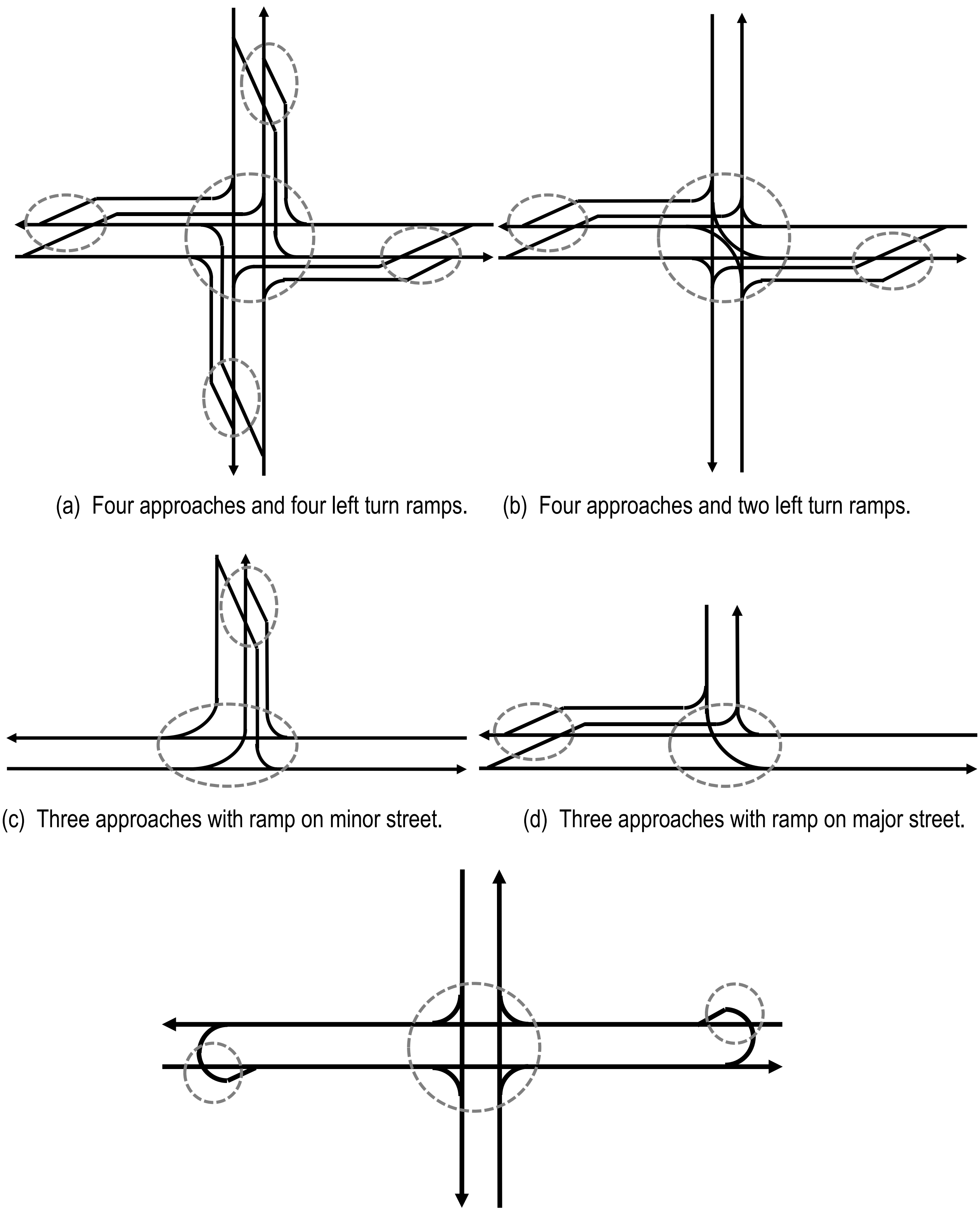


(a) With one half-signal and a left merge.



(b) With a second half-signal.

Figure 2. Continuous green T designs.



(a) Four approaches and four left turn ramps.

(b) Four approaches and two left turn ramps.

(c) Three approaches with ramp on minor street.

(d) Three approaches with ramp on major street.

(e) Median u-turn.

Figure 3. CFI and median u-turn designs.

GRADE-SEPARATED INTERSECTIONS

Grade separated intersections are connections between two non-freeways that use a bridge. Most of the time the roadways are arterials. They are common; the author counted 157 grade-separated intersections in North Carolina as of Fall 2016. In the likely event that a grade-separated intersection serves two arterials that meet in an urban and suburban area, good signal progression is usually desired in all four directions.

Problem with Using an Interchange at a Grade-Separated Intersection

Most grade-separated intersections in North Carolina use interchange designs such as diamonds. There are several common problems with most interchange designs at the meeting of two arterials, including poor signal progression. Using an interchange design, on one arterial the traffic streams only encounter merges and diverges. As noted above, without signals often enough a traffic platoon loses its discipline and begins to act random, which hurts the arrival pattern at the next signal. The arterial that has the merges and diverges feels like a freeway to drivers through the interchange, increasing speeds and creating potential rear-end crashes at the next signal. Raleigh has an example of this on US-401 approaching downtown from the south, where a grade-separated intersection with an interchange design creates a speeding problem and a rear-end crash potential at the first signal past the interchange. Meanwhile on the other arterial an interchange design like a diamond usually imposes two full signals at a spacing that does not provide good two-way progression. Using a typical interchange design like a diamond at the meeting of two arterials typically means that there will be good progression in one of the four directions.

An interchange design at the meeting of two arterials can use signals instead of merges on the roadway that otherwise feels like a freeway. These signals would be just half signals and would usually not bring capacity problems to those junctions, so the benefit those signals would bring in promoting progression may be greater than the costs. Agencies should consider such signals at grade-separated intersections where better progression on the arterial can result.

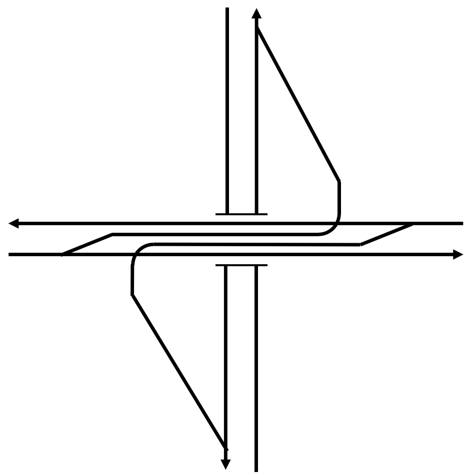
There are a few interchange designs that provide good progression on both directions of the arterial with signals. The next section of the paper describes those. Those interchanges still likely bring other drawbacks when applied at a grade-separated intersection but may be superior to a diamond or other common interchange design.

Grade-Separated Intersection Designs that Promote Progression

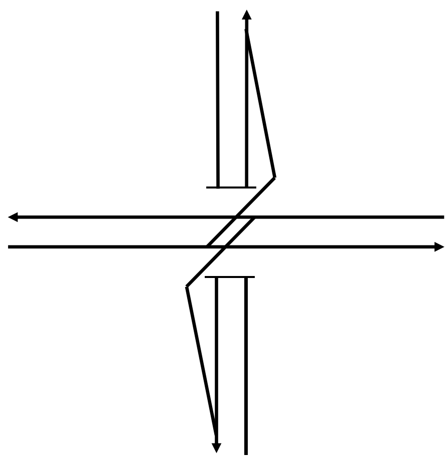
There are many grade-separated intersection designs that promote progression in all four directions. Six of the designs can be derived by thinking about the ways that drivers can make a left turn at a grade-separated intersection or interchange. Figure 4 shows three such ways to make a left turn: in a contraflow fashion beginning prior to the bridge, in a single-point fashion on the bridge, or in a diamond interchange fashion after the bridge. Contraflow left turns need left turn lanes on the bridge, single-point left turns need a wider and longer bridge, and diamond-style left turns have lower traffic capacity than the other two styles because the left turns must traverse both signals. A grade-separated intersection design can be thought of as a way to make the left turn from one roadway combined with a way to make the left turn from the other roadway. Figure 5 shows three of the six grade-separated intersection designs that promote four-way progression that result from combining the left turn methods. Part a in Figure 5 shows contraflow left turns on both arterials; besides promoting progression in all four directions this design would have many advantages in traffic capacity, pedestrian service, and cost. Part b in Figure 5 shows single-point left turns on both arterials; this design, called a “two-level signalized intersection,” is patented (7) but would be compact. Part c in Figure 5 shows single-point left turns on one arterial and diamond-style left turns on the other arterial; Eyler promoted this “half superstreet half single-point” concept a few years ago (8) and it too would seem to have many great features in addition to progression. The other three combinations of left turn styles not shown in Figure 5 also seem to have potential.

Other grade-separated intersection designs that promote four-direction progression use loop ramps. Figure 6 shows a design with one loop ramp—a connector road in one quadrant of the intersection—and superstreet intersections at both ends of the connector road. Motorists would need great signing to navigate the design in Figure 6, but it would have many positive attributes. Figure 6 also shows grade-separated intersection designs that use two loops. The designs in Figure 6 could be retrofits for one-loop or two-loop interchange designs that are not serving well at grade-separated intersection locations.

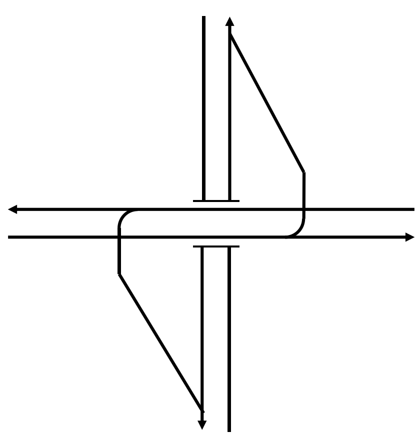
A final grade-separated intersection design that promotes four-direction progression is the echelon as shown in Figure 7. The echelon raises one direction of each arterial to the upper level while keeping the other direction of each arterial at grade. Each direction of each arterial thus negotiates one two-phase half-signal. All left turns are direct. Two of the left turns would require a left merge or a second signal. An echelon was built in the late 1990s in the Miami, FL area (9). Echelons are likely costly, with much earthwork or many retaining walls, and would not serve pedestrians very well, but they would provide superb capacity with no out-of-direction travel.



(a) Contraflow left turns.

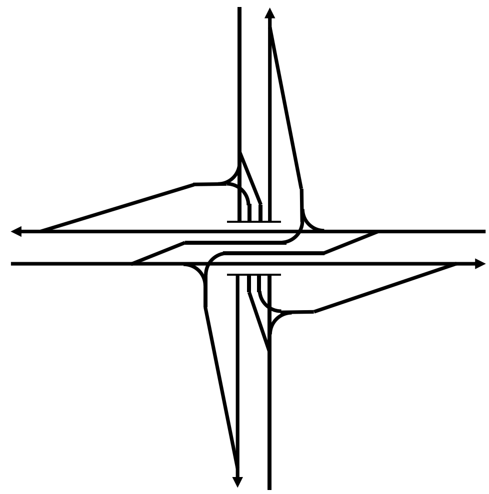


(b) Single-point left turns.

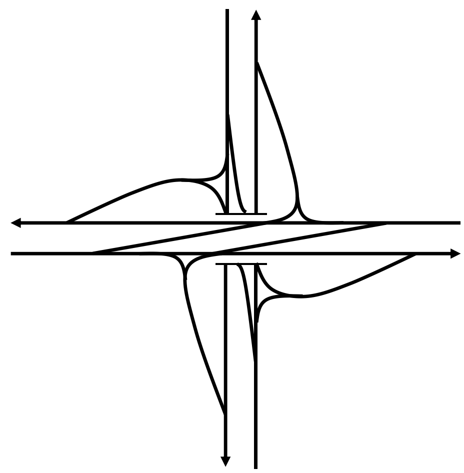


(c) Diamond-style left turns.

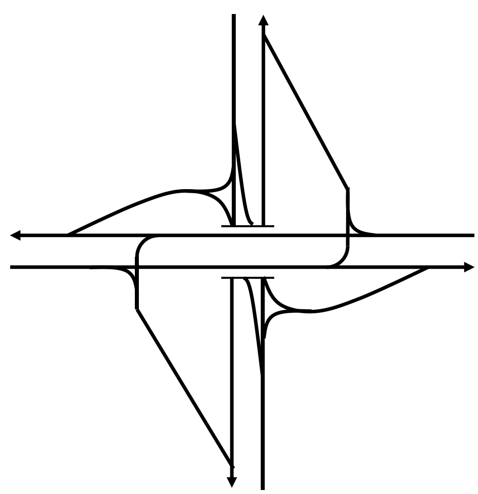
Figure 4. Three ways to make left turns at a grade-separated intersection or interchange.



(a) Contraflow left turns on both arterials.

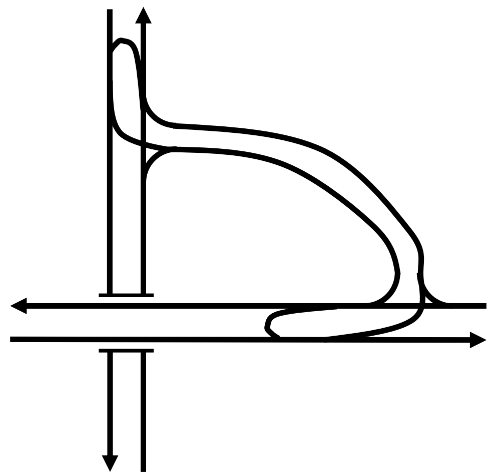


(b) Single-point left turns on both arterials (7).

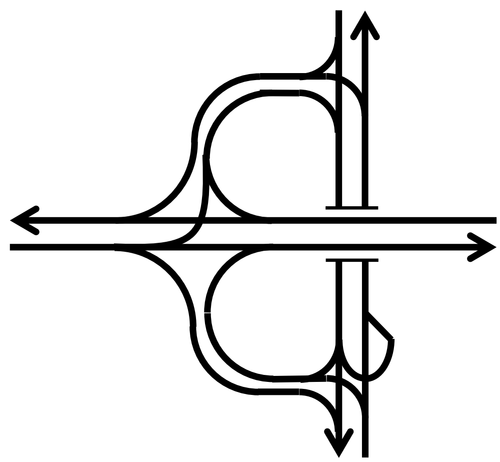


(c) Single-point left turns on one arterial and diamond-style left turns on the other arterial (8).

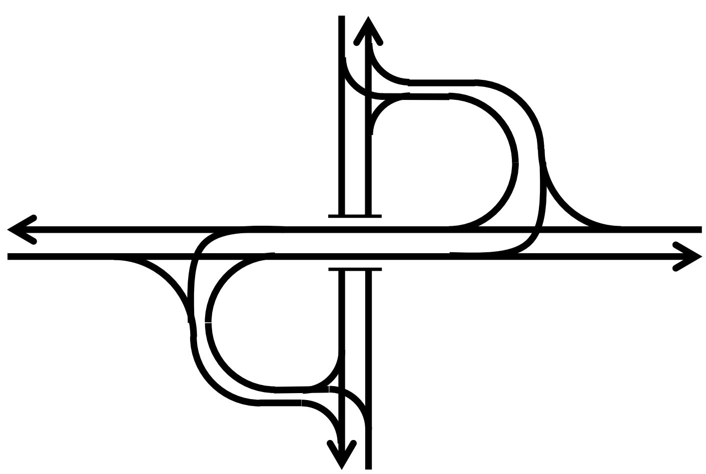
Figure 5. Three grade-separated intersection designs created by combining left turn styles from Figure 4.



(a) Single quadrant grade-separated intersection with superstreets.



(b) Two loops on same side of one arterial.



(c) Two loops on diagonal corners.

Figure 6. Grade-separated intersection designs with loops that promote four-direction progression.

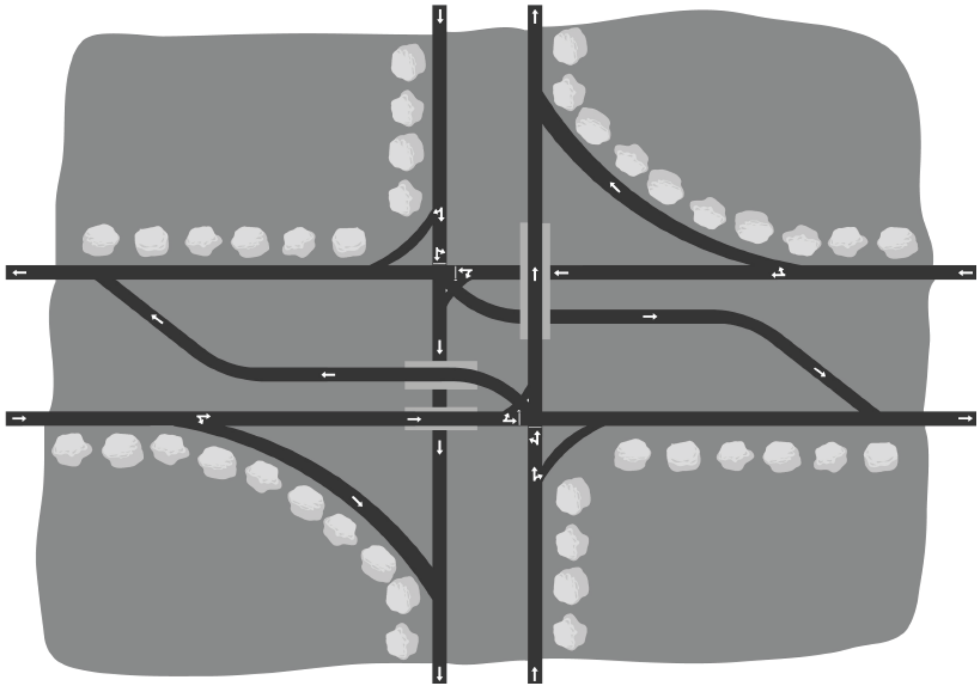
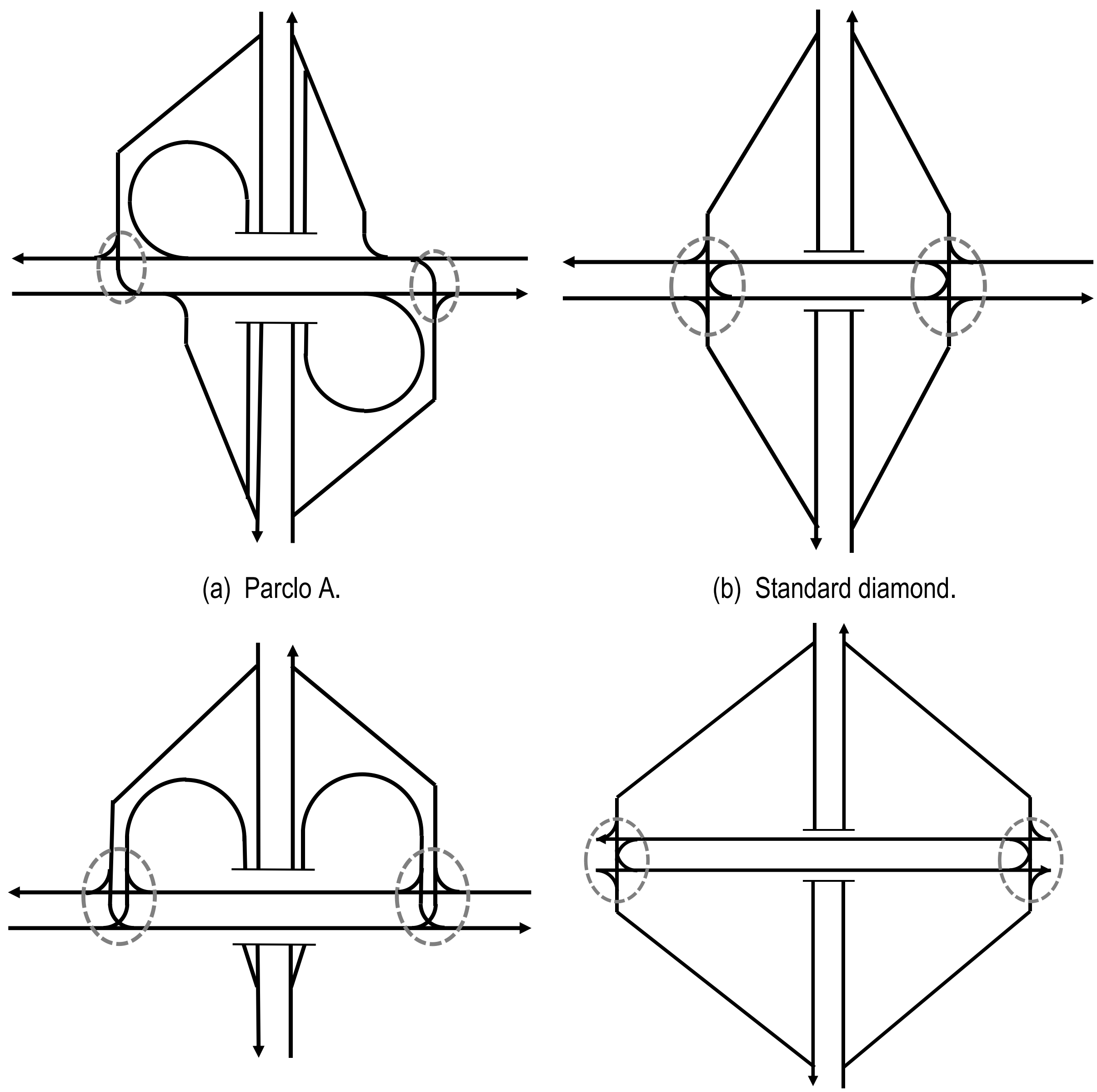


Figure 7. Echelon grade-separated intersection.

INTERCHANGES

Service interchanges, the subject of this section, are junctions between a freeway and a non-freeway that require at least one bridge. Progression is therefore of interest only on the non-freeway, which is usually an arterial.

There are at least nine fairly common service interchange designs in use across the US. Figure 8 shows four of those common designs that offer poor two-way progression potential. Unfortunately in this category are some of the most common designs in use, including the standard diamond which is the most common. Standard diamonds have two full signals with three basic phases each, spaced at 600 to 800 feet, which is usually a spacing on the outer edge of the range in which simultaneous progression will work. A parclo A has two loops, which serve the left turns from the arterial to the freeway. A parclo A has two full signals with two basic phases each, usually spaced around 1200 feet apart which is in the middle of the progression dead zone. The parclo AB, with two loops on the same side of the arterial, and a spread diamond both have two full three-phase signals spaced at around 1200 feet and can be regarded as the common service interchange designs that provide the worst two-way progression potential.



(a) Parclo A. (b) Standard diamond.

(c) Parclo AB. (d) Spread diamond.

Figure 8. Common service interchange designs with poor two-way progression potential.

Figure 9 shows the four common service interchange designs that have moderate progression potential. Three of the designs in Figure 9 have one full signal, and the fourth design in Figure 9 has a unique arrangement of its two full signals that make two-way progression more feasible than the designs in Figure 8. Part a of Figure 9 shows a median u-turn interchange which is common in Michigan (10). A median u-turn interchange reroutes the left turns from the arterial to the freeway to u-turn crossovers over the freeway. At the main junction of a median u-turn interchange is a large full two-phase signal. Part b of Figure 9 shows a single-point interchange where all four left turns are made in the middle of the large bridge. A single-point interchange has one large full three-phase signal. Part c of Figure 9 shows a tight diamond interchange where the ramp terminals are typically 200 to 300 feet apart. A tight diamond has one large full four-phase signal; it has relatively poor capacity but typically low impacts and costs. Finally, part d of Figure 9 shows a diverging diamond interchange (DDI) which is a relatively new design in the US (11). A DDI has two two-phase full signals spaced usually at 500 to 900 feet where the through movements cross and then re-cross each other. A DDI produces an unusual progression pattern downstream and the spacing guidelines in Table 1 do not apply to it. A recent NCHRP project described how to time the signals at a DDI to produce the best progression possible (12).

Figure 10 shows four interchange designs that use only half-signals on the arterial are thereby provide outstanding two-way progression potential. Part a of Figure 10 shows a parclo B interchange, which uses loops to serve the left turns from the freeway to the arterial. Parclo B interchanges are relatively rare in the US but they are a generally superior design. Parclo B interchanges take the same space as a parclo A, but due to their signals provide much better service than parclo A's. Parclo B's are also better than parclo A's in terms of pedestrian service, lane balance, and unusual maneuvers required of drivers. Part b of Figure 10 shows a FRE interchange (13). All four left turns use downstream u-turn crossovers so a FRE interchange does not have a high capacity. The author does not know of a FRE that has been built in the US or elsewhere yet. Part c of Figure 10 shows a synchronized interchange, which is like the FRE but also includes contraflow lanes for the left turns from the arterial to the freeway. The author created the synchronized design a few years ago and does not know of a previous publication or that it has been built anywhere. The FRE and synchronized interchanges would provide excellent pedestrian service and have small footprints, with the main drawbacks being the impacts of the u-turn crossovers on the arterial 600- to 800-feet from the interchange. Finally, part d of Figure 10 shows a Milwaukee B interchange which was published by Eyler (8). The Milwaukee B operates like a parclo B but uses bridge crossovers for the left turns from the freeway instead of loop ramps. Thus, the Milwaukee B can be thought of as a substitute for the parclo B where there is no room for the loops. The Wisconsin DOT built a similar interchange a few years ago on I-894 near Milwaukee which had crossovers for the left turns from the arterial to the freeway—a Milwaukee A—but no one has built a Milwaukee B to the author's knowledge.

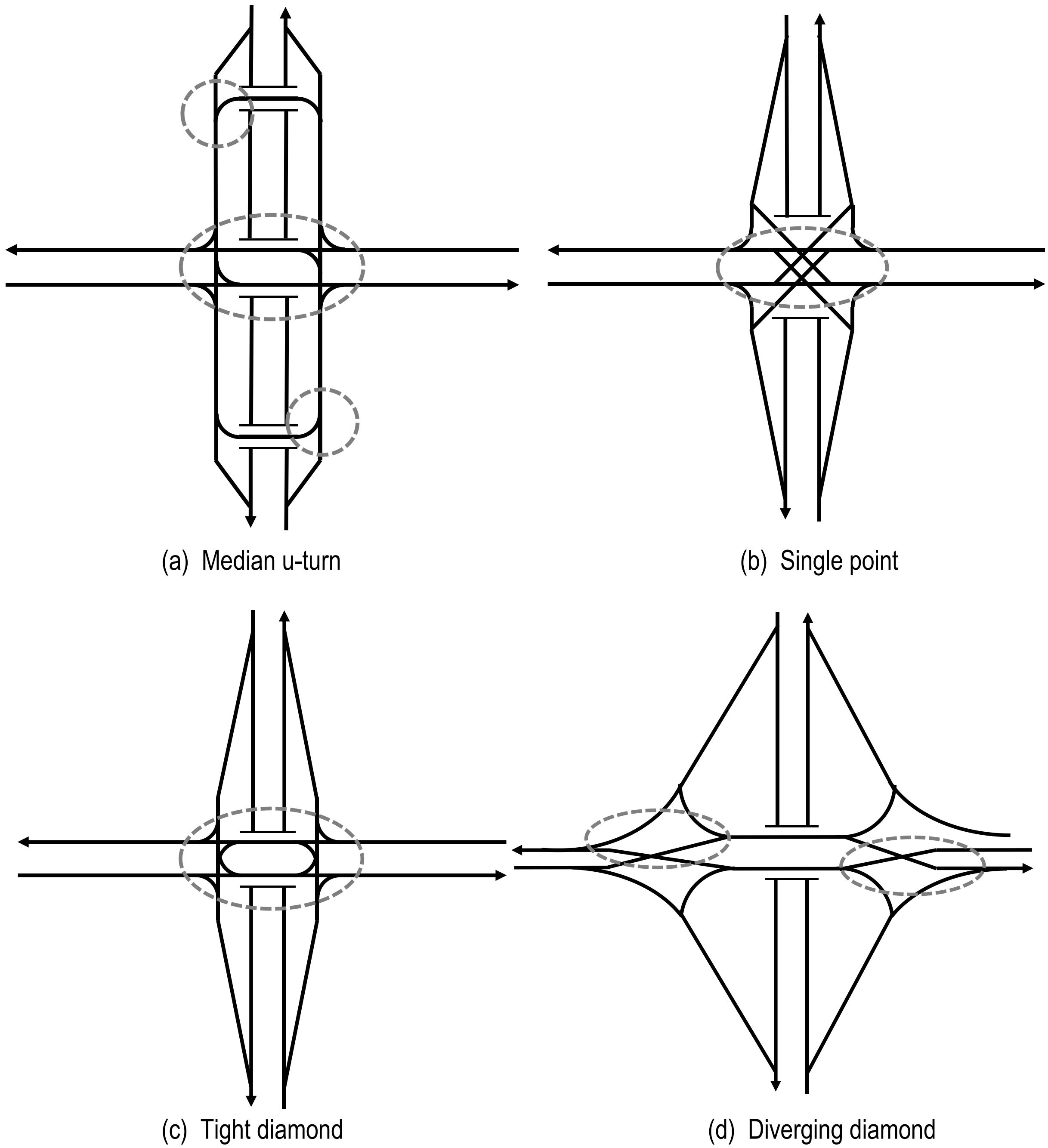


Figure 9. Common service interchange designs with moderate two-way progression potential.

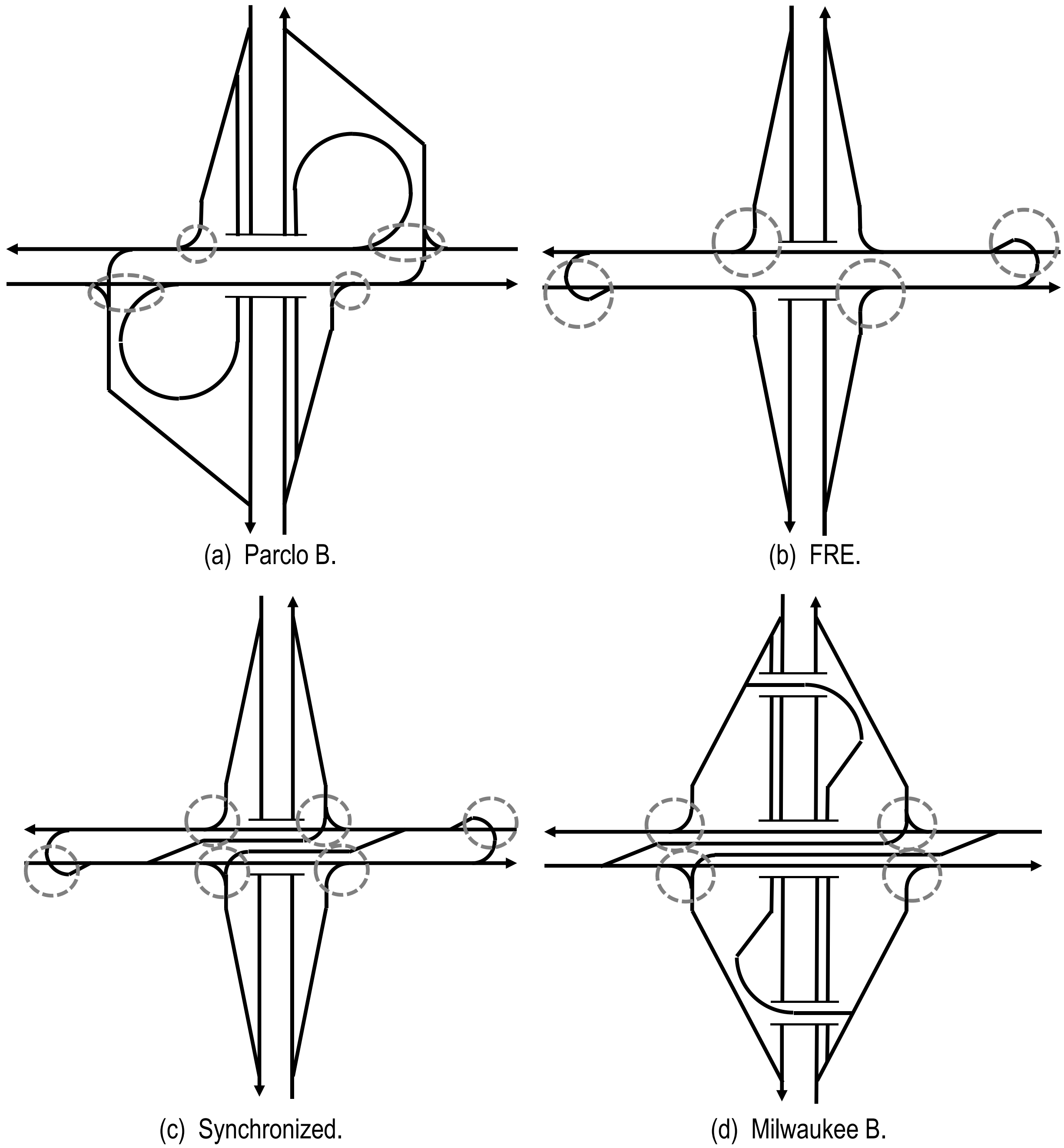


Figure 10. Service interchange designs with great two-way progression potential.

Many of the interchange projects agencies will undertake in the next few years will involve trying to improve a failing design of the types shown in Figure 8 that provide poor progression potential. Fortunately, there are good retrofit ideas for the poor designs in Figure 8. The best retrofit of a poor design in Figure 8 is to use its space to create a design with excellent potential. If there is room for loops on the far right sides, a standard diamond, parclo A, or spread diamond can be made into a parclo B. If there is room for u-turn crossovers downstream, a diamond, parclo A, or spread diamond can be converted into a synchronized interchange. If there is no room for far side loops or u-turn crossovers, there may still be room for Milwaukee B bridges. Failing all of that, it would still be an improvement in progression potential and perhaps other ways to convert half of the interchange to a form that only needs half signals. For example, an interchange that has a parclo A loop on one side of the freeway and a parclo B loop on the other side would only have one two-phase full signal and much better progression potential than a complete parclo A. For a parclo AB, agencies could consider installing superstreet junctions at one or both of the ramp terminals, or at least CFI elements at one or both ramp terminals to reduce the number of basic phases.

CONCLUSION

Progression is one of the best things traffic engineers do for travelers, but good progression in urban and suburban America is rare. More often, arterial corridors force too many drivers to stop for too long at too many signals. In most of those places, good progression is not possible because there are too many of the wrong kinds of signals spaced in a sub-optimal way. No amount of smart people, software, and hardware can rescue an arterial design with poor progression baked in due to too many signals of the wrong kinds at the wrong spacing.

Progression on an arterial does not usually happen by accident. When we get the chance to build or rebuild an arterial, we must design for progression. This paper provided intersection, grade-separated intersection, and interchange designs that allow for good progression, by using signals that only affect one direction of the arterial (half-signals) or by reducing the number of phases. Progression capability is not affected by the spacing of half-signals. There is no need for half-signal when the spacing between full signals is good. However, when full signals are employed and not spaced well to promote two-way progression, this paper showed that there are feasible designs available that provide the capability for excellent two-way or four-way progression. Planners and designers tasked with building or rebuilding an arterial should not engage in scope creep, but should look upstream and downstream from their project limits to see where signals or future signals are located and should choose a design for their project that would fit with those other signals. Lots of factors go into choosing an intersection, grade-separated intersection, or interchange design, but on most corridors the progression capability should be a big factor.

There are several avenues for promising future research on designing for progression. The NCDOT has commissioned a research project to begin in the summer 2017 to study promising new grade-separated intersection designs like the ones shown above. That project will include the development of typical designs, cost estimates, traffic simulations for vehicles and pedestrians, and patent investigations. The results should be available in 2019. Meanwhile, a student at Wayne State University is completing a dissertation on the synchronized and Milwaukee B interchange designs, including many of the same elements as the NCDOT study of grade-separated intersections. Preliminary simulation results are very promising for the Milwaukee B design. The student should finish in late-2017.

Ultimately, FHWA and the state DOTs need to make sure the new and rare designs outlined above are implemented so that researchers can study them in the field. There is still not a good method for predicting the safety of a new design, for example, so implementations will be necessary to start to develop crash modification factors. Traffic operations and cost estimates will need to be validated as well. Once some field implementation is done and documented, agencies can begin adding the new designs to manuals, policies, and specifications so that they have a chance to be part of the routine toolbox available to designers.

One other future project is worth mentioning: agencies need to find a way to better incorporate progression into traffic impact analyses for new development. Too many signals are placed at the ends of new driveways and side streets that work well in isolation but not as part of a signal system in a road corridor. A poorly spaced full signal can disrupt progression even if it provides green to the arterial through movement for a majority of the cycle.

REFERENCES

1. Roess, R.P., et al., *Traffic Engineering*, Prentice Hall, 2011.
2. Kramer, R.P., “New Combinations of Old Techniques to Rejuvenate Jammed Suburban Arterials,” *Proceedings, Strategies to Alleviate Traffic Congestion*, ITE, 1987.
3. Hummer, J.E., et al., "Restricted Crossing U-turn Informational Guide", Federal Highway Administration, Washington, DC, August 2014.
4. FHWA, “Continuous Green T-Intersections,” FHWA-SA-09-016, 2009.
5. Steyn, H., et al., "Displaced Left Turn Informational Guide", Federal Highway Administration, Washington, DC, August 2014.
6. Reid, J., et al., "Median U-turn Informational Guide", Federal Highway Administration, Washington, DC, August 2014.
7. Shin, E.K., et al., “Two-Level Signalized Intersection,” *Transportation Research Record 2060*, 2008.
8. Eyler, D.R., “Arterial Interchange,” *Transportation Research Record 1912*, 2005.
9. Miller, N.C. and J.E. Vargas, “The Echelon Interchange,” *ITE Journal on the Web*, November 1999.
10. Dorothy, P., et al., "Operational Aspects of the Michigan Urban Diamond Interchange," *Transportation Research Record 1612*, 1998.
11. Schroeder, B.J., et al., "Diverging Diamond Interchange Informational Guide," FHWA-SA-14-067, Federal Highway Administration, Washington, DC, August 2014.
12. Cunningham, C.M., et al., “Traffic Signals at Diverging Diamond Interchanges and Adjacent Intersections, Interim Report, NCHRP 3-113, February 2015.
13. Click, S.M., et al., "Evaluation of Traditional and Nontraditional Interchange Treatments to Preserve Service Life of Narrow Over- and Underpass Roadways," *Transportation Research Record 2171*, 2010.