Selecting Optimum Intersection or Interchange Alternatives

Guidance for the staff and consultants of the

Congestion Management Section
Mobility and Safety Division
North Carolina Department of Transportation

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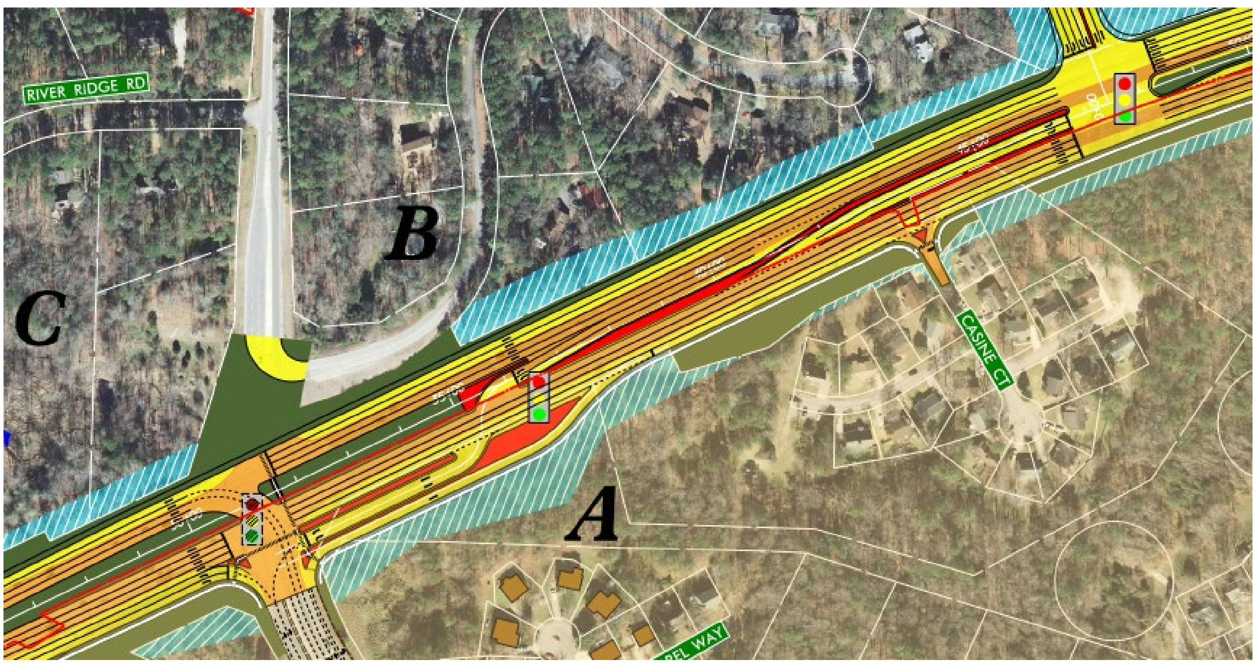

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NEED FOR ALTERNATIVES

A basic configuration serves well at most intersections and interchanges. However, many intersections and interchanges with a basic configuration will not be able to serve high future traffic demand levels very well from a capacity or a safety point of view without expansive widening. In turn, widening often means acquiring right of way, moving utilities, forcing pedestrians and bicyclists to cross longer distances, and other negative impacts. Thus, there is a great need for analysts and designers to consider alternative intersection and interchange configurations as a practical way to improve safety and efficiency. The next few sections discuss the methods analysts and designers should use to decide on an intersection or interchange alternative early in the project development process.

BASIC PRINCIPLES

The design of safe and efficient intersections and interchanges relies on five core principles. Analysts and designers able to adhere to these principles will usually produce quality products that will serve well for decades, while violating these principles will usually mean compromised products that fail well before the design year. These principles have guided good junction design for decades and should serve well into the automated vehicle era to come.

The first principle of good junction design is to minimize the number of conflict points. A conflict point is a spot in a junction where two traffic streams cross, merge with, or divert from each other. A conflict point means crash potential, because one vehicle has to take action to avoid colliding with another vehicle or a pedestrian, and means delay potential since the action taken is often to decelerate or stop. Figure 1 shows that a conventional four-approach intersection has 32 vehicle-vehicle conflict points, 16 of which are the more dangerous crossing conflicts, and also shows that a roundabout has only 8 vehicle-vehicle conflict points, none of which are crossing conflicts. It is no surprise that research shows, on average, fewer crashes and less delay at junctions with fewer conflict points, all else equal.

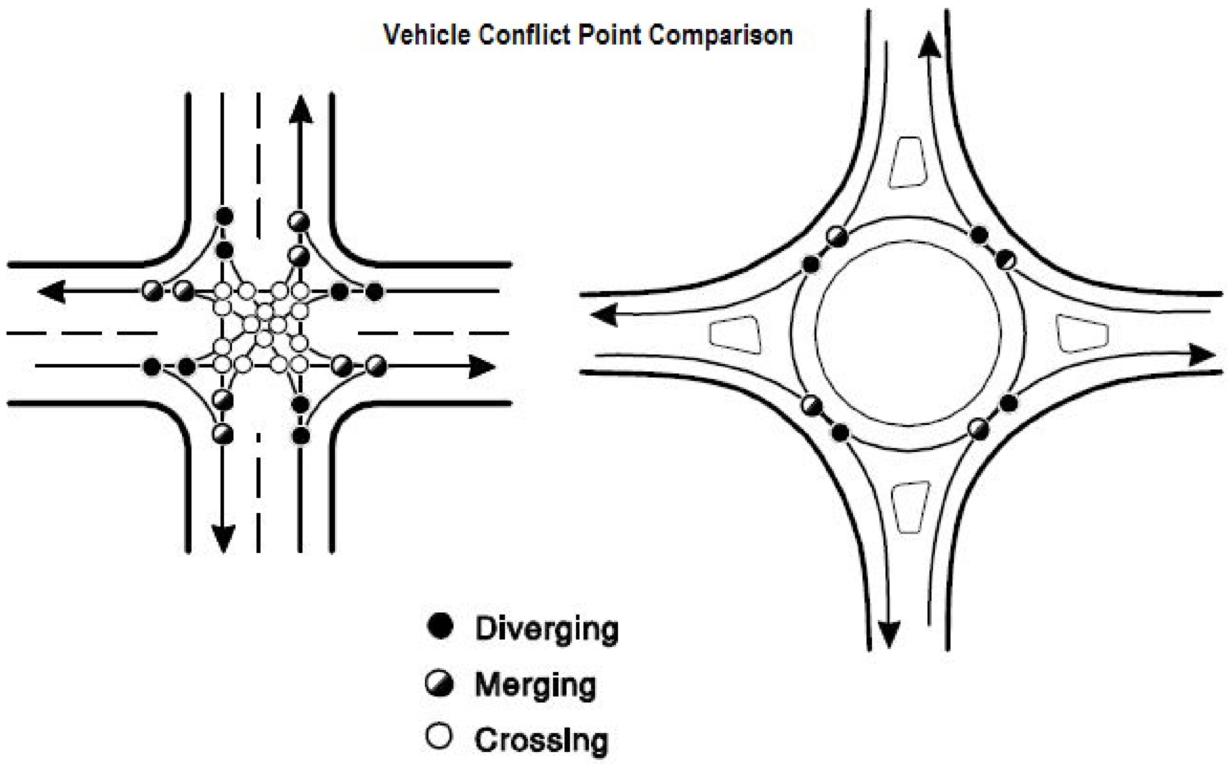


Figure 1. Vehicle-vehicle conflict points at a conventional four-approach intersection and at a roundabout (1).

The second principle of good junction design is to separate the conflict points. Separation gives drivers a chance to concentrate on fewer things at a time, gives drivers a chance to absorb messages from traffic control devices (TCDs) more easily, gives analysts and designers a chance to make messages on TCDs simpler, provides room for queuing, and provides room for lane changing. Typical practice at many alternative intersections and interchanges is to provide 400 to 800 feet between conflict points.

The third principle of good junction design is to favor the major street through movement, particularly is the major street is classified as an arterial. Arterials are planned to provide higher-speed mobility to large volumes of travelers making longer trips, and arterials also serve higher volumes of trucks and buses. Application of this principle often results in minimizing conflict points involving the major street through movement, minimizing the number of signal phases that that movement has to endure, and providing that through movement with longer green times at signals. Applying this principle might mean weighing measures of effectiveness differently for different movements at an intersection. Using traditional level of service measures at an intersection means all intersection users are considered equally important, but this third principle says that sometimes one second of delay experienced by a major street through vehicle is more important that one second of delay experienced by a minor street vehicle.

The fourth principle of good junction design is to increase the chances of signal progression by using half-signals instead of full signals. Signal progression is the ability to drive along a street at a steady speed and arrive at each signal during a green phase. A half-signal is one that only stops one direction of the major street. A full signal is one that stops both directions of the main street. Most signals are full signals, but signals on one-way streets are half-signals and usually good examples of the progression benefits that half-signals can provide. The reason that half-signals provide much better progression is that the spacing of half-signals does not matter to progression: they can be progressed well at any spacing. Full signals, on the other hand, must be spaced in a narrow range to be able to provide quality two-way progression. Table 1 shows full signal spacing ranges that provide decent two-way signal progression (defined as having the progression band be at least 40 percent of the cycle length) for some common cycle lengths. A spacing outside the limits shown in Table 1 would provide inefficient two-way progression. Half-signals remove the tyranny of signal spacing, and junction designs that use half-signals add great efficiency value.

The fifth and final principle of good junction design is to minimize the number of critical signal phases. Signals at four-approach intersections have either two, three, or four critical phases. A signal with no left turn phases has two critical phases, a signal with a protected left turn phase on one street has three critical phases, and a signal with a protected left turn phase on both streets has four critical phases. Each critical phase adds five or so seconds of lost time—time during which no one is using the intersection--to the cycle, so minimizing critical phases helps capacity and delay and the number of stops in that way. Plus, fewer critical phases means devoting more green time to the main street through movement, noted above as a worthy principle. Typically, a signal with two critical phases can devote 2/3 of the cycle to the main street through movement, a signal with three critical phases can devote 1/2 of the cycle to the main street through movement, and a signal with four critical phases can only devote 1/3 of the cycle to the main street through movement. Alternatives that use signals with two critical phases are most desirable.

Finally, analysts and designers should note that “safe systems” principles have developed in Australia and New Zealand in the past few years, and are in research stages in the US, that could add a couple new principles to the list above in the next few years. The core of a safe systems approach is to reverse engineer starting from how crashes cause injuries to people into how intersections can be designed to avoid those harmful actions. In practical design, a safe systems approach means reducing conflict points (principle one above), separating conflict points (principle two above), adjusting the angles of conflicts away from 90 degrees, and reducing the vehicle speeds at conflict points. A safe systems approach has a chance to change the intersection and interchange design process in the next few years.

Table 1. Full signal spacing that provides decent two-way progression.

		Simultaneous progression		Alternate progression	
Speed, mph	Cycle, sec	Low limit, ft	High limit, ft	Low limit, ft	High limit, ft
25	60	0	220	880	1320
30	60	0	260	1060	1580
35	60	0	310	1230	1850
40	60	0	350	1410	2110
45	60	0	400	1580	2380
50	60	0	440	1760	2640
55	60	0	480	1940	2900
25	80	0	290	1170	1760
30	80	0	350	1410	2110
35	80	0	410	1640	2460
40	80	0	470	1880	2820
45	80	0	530	2110	3170
50	80	0	590	2350	3520
55	80	0	640	2580	3870
25	100	0	370	1470	2200
30	100	0	440	1760	2640
35	100	0	510	2050	3080
40	100	0	590	2350	3520
45	100	0	660	2640	3960
50	100	0	730	2930	4400
55	100	0	810	3230	4840
25	120	0	440	1760	2640
30	120	0	530	2110	2640
35	120	0	620	2460	3700
40	120	0	700	2820	3960
45	120	0	790	3170	4750
50	120	0	880	3520	5280
55	120	0	970	3870	5280
25	150	0	550	2200	2640
30	150	0	660	2640	2640
35	150	0	770	3080	3960
40	150	0	880	3520	3960
45	150	0	990	3960	5280
50	150	0	1100	4400	5280
55	150	0	1210	4840	5280
25	200	0	730	No progression possible	
30	200	0	880	No progression possible	
35	200	0	1030	No progression possible	
40	200	0	1170	No progression possible	
45	200	0	1320	5280	5280
50	200	0	1470	No progression possible	
55	200	0	1610	No progression possible	

TOOLS TO AID THE SELECTION OF AN ALTERNATIVE

These days there are many intersection and interchange alternatives from which to choose, so at first making the optimum choice for a particular site appears to be daunting. Luckily, there are good tools available to help a designer make a good choice.

The main thing a designer should remember when considering intersection or interchange choices is to seek expert help. The professionals in the Congestion Management Section of the Mobility and Safety Division have decades of experience advising analysts and designers on intersection and interchange alternatives. At any stage of a selection or analysis, Congestion Management engineers can help in a timely way. Analysts and designers should not choose an alternative in ignorance of the choices or in haste.

Capacity

At an early stage of project development, the main tool that analysts and designers have to examine the capacity of alternative intersections or interchanges is the critical lane volume method. The method has been in use for decades. It provides a quick, easy, software-independent way to calculate a demand to capacity (often referred to as volume to capacity or v/c) ratio for the whole intersection. The method makes a host of assumptions (like fair signal timing and even lane distributions) that are OK for early in project development but not for later design refinement when better traffic analysis methods should be used. The method starts with a turning movement forecast. The 11 steps of the method for a particular junction are:

1. Sketch geometry, including numbers of lanes.
2. Assign hourly volumes to appropriate approaches and lanes.
   - Account for all flows.
   - Assume a distribution of volume across multiple lanes.
   - Adjust for left turns by dividing by 0.95, for right turns by dividing by 0.85, and for u-turns by dividing by 0.85.
3. Add highest EB left turn lane volume to highest WB through or right turn (if conflicting with left turn) lane volume.
4. Add highest WB left turn lane volume to highest EB through or right turn (if conflicting with left turn) lane volume.
5. Keep higher of result from step 3 or result from step 4.
6. Add highest NB left turn lane volume to highest SB through or right turn (if conflicting with left turn) lane volume.
7. Add highest SB left turn lane volume to highest NB through or right turn (if conflicting with left turn) lane volume.
8. Keep higher of result from step 6 or result from step 7.
9. Add the results from steps 5 and 8.
10. The number of non-zero numbers added to get step 9 is the number of critical phases at the signal.
11. Compute the v/c ratio by taking the result from step 9 and dividing by the estimated capacity. Estimated capacity is usually 1420 vphpl for four critical phases, 1490 for three critical phases, or 1560 for two critical phases.

If an intersection or interchange has more than one signal (like almost all alternative intersections and most interchanges) repeat steps 1-11 for each signal, then identify the governing (highest) v/c for the entire complex.

The critical lane volume method is implemented in software packages like CAP-X distributed by FHWA (2) and VJUST distributed by the Virginia DOT (3), and those packages are fine options for analysts and designers. However, CAP-X and VJUST have limitations and assumptions that might not be good for particular projects, so when CAP-X and VJUST fall short analysts and designers should know how to apply the method in their own spreadsheets or seek help from the Congestion Management Section. Of course later in the project development process traffic engineers could use a detailed traffic analysis software package to model the performance of alternatives in terms of level of service, delay, travel time, queue lengths, speeds, or other desired measures.

Safety

In the traditional highway design process, analysts and designers did not use models to estimate the numbers of crashes that different alternatives would produce. In large part this was because good models to estimate numbers of crashes were not available. However, in recent years quite a library of intersection and arterial safety studies has been assembled. The FHWA and their state DOT partners have invested hundreds of millions of dollars in research on the safety performance of different measures and designs at intersections. Most of this research has been cataloged in an easy-to-use website called the "Crash Modification Factors Clearinghouse" (4) maintained for the FHWA by the University of North Carolina Highway Safety Research Center (HSRC). Even better, safety researchers at the HSRC have rated the quality of each of the studies in the Clearinghouse, on a scale of zero stars (poor or unknown quality, result should not be trusted) to five stars (excellent quality, trustworthy result) so that consumers of the safety information do not have to make that judgment themselves. The Clearinghouse contains thousands of crash modification factors (CMFs), which are defined as the ratio of the estimated crash frequency after an intervention to the crash frequency before the intervention. A CMF below one thus means the intervention helped, while a CMF above one means the intervention did not help. The library full of CMFs for hundreds of interventions, each with a quality rating, is a tremendous resource that should be used during project development.

To help intersection project teams use the available CMFs more often and effectively, the author assembled charts showing the safest feasible intersection design (SaFID) for four-legged intersections for each combination of size and demand on the major and minor streets. The charts should prove to be a tool that is quick and easy to use. Project teams should start their investigations of alternatives with the design that the research shows to be the safest, and then examine other factors that are meaningful in a design decision. If project teams end up choosing an alternative that is not the safest according to the research, they should document why they did that. Starting with consideration of the safest feasible design may mean that project teams end up building safer intersections.

Sources

Most of the CMFs used to create the SaFID charts are from the CMF Clearinghouse (4). The author used only CMFs rated at three stars or better. The available documentation on the Clearinghouse website had to be clear on the before condition, the after condition, and the context in which the crash data were collected. This effort used CMFs for a generic four-legged intersection. In some cases, the author averaged CMFs from more specific studies to create an overall CMF; for example, if the Clearinghouse contained CMFs from one study for volume ranges of 10,000 vehicles per day or below, 10,000 to 20,000, 20,000 to 30,000, and 30,000 and above, the author averaged those four CMFs together to get an overall CMF for that study.

Table 2 shows the references used to assemble the SaFID charts from the Clearinghouse and elsewhere and the corresponding average CMF values. Note that a reduced conflict intersection (RCI) is also known as a restricted crossing u-turn (RCUT) intersection, superstreet, or j-turn and a continuous flow intersection (CFI) is also known as a displaced left turn intersection. An indirect left and cross (ILAC) intersection is a form of RCI that does not have left turn crossovers.

Table 2. CMF values and references.

Changing from…	Changing to…	All crashes		Injury crashes	
		Average CMF	References	Average CMF	References
Two-way stop control	All-way stop control	0.32	5	0.28	5 and 6
	Conventional signal	0.81	7-11	0.74	9-12
	One-lane roundabout	0.51	13-16	0.16	13
	Mini-roundabout	0.83	17	0.41	17
	Unsignalized RCI	0.60	18 and 19	0.42	18 and 19
	Right-in-right-out (RIRO)	0.55	20	0.20	20
	Unsignalized indirect left and cross (ILAC)	None		0.69	21
Conventional signal	One-lane roundabout	0.74	22	0.45	22
	Two-lane roundabout	0.89	15 and 22	0.54	22 and 23
	Signalized RCI	0.85	24	0.78	24
	Median u-turn (MUT)	0.63	25	0.77	25
	Partial CFI	0.88	26 and 27	0.86	27

Note that the CMFs for a RIRO intersection shown in Table 2 do not include increased crashes at u-turn locations, so the full magnitudes of the CMFs are likely quite a bit higher than the values shown.

The available set of CMFs described above captures most four-legged intersection designs used in the US as of 2023. In the CAP-X tool (2), published by FHWA, the only other four-legged intersection designs listed are full CFI (with four left turn crossovers as opposed to the partial CFI which has two left turn crossovers), quadrant, bowtie, and split. None of these is common in the US as of 2023. The only other at-grade intersection types common in the US that the author could think of are jughandle and offset intersections. On jughandles, while they are common in a few states, in North Carolina (with no existing jughandles) they are not considered to be a competitive design as they require more right-of-way than a partial CFI while delivering only a fraction of the delay-saving benefits. Meanwhile, on offset intersections a recent literature review conducted by the NCDOT did not provide any studies with trustworthy (likely to be three-star or better) CMF values, and the Clearinghouse does not mention offset intersections. As mentioned below (in the "Three-Legged Intersection" section) there is a published NCDOT crash reduction factor available for the creation of an offset intersection, but it is not in the Clearinghouse and therefore is of unknown quality. Overall, with the possible exception of offset intersections, the assertion is that in the list above we have a pretty full set of high-quality CMFs for common and feasible at-grade intersection designs.

Feasibility Rules

To construct the SaFID charts, the author also considered the feasibility of the various designs. The rules the author used included:

- Two-way stop control (TWSC) is feasible based on capacity calculations up to about 14,000 vehicles per day (vpd) on major streets with one through lane in each direction.
- All-way stop control (AWSC) is viable on two-lane roads with total entering demands less than 15,000 vehicles per day (vpd), based on capacity calculations and extensive North Carolina experience.
- AWSC is viable based on benefit-cost estimates when the minor street demand is greater than about 500 vpd.
- Right-in-right-out (RIRO) control is feasible based on capacity calculations when the minor street demand is less than between 1,000 and 5,000 vpd depending on the major street demand.
- Based on the latest national roundabout guide (1) a full-size single-lane circle can handle up to 25,000 vpd total entering demand.
- A single-lane full-size roundabout is viable based on benefit-cost estimates when the minor street demand is greater than about 1,500 vpd.
- Based on capacity calculations a signalized intersection with one through lane and one left turn lane on each approach can handle up to 30,000 vpd total entering demand.
- Based on capacity calculations a signalized intersection with one through lane, one left turn lane, and one right turn lane on each approach can handle up to 40,000 vpd total entering demand.
- Based on the latest national roundabout guide (1) a two-lane circle can handle up to 45,000 vpd total entering demand.
- Based on the FHWA guidebook (28) a signalized RCI can handle up to 25,000 vpd on the minor street.
- Making the same assumptions as for a signalized RCI, a signalized ILAC can handle up to 19,000 vpd on the minor street.
- Four-lane minor streets should always be signalized in RCIs, while two-lane minor streets should be signalized at RCIs with four-lane major streets at demands ranging from 2,000 to 15,000 vpd based on research conducted for the NCDOT (29).
- Median u-turn intersections only become feasible above minor street demand levels that support an unsignalized RCI.

Of course there are important exceptions to these rules that agencies make all of the time, but these should serve well to start.

One other technique needed to construct the SaFID charts was the ability to chain CMFs. If we have a CMF for the conversion of condition a to condition b, and a CMF for the conversion of b to c, and we can assume that individual CMFs are independent of each other, multiplying the CMF for a to b by the CMF for b to c should get us the CMF for a to c without losing much accuracy. For example, we do not have a qualifying CMF for all crashes for the conversion of a signalized intersection to AWSC. Fortunately, we have a good average CMF for the conversion of a two-way stop control (TWSC) intersection to a signal (0.81), so its inverse can be used to estimate the conversion of a signal to a TWSC intersection (1/0.81 = 1.23). This value multiplied by the CMF for the conversion of a TWSC intersection to AWSC (0.32) will provide the estimate we seek: 1.23 * 0.32 = 0.40.

SaFID Charts

Table 3 shows the overall four-legged SaFID chart, organized by the number of through lanes on the major and minor streets. The overall chart is dominated by four designs, including AWSC, a full-size one-lane roundabout, an unsignalized RCI, and a MUT. The only difference in outcome when using injury crashes instead of total crashes is when a four-lane major street meets a four-lane minor street; in this space a MUT is the safest feasible design for total crashes but a two-lane roundabout is the safest feasible design for a portion of the space based on injury crashes. The overall chart in Table 3 in turn refers to Figures 2-6 that show the safest feasible design for particular combinations of major and minor street numbers of through lanes. Note that some cells in Table 3 do not refer to accompanying figures as one design (the MUT) is the safest feasible for all of that cell.

Table 3. The overall safest feasible intersection design (SaFID) chart.

Major street number of through lanes	Minor street number of through lanes		
	Two	Four	Six or eight
Two	Mostly AWSC and one-lane full-size roundabout; see Figure 2	n/a	n/a
Four	Unsignalized RCI and MUT; see Figure 3	MUT for total crashes; two-lane roundabout and MUT for injury crashes, see Figure 4	n/a
Six	Unsignalized RCI and MUT; see Figure 5	MUT	MUT
Eight	Unsignalized RCI and MUT; see Figure 6	MUT	MUT

Figure 2 shows the SaFID details for intersections between two-lane major streets and two-lane minor streets. The demands are in terms of average annual daily traffic, or AADT, in vehicles per day. Figure 2 is dominated by AWSC and full-size one-lane roundabouts. TWSC, RIRO, and signals only appear in Figure 2 at demand levels in which AWSC and roundabouts are not feasible. In Figures 2-6 a point falling outside the boundaries shown is generally infeasible.

Figure 3 shows that an unsignalized RCI and a MUT are the safest feasible choices when a four-lane major street meets a two-lane minor street. Readers should note that a 2-1-2-1 roundabout is feasible in the lower-demand portion of Figure 3 and has virtually the same CMF for injury crashes as an unsignalized

RCI, but the unsignalized RCI received the nod in Figure 3 given other features that it provides such as generally lower installation costs.

Figure 4 shows the SaFID chart for an intersection with a four-lane major street meeting a four-lane minor street. Based on total crashes a MUT is the safest design for this niche, but based on injury crashes a two-lane roundabout is the safest feasible design in the lower-demand portion of the chart.

Figure 5 shows the SaFID chart for an intersection with a six-lane major street meeting a two-lane minor street, while Figure 6 shows the SaFID chart for an intersection with an eight-lane major street meeting a two-lane minor street. The MUT design dominates both charts, with unsignalized RCIs occupying the low demand portions. Figures 5 and 6 show the upper limits of feasibility for the unsignalized RCI based on capacity calculations.

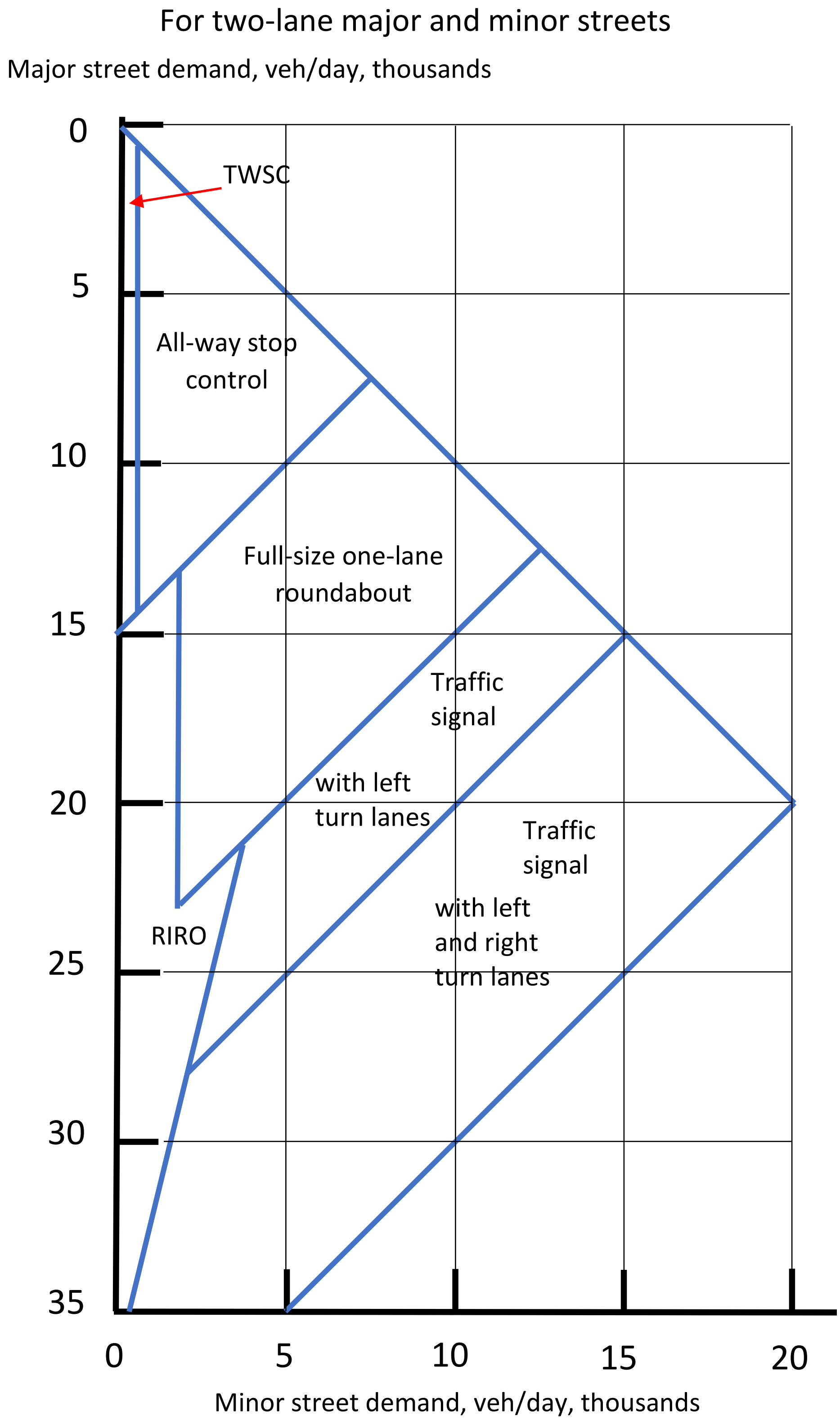


Figure 2. SaFID chart for two-lane major and minor streets.

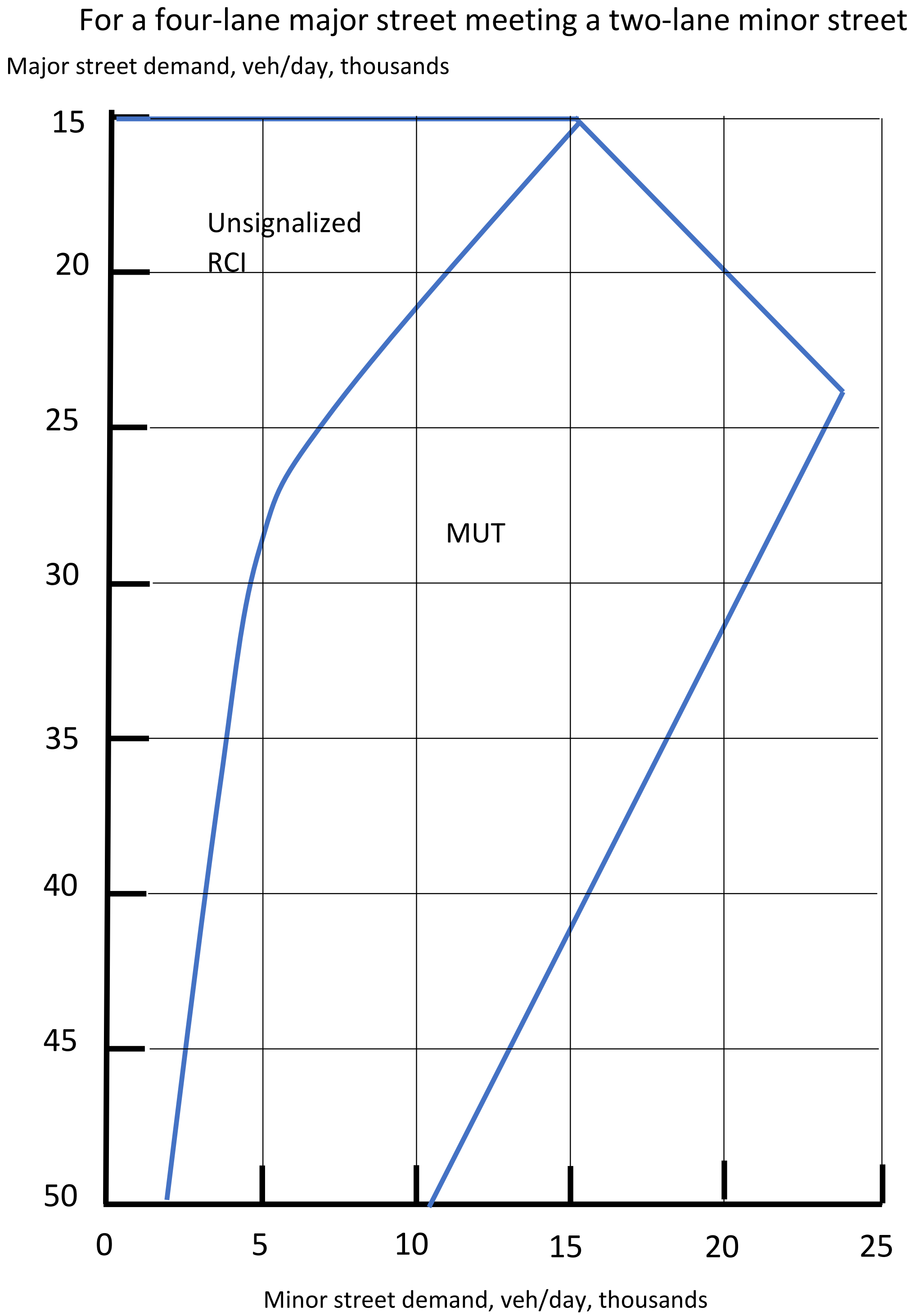


Figure 3. SaFID chart for a four-lane major street meeting a two-lane minor street.

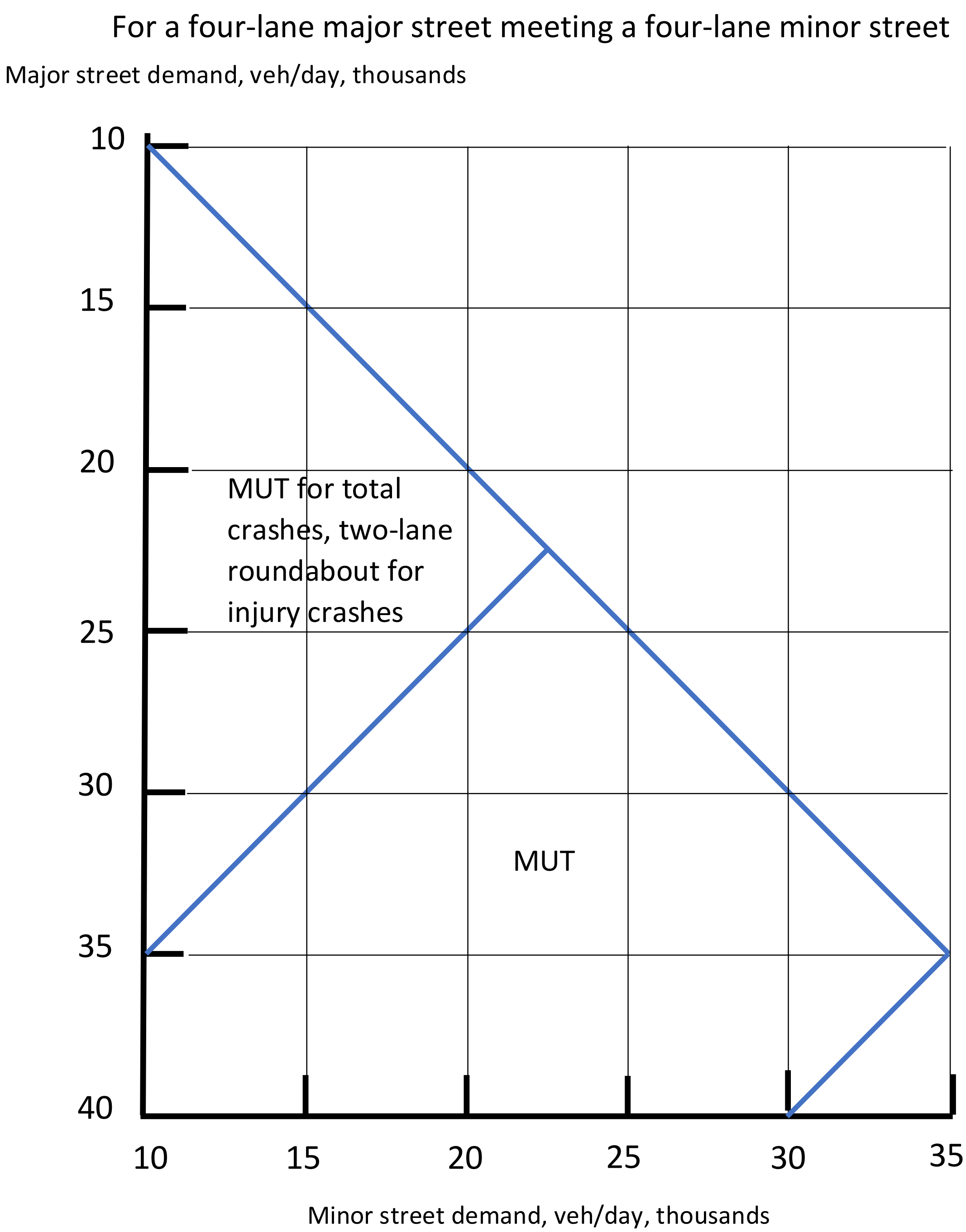


Figure 4. SaFID chart for a four-lane major street meeting a four-lane minor street.

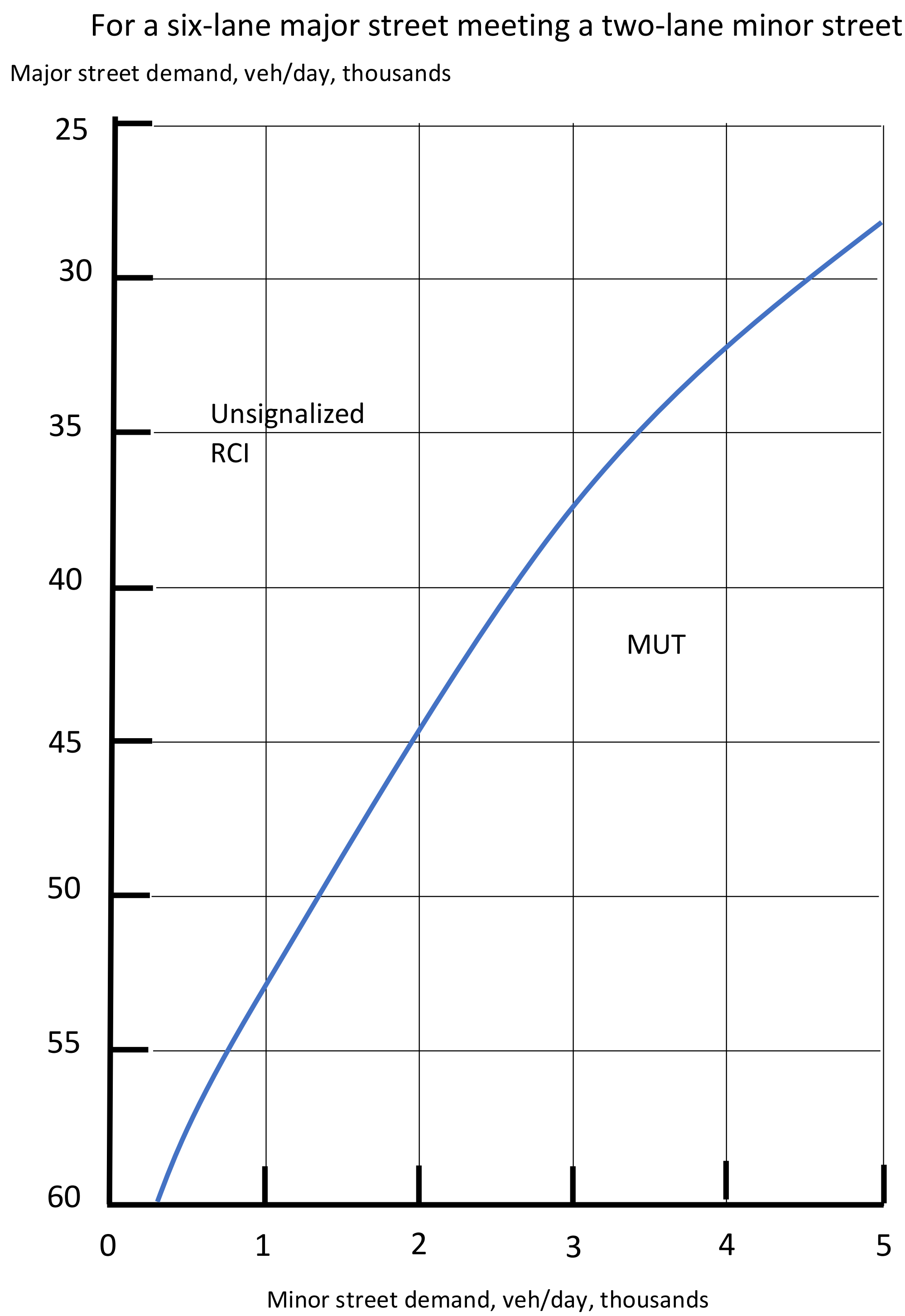


Figure 5. SaFID chart for a six-lane major street meeting a two-lane minor street.

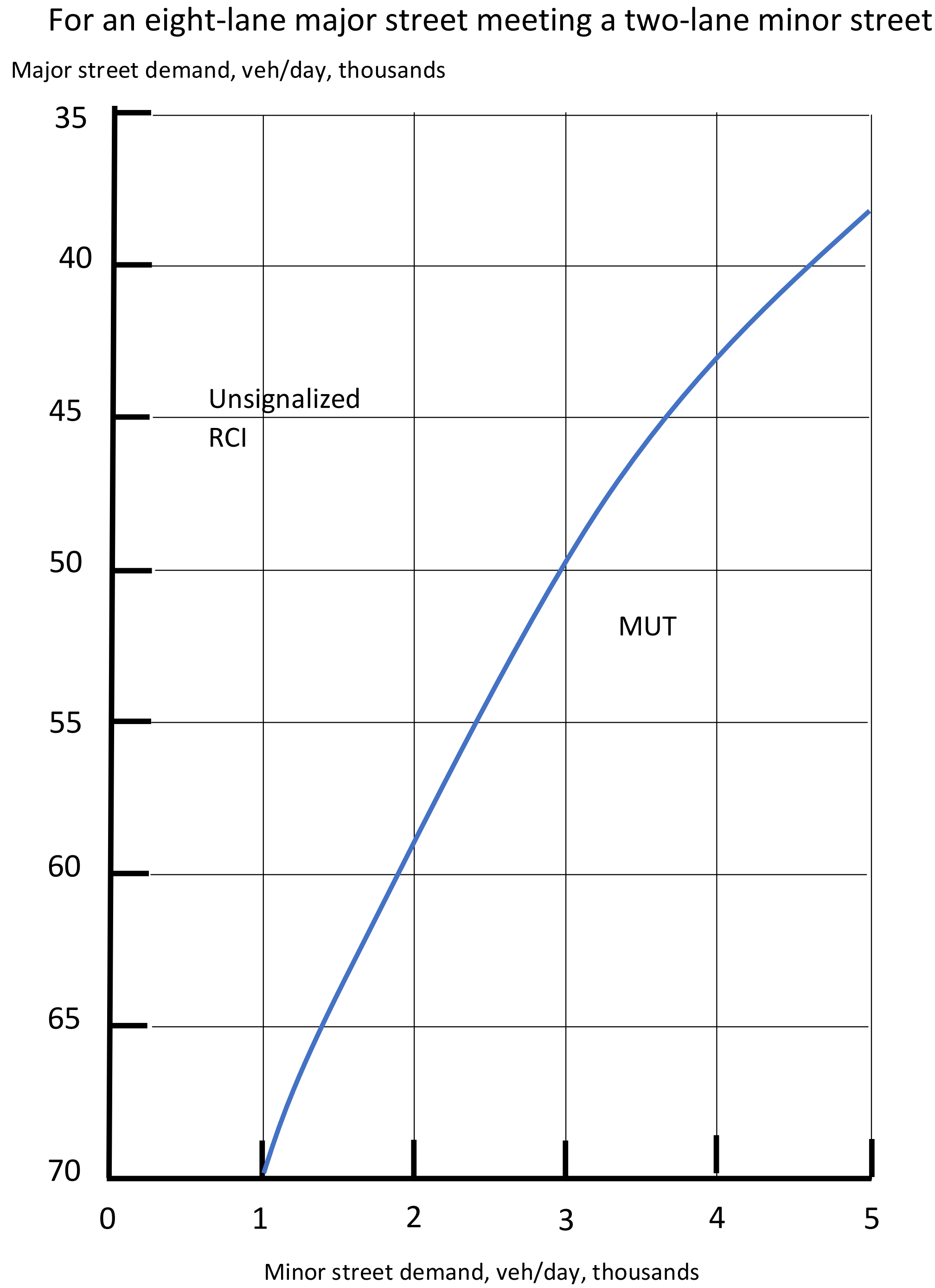


Figure 6. SaFID chart for an eight-lane major street meeting a two-lane minor street.

Table 3 and Figures 2-6 show that TWSC is almost never the safest choice according to the current literature. In other words, there is almost always a feasible design that has a lower CMF than TWSC. In addition, a conventional signal only shows up in the charts in relatively small slices of Figure 2, with two lanes on each street, at the highest demand levels handled with those cross sections where a roundabout is not feasible.

Mini-roundabouts, signalized RCIs, and partial CFIs did not show up in the SaFID charts with their current CMFs as there was always another design in their niches with a lower CMF. Since mini-roundabouts, signalized RCIs, and partial CFIs have CMFs below 1.0 they promise safety benefits over conventional designs and they have many other excellent features, so project teams should not dismiss those designs too readily.

Using the SaFID Charts

In view of the stated importance of safety to NCDOT, project teams should adopt the safest feasible intersection design as the default choice in all intersection improvement projects. Conventional TWSC and signal intersections are not generally the safest feasible options and should therefore generally not be the default designs. There are many reasons why a project team may not be able to build the safest feasible design in any particular project, including excessive cost, impacts, delays, effects on non-motorized travelers, and others. However, in all cases teams ought to be prepared to say why they did not end up building the option listed as the safest in Table 3 and Figures 2-6. Entering the project development process with the safest feasible design as the default should shift the burden of proof to advocates of generally less-safe designs, where the burden should lie.

One of the reasons not to choose the safest feasible design during a project is that the research justifying the design as the safest does not apply to the case in question. Indeed, there are many places where the existing research reflected in the CMFs in Table 2 is out of scope. Table 2 only applies to four-legged intersections, for example, and may not apply to a project improving a three-legged junction. Those claiming that their project site is out of scope of the research underlying Table 2 ought to be careful, though, not to stretch that argument too far. Just because the research has not been done on three-legged RCIs, for example, does not mean that those designs are less safe than conventional designs. Also, in view of some of the research results pointing out large errors in traffic forecasts (30), the safety results in the Clearinghouse might be some of the stronger models used during an intersection design process, not the weakest.

Analysts and designers should check the Clearinghouse periodically to see if good new CMFs have been posted for some the design alternatives they are considering. In future years good new safety performance functions (SPFs), which are detailed models predicting numbers of crashes at a junction based on multiple factors, may also appear in the Highway Safety Manual (31) or other sources to help analysts and designers consider safety more quantitatively.

Pedestrians and Bicyclists

NCHRP Report 948 was published in 2021 (32) and provides a new and improved way for project teams to examine pedestrian and bicyclist quality of experience at any intersection or interchange. Based on focus groups, surveys, and expert opinions, the researchers developed a method that scores each crosswalk and each left, through, and right bicyclist movement at an intersection or interchange on 20 different aspects. Each of the 20 aspects could be scored as “no flag,” meaning no unusual concern about that aspect of the pedestrian or bicyclist movement, a “yellow flag” meaning concern that that aspect of the movement could be inconvenient or uncomfortable, or a “red flag” meaning concern that that aspect of the movement could lead to more crashes. Table 4 shows the 20 aspects judged for flags during an example application comparing three intersection concepts very early in the planning stages. At that early stage the team working on the example project had to assume signal cycle lengths, median widths, bicycle paths through the intersections, and other aspects, but the assumptions were not too difficult. Aspects 1-13 apply to pedestrians and 4-20 apply to bicyclists. In the guidebook the research team provided detailed descriptions of each of the 20 aspects and criteria for what earns a yellow or red flag.

Table 4 shows that for pedestrians, all three intersection concepts had the same numbers of yellow flags, but the new intersection concept was best with four fewer red flags. Compared to the conventional intersection, the new concept added flags for aspect 3, non-intuitive motor vehicle movements, but eliminated flags for aspect 8 on long red times and aspect 10 on motor vehicle left turns. The new concept was better than a full CFI concept because it eliminated flags for aspect 8 on long red times. For bicyclists, Table 4 shows that the new concept was better than the conventional intersection with eight fewer red flags. The new concept added flags for aspect 5 on indirect paths and aspect 8 for long red times, but eliminated flags for aspect 10 on motor vehicle left turns and aspect 20 on off-tracking in multilane curves. However, the new concept had four more total flags than the CFI, adding flags for aspects 5 and 8. The results from Table 4 should help the project team decide whether the CFI or new concept or both remain as viable alternatives to later stages of the project development process.

Table 4. Results of an example 20-flag analysis.

Aspect	Pedestrian flags			Bicyclist flags		
	Conventional	CFI	New	Conventional	CFI	New
1. Motor vehicle right turns	X	X	X			
2. Uncomfortable/tight walking environment						
3. Nonintuitive motor vehicle movements		X	X			
4. Crossing yield or uncontrolled vehicle paths						
5. Indirect paths						X
6. Executing unusual movements					X	X
7. Multilane crossings	X	X	X	X	X	X
8. Long red times	X	X		X		X
9. Undefined crossing at intersections						
10. Motor vehicle left turns	X			X		
11. Intersecting driveways and side streets						
12. Sight distance for gap acceptance movements						
13. Grade change						
14. Riding in mixed traffic				X	X	X
15. Bicycle clearance times				X	X	X
16. Bicyclist crossing motor vehicle travel lane(s)				X	X	X
17. Channelized lanes					X	X
18. Turning motorists crossing bicycle path				X	X	X
19. Riding between travel lanes, lane additions, or lane merges				X	X	X
20. Off-tracking trucks in multi-lane curves				X		
Total number of yellow flags	4	4	4	16	20	16
Total number of red flags	12	12	8	48	32	40

POFID and BOFID Tables

Recently, the author combined the ideas from NCHRP Report 948 and the SaFID charts described above to produce tables that showed the pedestrian optimum feasible intersection design (POFID) and the bicyclist optimum feasible intersection design (BOFID). The aim was to provide, for any combination of major street size and demand and minor street size and demand, the feasible intersection concept that would minimize the number of flags for pedestrians and bicyclists. Like the SaFID charts above, the POFID and BOFID tables could give planners and designers a default concept for a particular spot that could be the starting place for detailed analysis.

The intersection designs considered included all of the four-legged concepts in the FHWA CAP-X tool (2) except the partial MUT and the split intersection, which are rare. The only other common four-legged intersection types that the author could think of are jughandle and offset intersections. While jughandles are common in a few states, in North Carolina they are not considered to be a competitive design as they require more right-of-way than a partial CFI while delivering only a fraction of the delay savings. Meanwhile, it seems that proect teams are much more often considering removing offset intersections than installing them. With the possible exception of offset intersections, the POFID and BOFID tables considered all common and feasible four-legged intersections.

To construct the POFID and BOFID tables, consideration was given to the feasibility of the various designs with the same rules as described above for the creation of the SaFID charts. Other assumptions included typical road geometry, one exclusive lane for each signalized left-turning movement, and one exclusive lane for each right-turning movement on multilane approaches. Typical turning percentages (ten percent lefts and rights from the main street), peak hour percentages (nine percent), and directional splits (60/40) also were assumed to translate daily volumes into hourly movement volumes as needed for NCHRP Report 948.

Each of four pedestrian crossing movements and a left, a through, and a right bicyclist movement from each approach were evaluated. For bicycle facilities, the assumption was a marked bicycle lane next to each curb and that bicyclists used the most convenient way to complete a left turn between using the motor vehicle lanes and using a green box on the far-right corner of the intersection.

Tables 5 and 6 show the POFID and BOFID tables that contain the feasible intersection design in each cell that minimized the weighted total number of flags. The weighting was achieved by multiplying the number of red flags by a factor of two before adding that result to the number of yellow flags. The weight of two acknowledges that safety is more important than comfort, but that comfort still matters. Note that the results do not change much for various other weights. Shaded cells in Tables 5 and 6 represent cases when a particular design minimized the weighted total number of flags for both pedestrians and bicyclists. Red lettering indicates a design that was also the safest feasible intersection design according to Table 3 based on total crashes.

For pedestrians in Table 5, the pattern was that AWSC was best at the smallest intersections; a roundabout was best at larger two-lane meets two-lane intersections; TWSC was best in the lower portion of the left column when a large main street meets a small minor street; a MUT was best at large intersections; and a MUT or its close variation bowtie were best in the middle of the table. On the left side of the table, where four-lane, six-lane, or eight-lane major street meets a two-lane minor street, the MUT is the best design for pedestrians down to some low level of demand at which the signal in the MUT is no longer justified; the table shows that low level of demand as 5,000 vpd on the minor street, but in the field that boundary varies around 5,000 vpd depending on the major street demand.

For bicyclists in Table 6 the pattern was similar with AWSC best at the smallest intersections; a roundabout at larger two-lane meets two-lane intersections; a MUT at large intersections; and a MUT or bowtie in the middle of the table. The differences between the POFID and BOFID tables were along the lower left side where unsignalized RCIs or TWSC were generally best for bicyclists; along the bottom row where signalized RCIs were best for bicyclists; and along the right side for four-lane major streets meeting smaller four-lane minor streets where signalized RCIs were best for bicyclists. Some might be surprised that RCIs did so well for bicyclists, but they reduce conflicts with left-turn vehicles, shorten signal cycles, and break up long road crossings, and in the final tally those advantages outweighed their disadvantages. As for pedestrians, on the left side of Table 5, where four-lane, six-lane, or eight-lane major street meets a two-lane minor street, a MUT or signalized RCI is the best design for bicyclists down to some low level of demand at which the signal in the MUT or RCI is no longer justified; the table shows that low level of demand as 5,000 vpd on the minor street, but in the field that boundary varies around 5,000 vpd depending on the major street demand.

The red lettering in Tables 5 and 6, showing designs that also were the safest in that cell according to the SaFID charts for total crashes (Table 3 and Figures 2-6 above), revealed that planners and designers often do not have to compromise motor vehicle safety to achieve an optimum pedestrian and bicyclist experience. AWSC, roundabouts, and MUTs, in their niches, generally provide optimum safety, pedestrian experiences, and bicyclist experiences. As with the SaFID charts, TWSC and conventional signal almost never appear in the POFID and BOFID tables. There still may be reasons to stay with TWSC and conventional signal during any particular project, but optimizing the pedestrian and bicyclist experience might mean starting with a different concept.

As an example of the application of the tables, consider a recent intersection project where a six-lane arterial that will carry about 32,000 vpd in the design year meets a four-lane arterial that will carry about 27,000 vpd. The POFID and BOFID tables (Tables 5 and 6) show that a MUT is optimum for pedestrians and for bicyclists at this place and show that a MUT is also the safest design for total crashes. This information should help build the confidence of the stakeholders as they consider the MUT, a relatively new design in North Carolina.

Table 5. Pedestrian optimum feasible intersection design (POFID).

				Minor street						
			Number through lanes:	2				4		6 or 8
Major street			Low AADT:	0	5,000	7,500	10,000	10,000	25,000 and above	Any
Number through lanes	Low AADT	High AADT	High AADT:	5,000	7,500	10,000	15,000	25,000		
2	0	7,500		AWSC	AWSC	n/a	n/a	n/a	n/a	n/a
	7,500	15,000		Roundabout	Roundabout	Roundabout	Roundabout or signal	n/a	n/a	n/a
4	10,000	15,000		TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	n/a	n/a
	15,000	20,000		TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	n/a	n/a
	20,000	25,000		TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	n/a	n/a
	25,000 and above			TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	MUT	n/a
6 or 8	Any			TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	MUT	MUT

Shaded cells represent cases when a particular design minimized the weighted total number of flags for both pedestrians and bicyclists.
Red lettering indicates a design that was also the safest feasible intersection design based on total crashes.

Table 6. Bicyclist optimum feasible intersection design (BOFID).

				Minor street						
			Number through lanes:	2				4		6 or 8
Major street			Low AADT:	0	5,000	7,500	10,000	10,000	25,000 and above	Any
Number through lanes	Low AADT	High AADT	High AADT:	5,000	7,500	10,000	15,000	25,000		
2	0	7,500		AWSC	AWSC	n/a	n/a	n/a	n/a	n/a
	7,500	15,000		Roundabout	Roundabout	Roundabout	Roundabout or signal	n/a	n/a	n/a
4	10,000	15,000		Unsignalized RCI or TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Signalized RCI	n/a	n/a
	15,000	20,000		Unsignalized RCI or TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Signalized RCI	n/a	n/a
	20,000	25,000		Unsignalized RCI or TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Signalized RCI	n/a	n/a
	25,000 and above			Unsignalized RCI or TWSC	Bowtie or MUT	Bowtie or MUT	Bowtie or MUT	Signalized RCI	MUT	n/a
6 or 8	Any			Unsignalized RCI or TWSC	Signalized RCI	Signalized RCI	Signalized RCI	Signalized RCI	MUT	MUT

Shaded cells represent cases when a particular design minimized the weighted total number of flags for both pedestrians and bicyclists.
Red lettering indicates a design that was also the safest feasible intersection design based on total crashes.

Other Aspects

After capacity, safety, and pedestrians and bicyclists have been considered early in project development, cost and access are usually the next considerations. The construction cost of an intersection or interchange depends on many factors that are unknown at early stages, but typically are roughly correlated to the size of the footprint and the number and size and complexity of bridges. The right-of-way (ROW) costs are of course dependent upon the size of the footprint, the number of parcels affected, and the real estate value of each parcel.

Access

Analysts and designers can judge the quality of access provided by intersection or interchange alternatives based on the number of driveways affected, the number of parcels with potential driveways affected, and the efficiency of the movements in and out of each driveway. Movements in or out of a driveway that require more turns and more traverses of traffic signals or stop signs would indicate a lower quality access. Figure 7 shows an example of how a designer could qualitatively consider the effect of a median u-turn (MUT) concept on the access to and from a restaurant on the corner of a major intersection relative to a conventional intersection. Later in the project development process, traffic engineers could apply more detailed traffic analysis models to produce quantitative estimates of delays or travel times for traffic to and from particular driveways or side streets as needed.

Progression

Finally, designers may want to consider the quality of signal progression a particular intersection concept offers if it is part of an arterial corridor with other signals nearby. Progression is one of the best tools traffic engineers can use; projects to provide or improve signal progression often provide benefit-to-cost ratios well above 50:1. The quality of progression an intersection concept can offer depends upon the type of signal it uses and the proportion of the cycle that must be devoted to minor street movements. As noted above, designs that use half signals that only stop one direction of the arterial, like on a one-way street, are best as they have the capability to offer "perfect progression". Perfect progression means that the progression band along the arterial is constrained only by the amount of green time provided at an intersection. The usual constraints of speed, cycle length, and signal spacing that hamper full signals (that stop both directions of the arterial) do not apply to half signals. For intersection designs with full signals, the constraints imposed by the time-space diagram apply but the severity of the constraints depends upon the proportion of the cycle that must be devoted to minor street movements. Some intersections with full signals typically only need to devote a small fraction of the cycle to minor street movements, meaning that there is plenty of green time available for progressing arterial movements. Table 7 shows how some alternative designs perform in this regard in terms of the percentage of the arterial on which the design would function without restricting the green band given that the signal devotes the minimum possible time to minor street movements. As an example table application consider an arterial segment 5,000 feet long radiating out from an existing full signal. If Table 7 shows that a particular design will "fit" along 60 percent of the arterial at some cycle length and bandwidth percentage that means that for 3,000 feet of the segment (let's say from 0 to 1,500 feet and from 3,500 to 5,000 feet from the existing full signal) one could place an intersection with the design in question and achieve a bandwidth equal to or larger than the given percentage but for 2,000 feet of the segment (let's say from 1,500 to 3,500 feet from the existing full signal) the design in question would not achieve the bandwidth shown. The designs named in Table 7 will be described in detail in later sections of this document.

Considering access to and from the restaurant on the southeast (bottom right) corner of this MUT in comparison to a conventional design:

- From the west--two signals, but likely lower delay;
- To the west--right, then u-turn, then through main signal, likely better;
- From the east--one signal then u-turn, likely no difference;
- To the east--no difference;
- From the north—right at main signal, then u-turn, then through main signal, likely worse;
- To the north—lower delay, likely better;
- From the south—shorter queue, likely better; and
- To the south—right, then u-turn, then through main intersection, then u-turn, then right at main intersection, worse.

- Overall—with four movements likely better, two movements likely the same, two movements likely worse, overall the MUT is likely better than a conventional design.

Figure 7. Example consideration of access for an alternative intersection relative to a conventional intersection.

Table 7. Progression quality of intersection designs with full signals.

Cycle, sec	Bandwidth, %	Percent of arterial on which a design would fit		
		Offset int., continuous green T, and thru-cut (need to serve one minor street left turn phase each cycle)	MUT, bowtie, full CFI, quadrant, and seven-phase signal (need to serve one minor street through phase each cycle)	Partial MUT, partial CFI, and reverse RCI (need to serve two minor street phases each cycle)
80	40	85	60	25
	50	65	40	5
120	40	97	80	57
	50	77	60	37
160	40	100	90	73
	50	83	70	53

INTERSECTION ALTERNATIVES

Traffic Calming

At some intersections, the primary goal is to discourage high vehicular volumes and/or speeds. Traffic calming, as it is termed, is typically appropriate on collector or local streets in residential areas and is often aimed at through traffic. Many measures have been used successfully at intersections to decrease vehicular volumes and speeds. Curb bulb-outs, textured crosswalks, and raised speed tables are design measures that assist crossing pedestrians, and these might also be considered traffic-calming measures. Other design measures that engineers use to calm traffic at intersections include:

- Roundabouts (see the section on intersection alternatives below),
- Chokers (narrowing lanes with curbs and/or landscaping),
- Semidiverters (allowing one-way in or out of the intersection on an approach),
- Forced-tum diverters (allowing no through movements for one street),
- Diagonal diverters (forcing two approaches to tum only left and the other two approaches to turn only right), and
- Vehicular cul de sacs (usually allowing nonmotorized and emergency users to get through).

If done well, traffic calming at intersections can improve the overall quality of service and safety for road users and will improve the quality of the environment surrounding the intersections. If done poorly, though, traffic calming can cause collisions, increase travel times, increase frustrations, and harm the nearby environment. Some of the important issues analysts and designers need to examine when considering traffic calming at intersections include visibility to the design feature, forgiveness of the design feature if struck, driver expectations, aesthetics of the design feature, access for emergency vehicles, and whether problems mitigated at one intersection will simply migrate to another location. The FHWA (33) has posted an excellent resource on traffic calming that will help analysts and designers negotiate some of these issues.

Frontage Roads

Frontage roads are local roads built next to arterials that handle all driveways that would otherwise intersect the arterial. Many frontage roads were built decades ago, and some still exist.

The main problem with frontage roads is that they create inefficient and potentially less safe intersections where they meet y-line roads that also meet the arterial. Figure 8 shows an example. If unsignalized, the junction of the frontage road and the road that meets the arterial is confusing for drivers, provides virtually no storage space, and has other issues. If signalized, that junction has the same issues plus each frontage road approach needs an additional signal phase, adding delay to all vehicles.

Figure 8. Example of a frontage road meeting a y-line near an arterial.

NCDOT has generally tried not to build new frontage roads along arterials for many years. In places where they exist, several options exist for conversion to more efficient intersection forms. Backage roads, built behind the land uses lining the arterial and absorbing all of the driveways for those land uses, are a popular option. Curving frontage roads so that they meet y-line roads at least several hundred feet from the arterial can increase efficiency and decrease crashes. Eliminating the frontage road is possible, especially if the space freed up can be used for more productive purposes and the arterial has a median and well-designed median openings in place.

One-Way Approaches

An intersection involving one or two one-way streets operates much more efficiently and probably more safely than a similar conventional intersection between two two-way streets. Reasons for this greater efficiency and safety include:

- Signals at intersections involving one-way streets require fewer phases, reducing lost time. At an intersection between a two-way street and a one-way street, only one left-turning movement is opposed by vehicular traffic.
- It is possible to establish perfect signal progression along a one-way street with any signal spacing at any speed because of the half-signals employed.
- The number of conflicts between traffic streams in the intersection is greatly reduced.
- Crossing pedestrians face fewer directions of conflicting vehicular traffic.

One-way streets have acquired a bad reputation among some planners for problems with past installations including the encouragement of higher speeds, motorist confusion, and the decline of adjacent businesses. However, none of these perceived flaws is a necessary condition of one-way streets, and many one-way streets exist that do not have these issues. One-way streets should remain in the designer's toolbox, especially in dense urban areas. In addition, particular intersection designs like the split (34) and town center (35) intersections take advantage of one-way street features and could be good solutions at some spots.

Three-Legged Intersections

Three-legged intersections should be generally safer than four-legged intersections. This is due to the reduced number of conflict points for drivers and pedestrians, meaning three-leg intersections are easier to drive or cross and there are fewer threats in case of a driver or pedestrian error. A three-legged intersection only has nine vehicular conflict points, compared to 32 vehicular conflict points at a four-legged intersection. A three-legged intersection only has 12 vehicle-pedestrian conflict points, compared to 24 such conflict points at a four-legged intersection.

The Crash Reduction Factor (CRF) Information Sheet maintained by the NCDOT Safety Unit (36) includes factors for the conversion of a four-leg intersection into two three-leg intersections (otherwise known as an "offset intersection"). In particular:

- In an urban area, if more than 30 percent of the entering traffic volume is on the minor road approaches, injury crashes should decrease by 33 percent,
- In an urban area, if more than 30 percent of the entering traffic volume is on the minor road approaches, property damage only crashes should decrease by 10 percent, and
- In a rural area, total crashes should decrease by 70 percent.

The rural crash reduction factor cited above is an interim measure for use until someone conducts better research. None of the three CRFs cited above is in the FHWA Countermeasure Clearinghouse so they have not received a quality rating. Offset intersections are discussed more below in the section "Alternative Designs."

As of this writing, there are only two CMFs or CRFs available for the three-legged versions of different intersection designs. First, the section "Alternative Designs" below describes the continuous green T intersection, for which high-quality CMFs are available, but the niche for the continuous green T intersection appears to be very limited. Second, recent research for the NCDOT provided a total crash CMF of 0.86 for a three-legged CFI based on a small sample of sites and crashes (27). We do not have CMFs for common and feasible treatments at three-legged intersections such as all-way stop control, standard roundabouts, mini-roundabouts, RCIs, and ILACs. It makes sense that the CMFs for three-legged treatments like those listed above would be nearer to values of 1.0 than CMFs for the four-legged versions because the conventional three-legged intersection is relatively safer; however, we do not know the magnitudes of the differences. An internal NCDOT study is underway to develop CMFs for some of these three-legged alternatives so hopefully at least some of this information gap will be filled soon.

The relative safety of three-legged intersections means planners and designers should choose that form more often if possible. The author is aware of the urban planning literature that encourages the creation of more four-legged intersections so that pedestrians may have more connections and continuity, however planners should be aware of the likely price in increased crashes that results. Perhaps planners can find compromises between these two philosophies, such as the creation of a shared-use path in the space where a fourth street leg for vehicles would have been. At locations where a three-legged intersection already operates, planners and developers should resist any urge to add a fourth leg and should instead choose to place a new minor street connection some distance from the existing intersection.

Intersections with More Than Four Legs

Intersections with more than four legs still exist in North Carolina. Due to the larger number of conflict points when there are five or six legs such intersections likely are much less safe and operate much worse than intersections with three or four legs. Unfortunately there are not quality published CMFs on this topic, but almost certainly many projects to treat such locations would provide good safety benefits. Common ways to treat intersections with five or six legs include rerouting the fifth or sixth legs to create new intersections some distance from the main intersection, making the fifth or sixth legs one-way (with traffic typically moving away from the main intersection), or using oval or peanut roundabouts as described below in the “Roundabouts” section.

Roundabouts

A modern roundabout, as shown in Figure 9, offers greater safety and efficiency than a conventional intersection in certain niches if designed and operated well. The idea of modern roundabouts came to the United States from Europe and Australia in the late 1980s, and modern roundabouts have since moved beyond the experimental stage to be a part of standard engineering practice in many U.S. agencies. Modern roundabouts differ from earlier, often unsuccessful, traffic circles because they have the following features:

- Yield control upon entry to the circle (traffic in the circle always has the right-of-way),
- Low design speeds for circulating traffic,
- All traffic diverts from a straight-line path through the intersection,
- No parking in or near the circle, and
- No pedestrians in the circle.

Figure 9. Modern roundabout.

Old traffic circles, like in the downtowns of several small towns in North Carolina, usually lack these modern design features and struggle with safety, capacity, pedestrian, and other problems.

Single-lane roundabouts have been proven in U.S. research to be safer than the conventional intersections they replaced as Table 2 previously illustrated. Traffic analysis software also typically shows that single-lane roundabouts that remain below capacity reduce delays compared to signalized intersections handling the same volumes. The total entering capacity of single-lane roundabouts is typically about 25,000 vehicles per day (1), meaning that single-lane roundabouts are a good solution for intersections between two collector streets. Note that roundabout operation can be hampered by extremely unbalanced traffic loading (low side street demand relative to main street demand) even when in the realm of the traffic volumes in the SaFID charts (Table 3). The 2010 Roundabout Guide stated, for example (37, page 3-30):

> A roundabout is unlikely to offer better performance in terms of lower overall delays than two-way stop control at intersections with minor movements (including cross-street entry and major-street left turns) that are not experiencing, nor predicted to experience, operational problems under two-way stop control.

Also note that roundabouts save some money long-term compared to conventional traffic signal control because they do not need electric power or signal maintenance.

Table 2 also showed that two-lane roundabouts have shown good safety benefits, especially in preventing injury crashes. Figure 10 shows the general capacity (level of service E to F boundary based on *Highway*

Capacity Manual calculations) of a roundabout with two lanes serving the major street and one lane serving the minor street, which is often referred to as a "2-1-2-1 roundabout" or "2x1 roundabout". The total entering capacity of roundabouts with two lanes all around the circle is typically about 45,000 vehicles per day (1), meaning that two-lane roundabouts are a potential solution for intersections between two minor arterials. Roundabouts that have more than two lanes in the circle have struggled in other states though (38) and should be generally discouraged in North Carolina until research is available showing their safety and efficiency in the US.

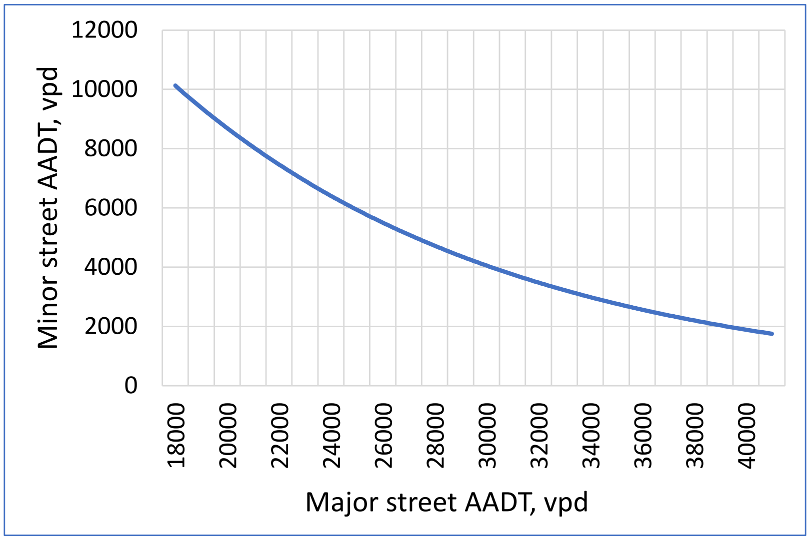


Figure 10. Capacity limits for a 2-1-2-1 roundabout.

Roundabout analysts and designers face many decisions, including design speed, circle diameter, circle roadway width, approach flares, and splitter island size and shape. The NCHRP has assembled an excellent information source for these and other roundabout design issues (1).

Mini-Roundabouts

Mini-roundabouts, with outside diameters below 90 feet, can also be an effective intersection treatment (1). At a mini-roundabout, the center is made of a material that is traversable by large trucks or buses but also discourages smaller vehicles from driving on it. The main virtue of a mini-roundabout in comparison to a full-sized roundabout, with an outside diameter above 90 feet where all design vehicles go around the circle, is a reduction in costs and impacts. A mini-roundabout typically costs one-third to one-quarter of a full-sized roundabout, and many can fit within the curb lines of an existing intersection. Table 2 showed that the CMF of a mini-roundabout replacing a two-way stop control intersection is 0.83 for total crashes and 0.41 for injury and fatal crashes, which are not as high as the CMFs for full-size roundabouts but still provide good crash reductions. The best available capacity model for mini-roundabouts is from 2014 (39) and shows an ideal capacity about 30 percent lower than a full-size roundabout. The Congestion Management Section has a spreadsheet application of the mini-roundabout capacity model available for use by analysts.

Modular Roundabouts

To reduce construction costs and times, designers may specify a modular roundabout instead of typical construction. Modular roundabouts use materials for the center island, the splitter islands, and the outside curbs that are screwed or bolted into place make installation quicker and cheaper. The first modular roundabout in North Carolina was installed over one weekend for a cost of only $30,000 in Division 14 in 2021 and has functioned well since installation. Modular roundabouts have also saved costs and functioned well in Virginia (40).

Peanut and Oval Roundabouts

At some junctions with more than four legs or where two intersections are very close to each other peanut or oval roundabouts could be a helpful solution. Figure 11 shows a peanut roundabout installation north of Wilmington, NC with a single circulating lane. The peanut replaced a complex junction that had merges, diverges, weaves, and small storage areas and has worked well for a number of years.

Figure 11. Peanut roundabout at US-117 and NC-133 in Castle Hayne, NC.

There are no published CMFs for peanut or oval roundabouts but it is likely that they provide good safety benefits compared to the poor alternatives. Peanut and oval roundabouts very likely provide much better pedestrian crossing opportunities than the before period conditions. Operationally, peanut and oval roundabouts require longer travel distances and provide higher conflicting volumes than standard roundabouts so good analyses are necessary to ensure that they provide the needed capacities.

Turbo Roundabouts

Turbo roundabouts have emerged as an interesting alternative in recent years and could be worth a look in some spots. A turbo is a form of 2x1 roundabout with three or four legs that tries to achieve enhanced safety and operations compared to a standard 2x1 roundabout by discouraging lane changing in the circular roadway and by encouraging slower entry speeds. A turbo does this through three main differences with standard 2x1 roundabouts, including:

- Separators between the lanes in the circle,
- Radial (90-degree) entry into the circle, and
- Many more traffic control devices.

Figure 12 shows a turbo roundabout from the Netherlands, where the turbo was invented, which illustrates all three traits listed above. Major street through vehicles (left-to-right in Figure 12) can use either entry lane on the approach. Minor street through vehicles use the left entry lane if there are two entry lanes. The lane separators in the circle in Figure 12 are raised curbs that try to discourage vehicles from crossing but hopefully do not cause safety or maintenance issues. Many European turbos have lane separators in the circle that are just painted but wider than typical lane markings. According to a database maintained by Dutch turbo researcher Dirk DeBaan there are about 700 turbo roundabouts operating across the globe, including 400 in the Netherlands, 25 outside Europe, and one in the US (in Jacksonville, FL). FHWA has published guidance on turbo roundabouts that could be helpful to planners and designers considering this option (41).

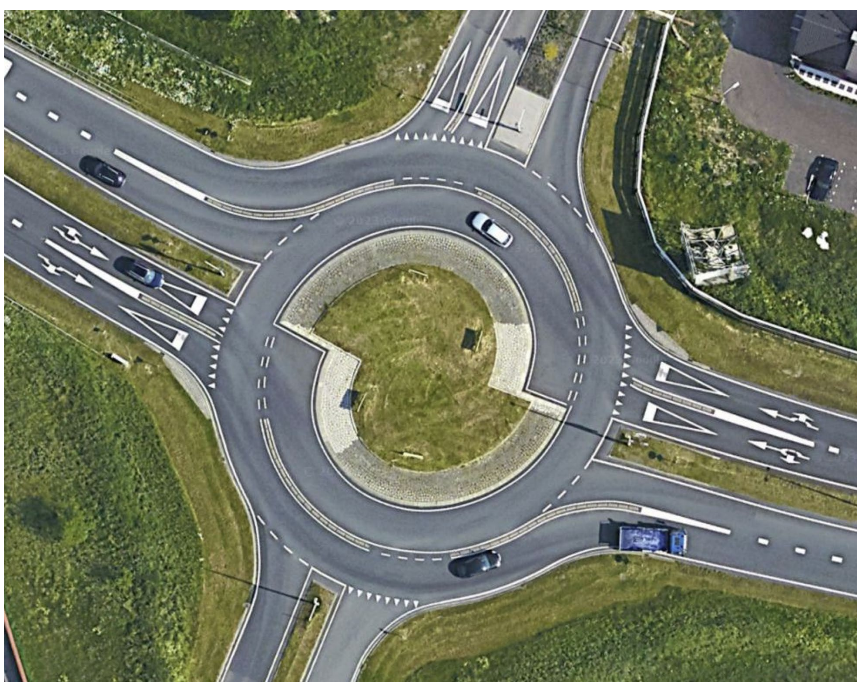


Figure 12. Turbo roundabout in the Netherlands.

The claim that turbo roundabouts are safer than standard roundabouts is grounded in the fact that many more drivers stay in their lanes in the circle, limiting sideswipe crashes. This might be offset to some extent by the more right-angle vehicle entries to the circle which could mean more severe crashes in the event of a driver error. Safety data from the Netherlands and other European countries show turbos to be safer than standard roundabouts, but the only turbo CMF published in the Clearinghouse (4) has only one star for research quality.

European data show that turbos have a higher capacity than standard roundabouts with the same number of lanes. This is because entering vehicles tend to accept smaller gaps, in part because drivers have an easier time turning their heads to look at oncoming traffic. There are no data on the behavior of American drivers at turbos yet, so we do not know if the capacity will also be higher at American turbo roundabouts.

Pedestrian crossing at a turbo is slightly better than at a standard roundabout with a similar number of lanes because the radial entry allows for shorter crossing distances. The quality of bicyclist experience at a turbo is difficult to judge; most European turbos discourage bicycle movements into the circle by providing shared-use paths around the turbo.

In the US turbo roundabouts may end up costing more than standard roundabouts with the same number of lanes because the diameters may have to be larger. This is due to the lane separators in the circle. A circle with raised lane separators that keeps large trucks from driving on or over the separators will likely mean larger turn radii. With turbos there will likely be some right of way savings on the entries due to the radial design but these savings will probably not offset the larger diameter of the circle.

At this point in the US the niche for consideration of a turbo roundabout might be where we need a bit more capacity than a standard 2x1 roundabout will provide and where the room for a larger diameter circle is available. However, planners and designers considering a turbo roundabout will confront a number of vexing questions. We do not have an American capacity model for turbos, we do not know how they will perform for safety, and we do not know how well bicyclists will perform at turbos. Hopefully more US data will be available soon to help answer some of the questions.

One final note on turbo roundabouts is that if US planners and designers take the idea to a political body or a public meeting they may not want to use the name. "Turbo" implies travel that is fast or automatic; the name may not have positive associations. A turbo is just a variation on a standard 2x1 roundabout, which is well-liked and well-accepted in many places across the US, so professionals taking the idea to non-professionals may want to downplay the uniqueness.

Roundabout Corridors

In recent years the concept of a corridor with several roundabouts has emerged and may be a viable alternative in some places. The main idea is that the agency would install roundabouts at the larger intersections and a raised median on the arterial between the roundabouts so that left turn demand from any driveways or side streets was redirected to the roundabouts. Figure 13 shows part of such a corridor in Marquette, Michigan on a four-lane arterial. The idea could apply to two-lane corridors as well.

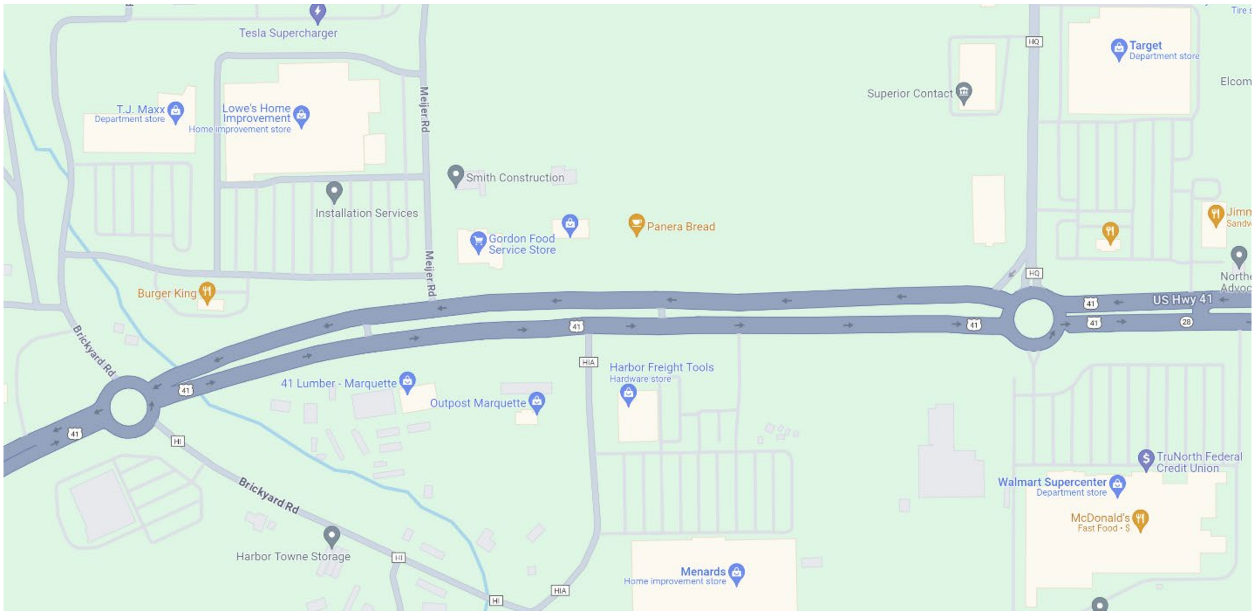


Figure 13. A portion of a roundabout corridor in a commercial area of Marquette, MI.

A roundabout corridor would likely mean superb safety for several reasons. First, the roundabouts themselves will likely be much safer than conventional treatments at those intersections, as documented above. Second, occasional roundabouts along a corridor would provide speed control. Third, the roundabouts would provide high quality pedestrian crossings, and the agency would have a chance to install additional crosswalks between roundabouts where appropriate taking advantage of the median. Finally, the driveways and side streets between roundabouts would be converted to RIRO junctions, which are much safer than full-movement junctions as documented earlier. There would be longer driving distances for left-turning vehicles into and out of driveways and side streets which could lead to increases in some types of crashes, but overall there should be little doubt that a well-designed roundabout corridor would be significantly safer than the same corridor with conventional intersections.

Roundabout corridors in the right places would likely reduce travel times compared to corridors with conventional intersections. The key to this aspect would be ensuring that each roundabout remained under capacity (guidelines on roundabout capacity were provided above). Roundabouts operating under capacity usually reduce the overall travel times of entering vehicles compared to conventional intersection treatments. When looking at a proposed roundabout corridor analysts would have to account for the extra vehicles using the roundabouts who were redirected from making direct left turns at driveways and side streets. At the driveways and side streets themselves delays at the RIRO junctions would almost certainly be reduced compared to full-movement treatments. The extra travel times for the left-turning vehicles getting back and forth to the nearest roundabout would have to be accounted for as well. The frequency of roundabout placement along the corridor would be a big factor in the travel time calculation. A designer could reduce the extra demand on roundabouts and the extra travel distance for left-turning vehicles to get to a roundabout by mixing in some left turn crossovers at busier driveways and side streets as shown in Figure 13. In sum, a roundabout corridor does not guarantee overall lower travel times but a roundabout corridor in a good place with a good frequency of roundabouts and left turn crossovers could show such savings.

On costs and impacts, a roundabout corridor will probably provide savings compared to a corridor with conventional intersections. The roundabout corridor will require more right of way at each roundabout intersection whereas conventional designs require wider approaches. The roundabout corridor would likely provide some space and cost savings between roundabouts, in that the median could be narrower than on a conventional corridor that has to provide space for left turn lanes.

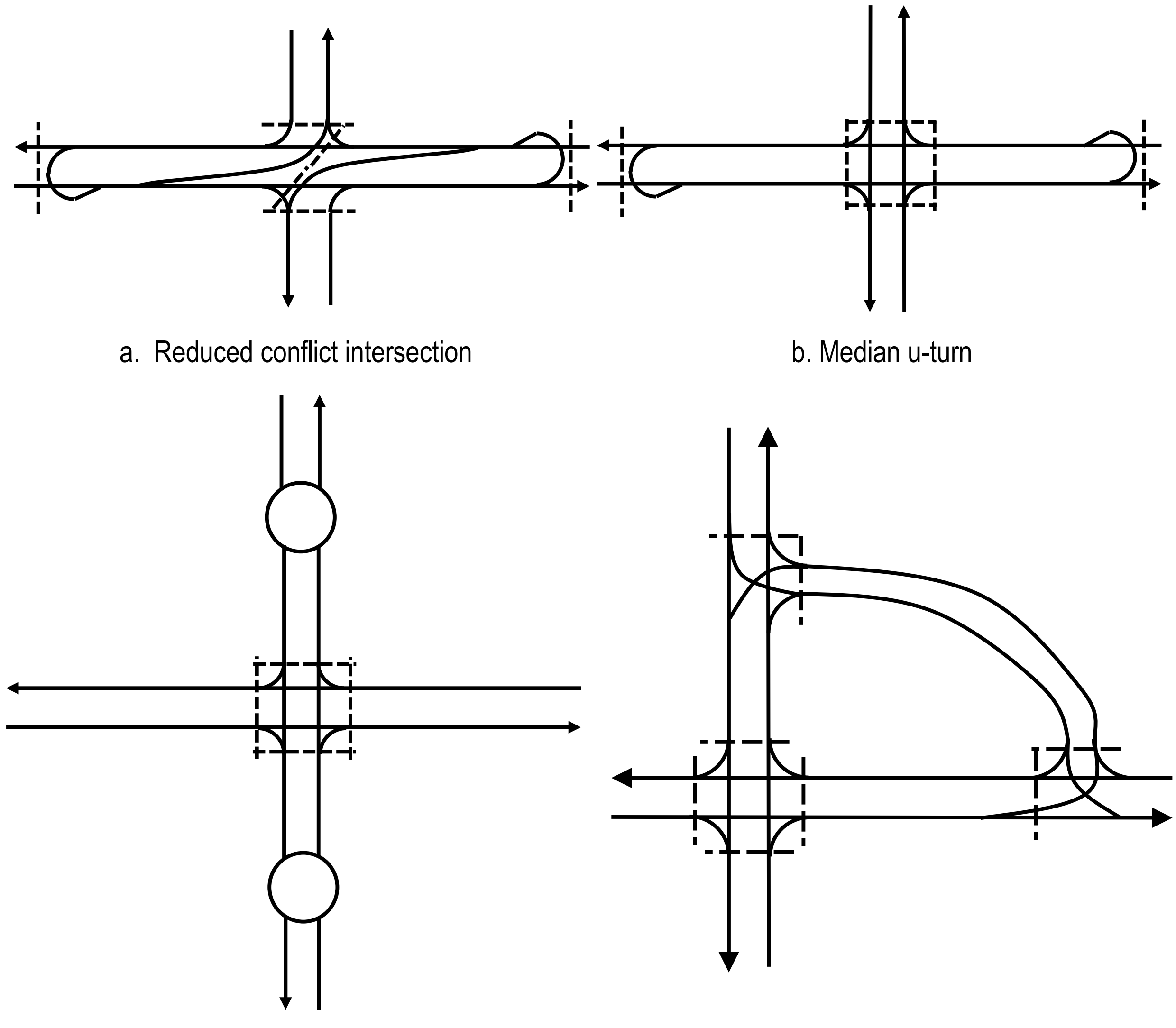
In sum a roundabout corridor might be a promising design for some places in the future. The niche would seem to be a corridor with two or more larger intersections suitable for roundabouts in terms of available space and traffic demands. Between roundabouts the distance should not be too long such that it inconveniences left-turning drivers too much. Also between intersections there should be enough driveways and side streets to justify the investment but not too many to degrade the safety or travel time savings.

Alternative Designs

In recent years a wide variety of alternative intersection designs has been developed and applied in North Carolina and other states. The alternative designs all redirect one or more movements from the main intersection, thereby achieving better adherence to the basic intersection design principles articulated above. The effects of the movement redirections could include fewer crashes, higher capacities, lower travel times, lower costs and impacts, better pedestrian and bicyclist crossing, and others.

Most Popular Alternatives

Figure 14 shows sketches of the most popular alternative intersections while Table 8 provides a summary of the general advantages and disadvantages and niches of the designs. The advantages and disadvantages in Table 8 are for a design in its niche relative to a conventional intersection design built to handle a similar traffic demand. The field continues to advance, with more alternatives being added and research providing more evidence, so analysts and designers should check with intersection experts before choosing a design based on Table 8.



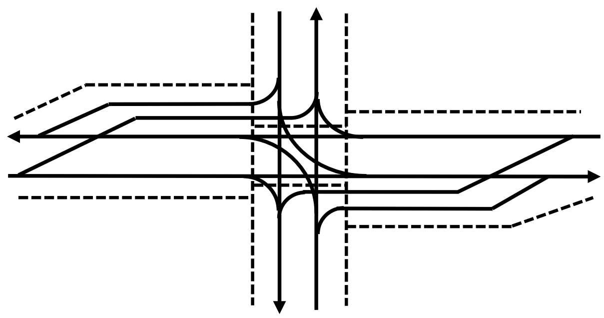
a. Reduced conflict intersection

b. Median u-turn

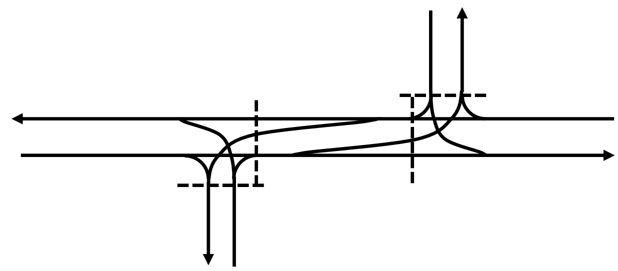
c. Bowtie

d. Quadrant roadway intersection

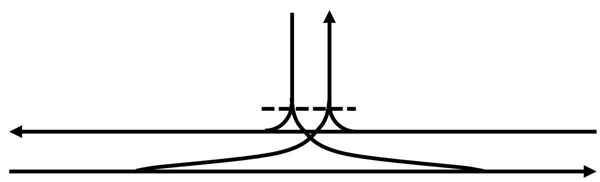
Figure 14. Sketches of popular alternative intersections.
Note that dashed lines show crosswalks.



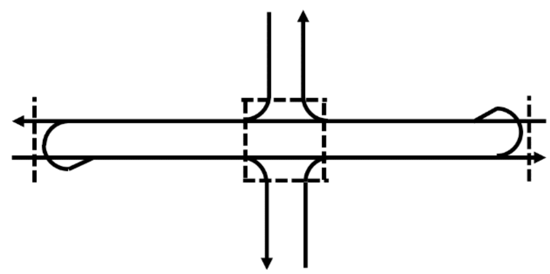
e. Partial continuous flow intersection



f. Offset intersection



g. Continuous green T intersection



h. Indirect left and cross intersection

Figure 14. Continued.

Table 8. General advantages and disadvantages and niches of popular alternative intersections.

Name	Advantages	Disadvantages	Niche
Reduced conflict intersection (RCI; aka, superstreet, j-turn, RCUT, synchronized street)	• Safety • Can increase capacity • Perfect signal progression • Speed control • Pedestrian crossing • Beneficial for most nearby businesses • Works well unsignalized or signalized	• Bicyclist crossing the major street • Public perception • Need ROW for bulb-outs at ends of u-turn crossovers • If signalized, higher signal cost	• Intersection of major four-lane, six-lane, or eight-lane arterial with minor street • Minor street demand less than 25,000 vehicles per day • Rural, suburban, or urban • Signalized or unsignalized • Three or four legs • ROW available for bulb-outs at the ends of the u-turn crossovers
Median u-turn (MUT)	• Safety • Increased capacity • Better signal progression • Pedestrian crossing • Beneficial for nearby businesses	• Lower capacity with higher left turn demands • Public perception • Need ROW for bulb-outs at ends of u-turn crossovers • Higher signal cost	• Intersection of major four-lane, six-lane, or eight-lane arterial with another major street • Left turn demand should be less than 20% of approach demand • Suburban or urban • Signalized • Four legs • ROW available for bulb-outs at the ends of the u-turn crossovers
Bowtie	• Safety • Increased capacity • Better signal progression • Superb pedestrian crossing • Beneficial for nearby businesses • Narrow major street ROW • Traffic calming and aesthetics on minor street	• Lower capacity with higher left turn demands • Public perception • ROW needed for roundabouts	• Intersection of major four-lane, six-lane, or eight-lane arterial with a collector or minor arterial street • Left turn demand should be less than 20% of approach demand • Suburban or urban • Signalized • Four legs • ROW available for roundabouts

Table 8. Continued.

Name	Advantages	Disadvantages	Niche
Quadrant roadway intersection (QRI)	• Increased capacity • Better signal progression • Pedestrian crossing • Beneficial for most nearby businesses • Small ROW at main intersection • Can put connector road in any quadrant	• Public perception • ROW needed for connector road • Potential driver confusion • Higher sign and signal cost	• Intersection of two arterials each with four lanes or more • Suburban or urban • Signalized • Four legs • ROW available for connector road • Can use one or two connector roads
Partial continuous flow intersection (CFI; aka, displaced left turn)	• Safety • High capacity • Better signal progression • Bicycle movements	• Public perception • ROW needed for ramps • Pedestrian crossing • Transit stops • Higher sign and signal cost • Access to nearby businesses	• Intersection of two arterials each with four lanes or more • Higher left turn demands • Where grade-separated intersection is being considered • Suburban or urban • Signalized • Three or four legs • Can use one to four left turn ramps • ROW available for ramps • Low pedestrian demand • Few nearby businesses to be harmed
Offset	• Increased capacity • Bicycle movements • Works well unsignalized or signalized • Minor street can turn left then right or right then left	• Public perception • Potential driver confusion • Pedestrian crossing • Higher sign and signal cost • Need offset to be large enough	• Intersection of arterial with collector or minor arterial • Rural, suburban, or urban • Signalized or unsignalized • Four legs • Low pedestrian demand • ROW available to provide large-enough offset

Table 8. Continued.

Name	Advantages	Disadvantages	Niche
Continuous green T (aka, Florida T, high tee, seagull)	• No delay in one direction • Perfect signal progression • Can work unsignalized or signalized	• Limited to single lane for left turn from stem • Potential driver confusion • Pedestrian crossing the major street • Bicyclist crossing the major street • Access to nearby businesses • Need long downstream distance available for merge • Encourages high speed	• Intersection of arterial with collector or minor arterial • Minor street demand low enough that only one left turn lane needed • Rural or suburban • Signalized or unsignalized • Three legs • No pedestrian or bicycle demand to cross arterial • Few nearby businesses to be harmed
Indirect left and cross (ILAC)	• Safety, particularly a reduction in severe crashes • Perfect signal progression • Speed control • Pedestrian crossing • Works well unsignalized or signalized • Could decrease the distance from the main intersection to the u-turn crossovers compared to an RCI	• Could decrease capacity • Will increase driving distances • Bicyclist crossing the major street • Public perception • Need ROW for bulb-outs at ends of u-turn crossovers • If signalized, higher signal cost	• Intersection of major four-lane, six-lane, or eight-lane arterial with minor street • Minor street demand less than 19,000 vehicles per day • Rural, suburban, or urban • Signalized or unsignalized • Four legs • ROW available for bulb-outs at the ends of the u-turn crossovers

The best sources of general information on designing the RCI, MUT, QRI, and CFI are a series of guidebooks produced by the FHWA (28, 42, 43, 44). Since a bowtie intersection is essentially a combination of roundabouts and MUT, analysts and designers should turn to those guidebooks for help (1, 42).

One of the perceptions of RCIs through the years is that it is not friendly to pedestrians crossing the major street. This is due to the diagonal crosswalk in the middle of the intersection as Figure 14 illustrates (the so-called “Z crossing”). This perception is not grounded in reality as seen in 20-flags analyses or travel time calculations, but persists nonetheless. A design variation that has had some success in overcoming that perception is to offset the two minor street legs by just 50 feet or so to allow a 90-degree crosswalk. Figure 15 shows a concept for an offset RCI. Motorists would never notice the shift, but pedestrians would likely appreciate it.

Figure 15. Offset RCI concept to provide 90-degree crosswalk.

Figure 14 shows, and Table 8 discusses, a partial CFI which is a four-legged intersection with two ramps for left-turning traffic, usually on the major street, and three critical signal phases. This is the most popular type of CFI that has been built to this point in the US. The CMF in Table 2 pertained to a partial CFI with two left turn ramps on the major street approaches. Project teams should consider that there are other versions of CFI, including a three-legged version with one left turn ramp (and two critical signal phases) and four-legged versions with one, three, or four left turn ramps. A four-legged CFI with four left turn ramps is called a “full CFI” and has just two critical signal phases. A full CFI delivers an enormous traffic capacity, but with correspondingly large costs and impacts.

Offset intersections are the subject of research sponsored by the NCDOT and the final report should be of some help to analysts and designers (45). The report generally showed that offset intersections may be safer than a conventional intersection handling the same traffic demand, due to having fewer conflict points, and would often result in less delay than a conventional intersection handling the same traffic demand due to needing fewer signal phases. The report provided guidance on the minimum offset distance one should provide and whether a left-then-right or a right-then-left design is better given certain demands.

The continuous green T (CGT) intersection has been the source of some research attention in recent years and analysts and designers could use that information to help design one (46). However, the CMFs for the conversion of a conventional three-legged intersection to a continuous green T intersection are not great (0.96 for total crashes and 0.85 for injury crashes, earning three stars each in the FHWA Clearinghouse, reference 46). Since the CGT has many disadvantages and limitations, since the safety benefits are limited, and since the competition is tough (i.e., RCIs for low and moderate demand cases, CFIs for higher-demand cases) the number of CGT intersections installed in the end will likely be low.

Newer and Rare Three-Phase Alternatives

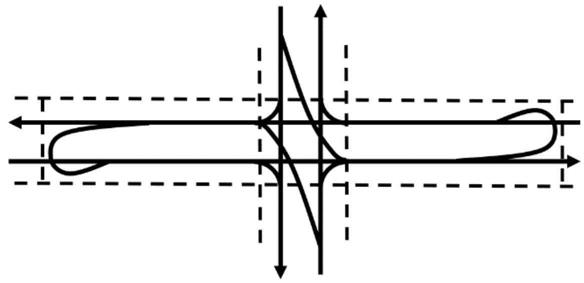
A jughandle intersection is a three-phase design is popular in New Jersey and some other northeastern states but is not considered to be a competitive design in North Carolina. A jughandle redirects major street left turns to a ramp that diverges from the right side of the arterial; the ramp terminal at the minor street is typically controlled by a stop sign. The reasons that jughandles are not considered competitive in North Carolina are the difficulty the redirected vehicle has making a left turn onto the minor street, the poor quality of pedestrian crossings, the fact that driveways and side streets cannot exist where the ramps are located, and that the jughandle requires a great deal of ROW. In essence, the jughandle has most of the disadvantages of the partial CFI but delivers only a fraction of the capacity.

A design called a partial parallel flow intersection also provides for three-phase operation. Figure 16 shows a partial parallel flow intersection operating in New Jersey. The design is similar to a partial CFI but the left turn crossovers are brought up next to the minor street. The redirected left turn roadways end several hundred feet from the main intersection at full two-phase signals (the secondary signals have to stop both directions of the minor street to allow redirected left turn vehicles to complete their turns). The partial parallel flow intersection has an advantage over a partial CFI in that the left turns from the major street are made at almost the usual spot, which should eliminate some driver confusion. However, the partial parallel flow design has many of the same disadvantages as the partial CFI and has a lower capacity and efficiency than a partial CFI due to the secondary signals being full instead of half signals. The two-phase version of the parallel flow intersection (with four left turn crossovers) was patented after it was introduced (47) so project teams considering a partial parallel flow intersection should engage legal help before proceeding.

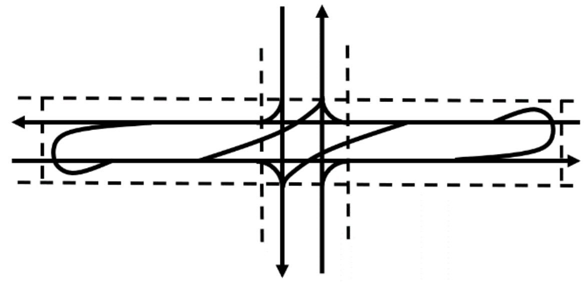
Figure 16. Partial parallel flow intersection in at US-130 and NJ-168 in New Jersey.

Project teams should be aware that there is a set of newer three-critical-phase intersection designs emerging that could be viable alternatives in certain circumstances. The two-phase designs described above--such as the RCI, the MUT, and the full CFI with four left turn ramps--are superior to most competitors in capacity, likely superior in safety, and likely superior in other dimensions. However, two-phase designs sometimes present project teams with difficulties in that they may be opposed vigorously by various stakeholders, they require more ROW and have otherwise larger impacts than other designs, and they may not function as well with certain demand patterns. A three-phase design can serve as a compromise when a project team wants to preserve as many of the positive features of the two-phase designs as possible while mitigating the difficulties. Figure 17 shows six newer or rare three-phase designs that redirect at least one movement to remove a critical phase. The sketches in Figure 17 are not intended to show all feasible versions of each design; for example, crosswalks and u-turns can be configured differently from that shown while still maintaining the essence of the idea. Note that four of the six three-phase designs in Figure 17 have been built at least once in the US as far as we know (a, c, d, and e) and four of them (a, d, e, and f) have been discussed in professional publications. Documented relative strengths and weaknesses of each of the six designs include:

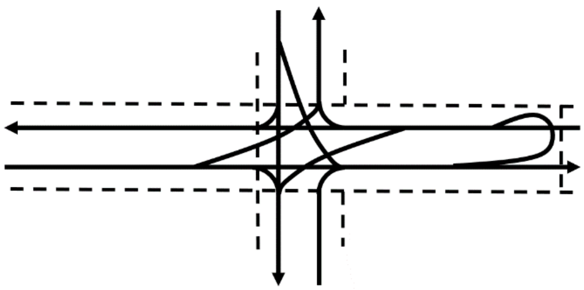
a. Partial median u-turn (redirects major street left turns)—stronger in capacity and pedestrian service, weaker in progression;
b. Redirect minor street lefts to u-turn crossovers—Stronger in pedestrian service, no known particular weaknesses;
c. Redirect left and through from one minor leg to a u-turn crossover—Stronger in conflict points and extra ROW needed, weaker in capacity;
d. Thru-cut (redirects minor street through movements)—Stronger in capacity and progression, weaker in pedestrian service;
e. Reverse RCI (redirects major street left turns and minor street through movements)—Stronger in conflict points and pedestrian service, weaker in capacity and extra travel distances required; and
f. Seven-phase signal (redirects one minor street through movement)—Stronger in capacity, extra travel distance required, and extra ROW needed, weaker in conflict points and pedestrian service.



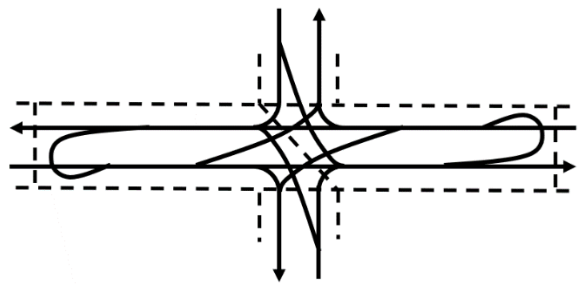
a. Partial MUT (redirects major street left turns).



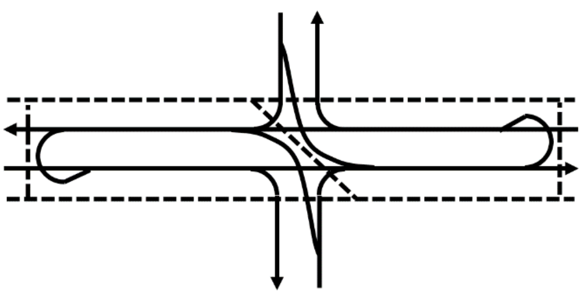
b. Redirect minor street lefts to u-turn crossovers.



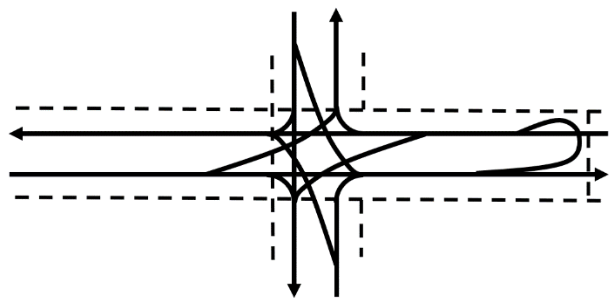
c. Redirect left and through from one minor leg to u-turn crossover.



d. Thru-cut (redirects minor street through movements).



e. Reverse RCI (redirects major street left turns and minor street through movements).



f. Seven-phase signal (redirects one minor street through movement).

Figure 17. Sketches of newer alternative intersections with three-phase signals. Note that dashed lines show crosswalks and sidewalks.

Figure 17 shows the newer three-phase alternatives with u-turn crossovers to accommodate the redirected movements. However, the designs may be implemented without u-turn crossovers if there are other ways to complete the redirected movements. This is especially true for designs a through d in Figure 17 that redirect only two movements and for design f in Figure 17 that redirects only one movement. For the thru-cut, for example (design d in Figure 17), if the south leg of the intersection serves a development and there is another outlet from the development, a northbound through movement can use the other outlet to access the major street, travel along the major street to the thru-cut, and make a turn to complete the desired movement.

The thru-cut, shown in Figure 17d, appears to be the newer three-phase design that has the best chance of seeing widespread implementation. This is likely due to the capacity and progression improvements it can deliver compared to a conventional intersection at a modest cost, particularly if u-turn crossovers are not needed. North Carolina currently has three thru-cuts open, at:

- Arrowood Road and Green Ridge Drive/Arrowpoint Boulevard in Charlotte,
- South Main Street at Village Walk Drive in Holly Springs, and
- Christenbury Parkway west of Derita Road in Concord.

Crash data obtained by the NCDOT Safety Unit show that the Holly Springs thru-cut has performed splendidly. Comparing 1.5 years of two-way stop operation prior to construction to 3.5 years of operation after thru-cut construction, total crashes per year reduced by 67 percent and injury crashes per year reduced by 61 percent while traffic volumes per year went up by 71 percent.

Figure 18 shows the thru-cut operating in Holly Springs. The pedestrian service at a thru-cut is relatively weak because the crossing of the major street is made on a diagonal crosswalk, which is a longer path than usual and means that the left turn phase with that crossing must be held for a longer time. To overcome that perceived weakness, project teams could use an offset thru-cut design as Figure 19 shows. Like the offset RCI, offsetting the minor street approaches by just 50 feet or so would allow a 90-degree crosswalk without, it appears, sacrificing any vehicular efficiency.

Figure 18. Thru-cut intersection at South Main Street and Village Walk Drive in Holly Springs, NC.

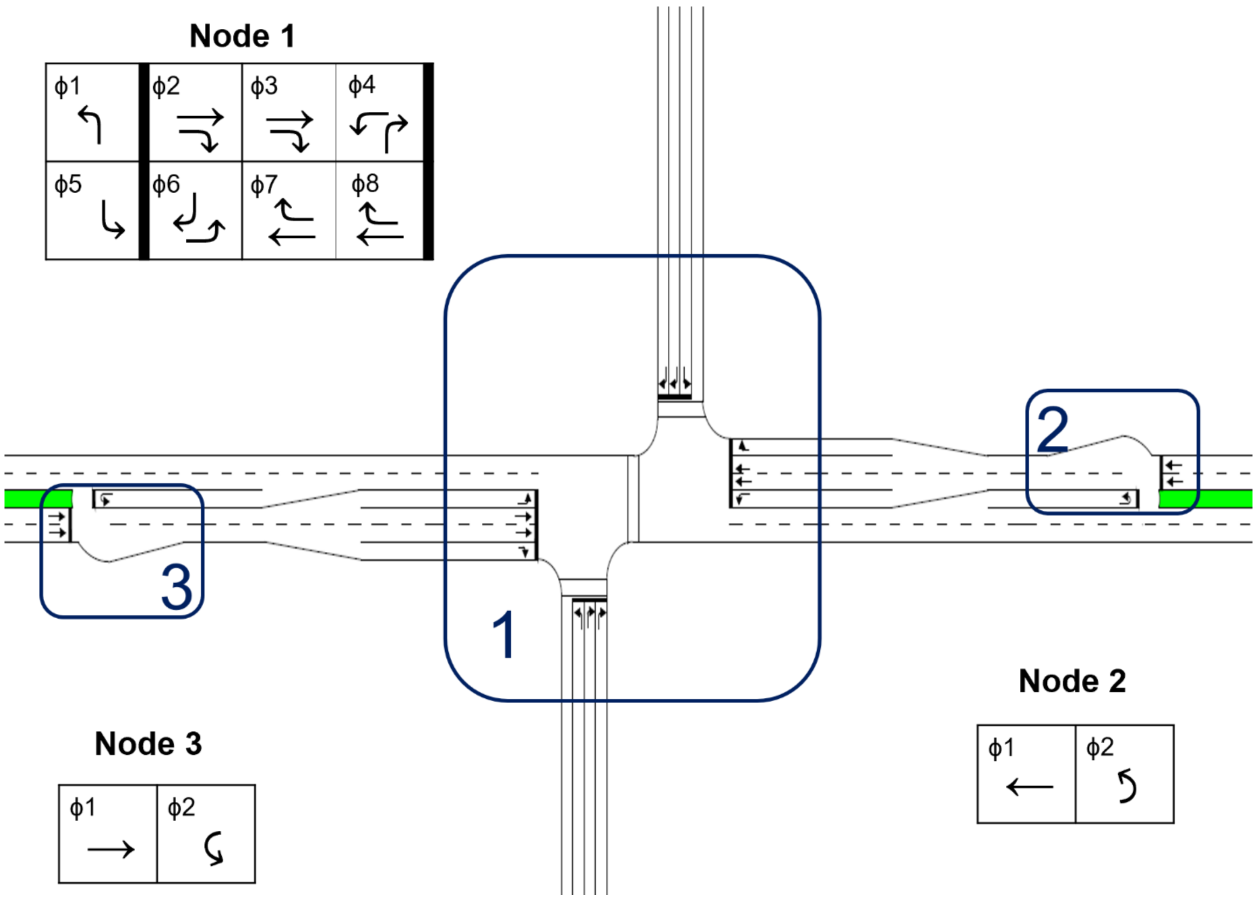


Figure 19. Sketch and signal phasing for an offset thru-cut intersection.

None of the newer three-phase designs is strong across all dimensions, so planners and engineers will need to continue to carefully select the best design for each spot of interest. Empirical data are thin on these six designs, especially in terms of safety data, in large part because they are so new, so hopefully as more are built in the next few years we will gather more information and be able to make more confident projections. When more empirical data are available they may show that one or more of these new three-phase designs is worthy of widespread implementation, delivering great benefits while reducing costs and impacts compared to the competitors.

Partial and Hybrid Alternatives

Partial and hybrid alternative designs also exist and could provide a great solution at a particular spot (48). We noted above that most CFIs in the US are actually the partial version with two left turn ramps, for example. A partial or hybrid design could be tailored to fit a spot that has unbalanced traffic demands or ROW challenges in one or two quadrants. A partial or hybrid design could also take advantage of the good features of an alternative design while mitigating its disadvantages, Several hybrid designs involving the QRI concept look promising. The first QRI installed in NC in 2012 included an RCI feature on its northeast side as Figure 20 shows. This was done, in part, to limit the number of signal phases at that northeast secondary intersection which had to have four legs. There is little sense in making a large effort to reduce the signal phases at the main intersection while allowing a secondary intersection to have four critical phases. Part a of Figure 21 shows a promising QRI and roundabout combination, while part b of Figure 21 shows a QRI with one u-turn crossover. The QRI with one u-turn crossover is particularly promising because it redirects a left turn movement to the u-turn crossover that would otherwise have to make a looping type of movement using the connector road thereby going through the main intersection twice.

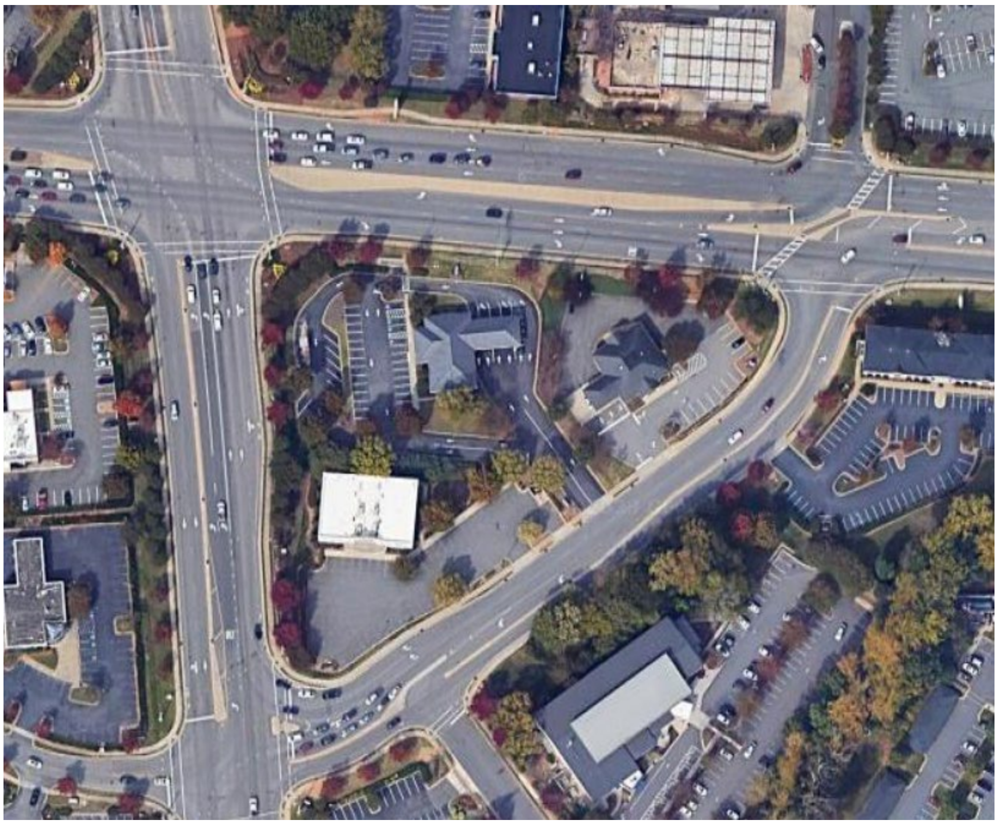
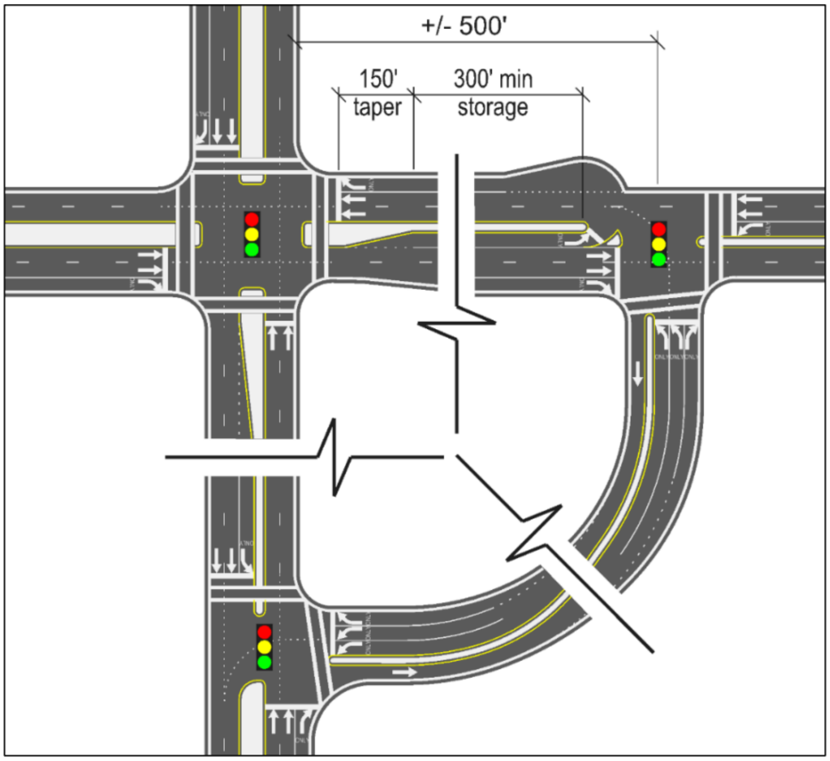
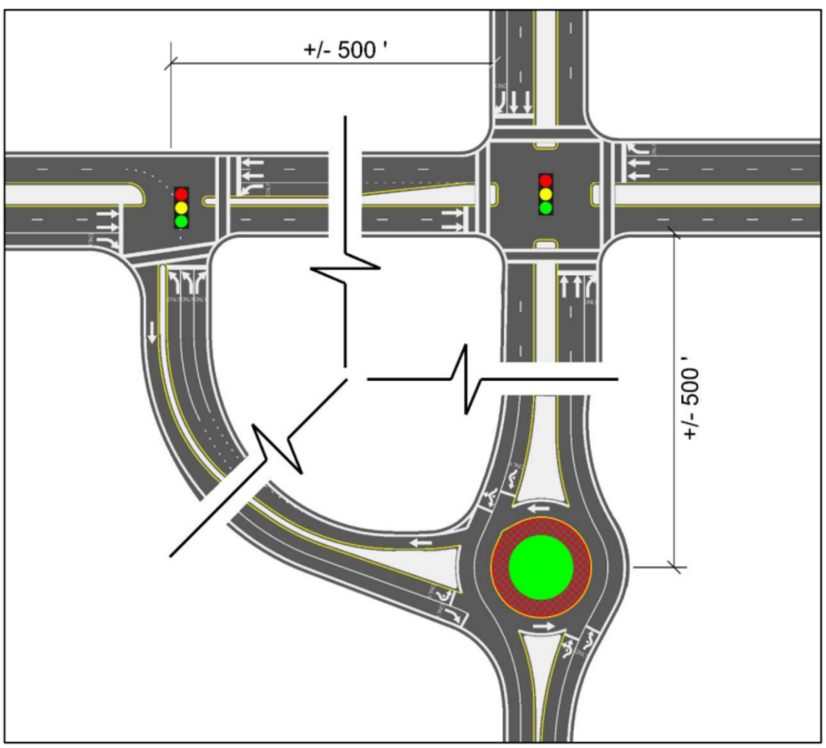


Figure 20. QRI that includes an RCI feature at US-21 and NC-73 in Huntersville, NC.



a. QRI with one u-turn crossover.



b. QRI with one roundabout at secondary junction.
Figure 21. A couple promising QRI hybrids (43).

Another promising hybrid concept combines CFI and MUT features as Figure 22 shows. This concept is being designed as of 2023 for locations in Divisions 7 (as shown in Figure 22) and 10. The idea is to redirect a very heavy left turn movement to the CFI left turn crossover while redirecting the opposing left turn movement, which hopefully has a much lighter demand, to the u-turn crossover. With this design, most impacts are confined to one leg of the intersection and the main signal has three critical phases. This CFI and MUT combination boosts capacity compared to a conventional intersection while treating pedestrians and nearby businesses relatively well.

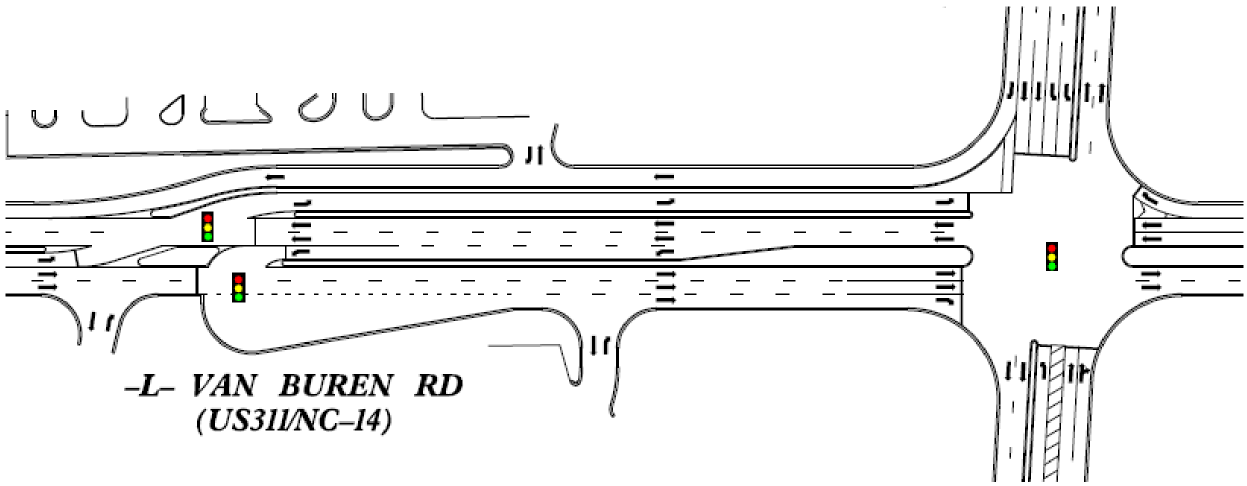


Figure 22. CFI and MUT combination concept for Eden, NC.

Dual Left Turn Lanes, Including Positive Offset and Dynamic Left Turn Intersections

Dual left turn lanes are a popular option to add capacity at an intersection with single left turn lanes. Of course, there needs to be at least two receiving lanes as well. Project teams can consider adding a second receiving lane of finite length to a leg that only has one such lane, but should make sure that the added lane is long enough to encourage use and not create safety issues. NCHRP Report 707 provides equations to estimate the usage of short receiving lanes (49).

A recent study by the NCDOT Traffic Safety Unit provided a CMF for the addition of a second left turn lane. Previously, the available safety information had been older and of lower quality. The Safety Unit study included 14 sites across NC at which a second left turn lane had been added to one approach but nothing else substantial had changed from the before to the after period. The Safety Unit used a good analysis method; once the study is loaded into the CMF Clearinghouse it should receive a high score for quality. The CMF for total crashes at the entire intersection was 1.00 and the CMF for injury crashes was 0.98, indicating that the addition of a second left turn lane on an approach will likely result in no real safety change. Projects to add dual left turn lanes may help efficiency but do not appear to move the needle on safety.

Project teams considering using dual left turn lanes on an approach to a signalized intersection should be aware that there are several options for how to operate those lanes. The conventional method of operation has been to use protected left turn signals throughout the day when there are dual left turn lanes.

However, this often results in significant excess delay during non-peak hours when the signal serves the left turn phase with low left turn demand, and can also contribute to additional delay during peak periods at certain locations. Other options that might reduce delay at approaches with two existing or potential left turn lanes include:

- Operating both left turn lanes with protected-permissive signal control--either all day or during portions of the day—if the sight distance for left-turning vehicles from both left turn lanes is good, oncoming through demands are lower (at least during non-peak times), and oncoming through speeds are not high;
- Striping out one left turn lane and operating the remaining left turn lane as a positive offset single left with protected-permissive or permissive signal control if the sight distance for left-turning vehicles is good and the peak-hour left turn demands are not too high; or
- Operating a “dynamic left turn intersection” (DLTi) approach.

A DLTi is a new way to operate an intersection approach with dual left turn lanes. With a DLTi, both left turn lanes are operated with protected-only phasing during peak and potentially other higher volume periods when more capacity is needed. During lower volume periods, only the left-most left turn lane remains open, under protected-permissive or permissive operations. Figure 23 shows the main traffic control devices for the DLTi. These devices include changeable lane control signs over both left turn lanes. The signs over the right-most left turn lane change from showing a white arrow during peak periods, indicating that this is a lane from which to make left turns, to a red X under lower volume times, indicating that the lane is closed. LED lane control signals over the left-most left turn lane, which is always open for left turns, always display a white left turn arrow (note that Figure 23 shows a static rather than LED sign over the left-most left turn lane). There are two sets of changeable lane control signs, one on span wire near the entry to the left turn lanes and one on the signal span on the far side of the intersection next to the traffic signal displays. A static black-on-white sign that says, “LANE CLOSED ON RED X” can be posted next to the changeable lane use sign over the right-most left turn lane. The traffic signal controlling both left turn lanes is a single four-section display hung over the lane line between the two left turn lanes. The signal suppresses the flashing yellow arrow during peak periods (i.e., operated as protected-only) and will display a flashing yellow arrow during non-peak periods (i.e., operated as protected-permissive). Enhanced pavement markings help guide vehicles through the DLTi. A DLTi might be a good option for project teams to consider when there is too much left turn demand for all-day single-lane operation and permissive turns from one left turn lane are feasible, but permissive left turns from both left turn lanes are infeasible or challenging. An informational report summarizing the options for operating dual left turn lanes has been posted on the Congestion Management website (50).

Figure 23. Main traffic control devices for the DLTi.

Intersections on Undivided Four-Lane Arterials

In North Carolina, there were over 800 miles of state roads with undivided four-lane cross-sections as of 2020 and many more miles on city streets. Unfortunately, safety, operations, and pedestrian service are often poor on such roadways. On safety, four-lane undivided is among the worst cross-sections, with crash rates almost twice as high as other common cross-sections in urban areas in North Carolina (51). The reasons for those awful rates include frequent lane changing, long queues, unexpected stops, mostly permissive left turns, motorists reaching high speeds between queues to make up wasted time, and head-on crash potential.

Undivided four-lane roads operate poorly in large part because with more than minimal left turn demand they see a large loss of capacity at intersections. The left lane often becomes a de-facto left turn lane, unless typical split-phase signals are used on the major street which in turn means a large loss of capacity. Progression through several signals, a huge factor in helping reduce delay and control speeds on many arterials, is often impossible on urban undivided four-lane arterials due to poor signal spacing and lack of capacity.

Pedestrian service is often poor in urban undivided four-lane corridors despite the fact that such corridors often serve larger pedestrian demands. The cross-section makes it difficult to build median refuges for crossing pedestrians. There are numerous conflicts with turning vehicles at the intersections. Unsignalized midblock crossings are typically discouraged in such corridors, and agencies may be reluctant to add signalized or active midblock crossings that would add even more motorist delay.

Adding urgency, many urban undivided four-lane corridors with poor vehicle and pedestrian service are located in communities with high minority and lower-income populations. The aging and ill-suited roadway likely contributes to depressed property values and business opportunities in such corridors. Projects to improve the roadway could help struggling communities.

The standard treatment for an urban undivided four-lane arterial with a lower demand is a four-lane to three-lane restriping road diet. There is a large available literature on road diets and many such examples, most successful, improving safety, efficiency, pedestrian experience, and livability. However, four-to-three road diets have a maximum feasible demand, above which the congestion created is usually intolerable. In North Carolina, that threshold is 20,000 vehicles per day (vpd). With a demand above 20,000 vpd, the available treatments are much less obvious. Widening on such corridors—to four lanes with a median or to five lanes--is often costly, impactful, and unpopular. On cost, with high prices for real estate these days a widening project in an urban setting can easily cost tens of millions of dollars per mile. A widening option may not help pedestrians much either.

Table 9 shows 15 possible treatments on an urban undivided four-lane arterial when a road diet or widening are infeasible. No treatment is perfect, and project teams will often need to mix and match the treatments to achieve good results. The treatments fall into three general categories, including restriping (treatments 1-5), roundabouts (treatments 6-8), and redirecting movements (treatments 9-15). When they are available, Table 9 provides high-quality CMFs for a treatment; as noted earlier a CMF is the ratio of the crash frequency after a treatment to that before a treatment. While some treatments are familiar and common, others are new or rare. Most of the treatments are attempts to either get through drivers to use both lanes or to allow agencies to acquire right of way where it is more available and less impactful. The hope is that project teams will make the attempt to improve such corridors and not just choose the “do nothing” option when a road diet or widening are not feasible.

Most of the treatments should be familiar, but several are new or newer and likely require more explanation. Treatment 3 would restripe the cross-section to have two through lanes in one direction, a two-way left turn lane (TWLTL), and one through lane in the other direction. Treatment 11 is a new signal phasing idea as depicted in Figure 24. Treatment 11 would redirect minor street left turn and through movements and would require a two-stage pedestrian crossing of the major street but would result in full usage of both major street lanes and plentiful green time for those major street movements. We should note that Treatments 10, 11, and 12 all rely on redirected movements and may be expensive if crossovers or roundabouts have to be built for the u-turns but could be relatively low cost if the redirected movements can be handled using existing connecting streets. Finally, Figure 25 provides a sketch of Treatment 14, a u-turn crossover with a full signal, which is an adaptation of a jughandle intersection concept. The advantage of Treatment 14 over Treatment 13, a typical u-turn crossover, is that number 14 does not need a large bulb-out and should therefore have much lower costs and impacts.

Table 9. Summary of 15 potential treatments for intersections on undivided four-lane arterials.

No.	Name	Conditions	Potential effects compared to undivided four-lane with conventional signals			
			Safety	Operations	Pedestrians	Cost and impacts
1	Four-to-five restriping	Existing width 48 ft or more	CMF of 0.5 for total crashes (52)	Large added capacity	Can install islands in center lane	Relatively inexpensive
2	Add median	Existing width 44-48 ft	No published CMF; effects are unclear	No change	Could provide refuge in median	Relatively inexpensive
3	2-1-1 configuration	Peak demand higher in one direction than other	No published CMF; likely improved safety	Larger capacity in one direction	Can install islands in center lane	Relatively inexpensive
4	Road diet with extra lane at large intersection	Extra lane could be left turn, through, or right turn lane	No published CMF; likely improved safety	Some added capacity	No change	Relatively inexpensive
5	Reversible lanes	2-1-1 during one peak becomes 1-1-2 in other peak	CMFs of 1.3 for total and injury crashes (53)	Large added capacity	No change	More expensive than just restriping
6	Roundabout at intersection	2-1-2-1 configuration around circle	Average CMF of 0.89 for total and 0.54 for injury crashes (Table 2)	Capacity similar, delays lower	Somewhat improved (54)	Relatively high cost
7	Midblock roundabout	Facilitate u-turns	No published CMF; likely improved safety	High capacity	Good additional crossing opportunities	Lower cost than roundabout at intersection
8	Bowtie intersection	Two roundabouts on minor street, no left turns at main intersection	Likely similar to MUT	High capacity, two-phase signal	Like a MUT, excellent for pedestrians	High cost for roundabouts

Table 9. Continued.

No.	Name	Conditions	Potential effects compared to undivided four-lane with conventional signals			
			Safety	Operations	Pedestrians	Cost and impacts
9	MUT intersection	U-turns on major street, no left turns at main intersection	CMF of 0.63 for total and 0.77 for injury crashes (25)	High capacity, two-phase signal	Excellent for pedestrians (54)	High cost for u-turn crossovers or roundabouts
10	Partial MUT	Redirect left turns from major street	No published CMF; likely improved safety	Some added capacity	Like a MUT, excellent for pedestrians	High cost if u-turn crossovers or roundabouts needed
11	Two-phase split-phase signal (Figure 24)	Redirect left turn and through movements from minor street; need pedestrian refuge	No published CMF; likely improved safety	Large added capacity, progression depends on signal spacing	Two-stage crossing, but short delays	High cost if u-turn crossovers or roundabouts needed
12	Right-in-right-out	Median or channelization	CMF of 0.55 for total crashes (20)	Effects depend on how redirected movements are made	Could provide refuge in median	High cost if u-turn crossovers or roundabouts needed
13	U-turn crossover with half-signal	Could be unsignalized; large bulb-out needed	Good safety record as part of other designs	High capacity, easy to progress	Could install crosswalk with crossover	High cost for u-turn crossover
14	U-turn crossover with full two-phase signal (Figure 25)	Needs great signing to direct u-turning drivers to right	No published CMF; effects are unclear	Capacity not as high as half-signal	Could install crosswalk with crossover	Lower cost; may only need 20 ft extra on each side of road
15	Midblock pedestrian crossing	Median 6 ft or wider	CMF with ped hybrid beacon was 0.88 for total and 0.81 for injury crashes (55)	Minimal effects	Excellent for pedestrians	Relatively inexpensive, but some cost to provide median

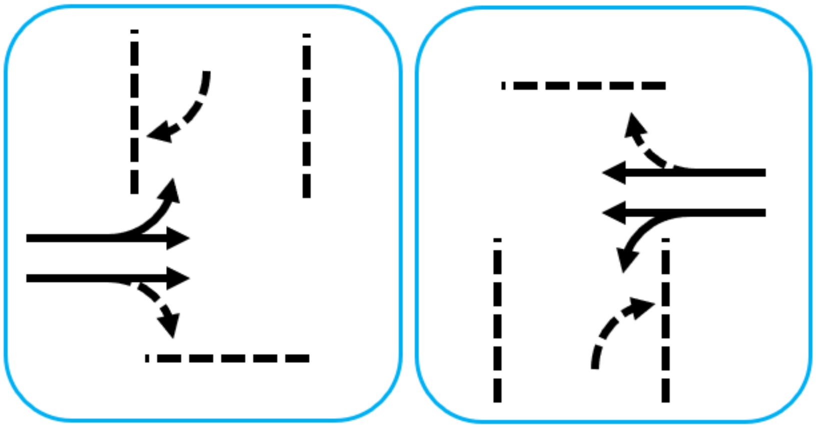


Figure 24. Signal phasing diagram for a two-phase split-phase treatment, assuming an east-west arterial. Note that solid arrows represent protected vehicle movements, dashed arrows represent permissive vehicle movements, and dashed lines represent pedestrian movements.

Figure 25. A u-turn crossover with a full signal.
Note that crosswalks and sidewalks are indicated with a dashed line.

Grade-Separated Intersections

An intersection between two non-freeways that uses a bridge for at least one of the movements is called a grade-separated intersection. In most cases the bridge separates the through movements on one street from the through movements on the other street. Based on a recent inventory by the author, North Carolina has over 160 grade-separated intersections, with more in the project pipeline. Grade-separated intersections are more costly and impactful than at-grade intersections, but usually provide superior capacity, shorter travel times, and maybe fewer crashes.

Analysts and designers can typically use an interchange design at a grade-separated intersection spot, whereby one or both streets have only merges and diverges. However, this often causes problems including:

- Weaving demands after a merge,
- Speeding on a street with merges and diverges that feels like a freeway to drivers,
- Failure to meter traffic demands heading toward the next signal,

- Pedestrians crossing ramp terminals, especially with merging and diverging,
- Bicyclists crossing ramp terminals, especially with merging and diverging,
- Large ROW, and
- Long frontage distances where driveways and side streets are not allowed.

Given the above list, grade-separated intersection designs that are not interchanges, minimizing or eliminating merges and diverges, are becoming more common in project discussions at NCDOT.

Most grade-separated intersections in North Carolina that are not interchange designs use a connector road to handle all turning movements, with a bridge carrying one street over the other. Figure 26 shows an example. The connector road design has many virtues and should be considered during some grade-separated intersection projects.

Figure 26. Example grade-separated intersection using a connector road (Hillsborough Road at Hillandale Road in Durham).

CAP-X (2) includes two grade-separated intersections in its menu: the echelon and the center turn overpass. These are interesting designs that have many virtues, but they are also patented (as of 2021) so analysts and designers need to be cautious of the legal situation before choosing one of them. Fortunately, once we consider combinations of movements, there are dozens of other interesting grade-separated intersection alternatives. For example, Figure 27 shows a design proposed by Eyler (56) with single-point-style left turns on the top level (the north-south roadway in Figure 27) and MUT-style left turns (u-turn then right turn) on the bottom level. The sketch implies that the design could be compact and could serve pedestrians well. The design should also lead to efficient vehicle movements, as each through movement on the top level encounters one two-phase half-signal and each through movement on the bottom encounters two two-phase half-signals that are simple to coordinate with each other.

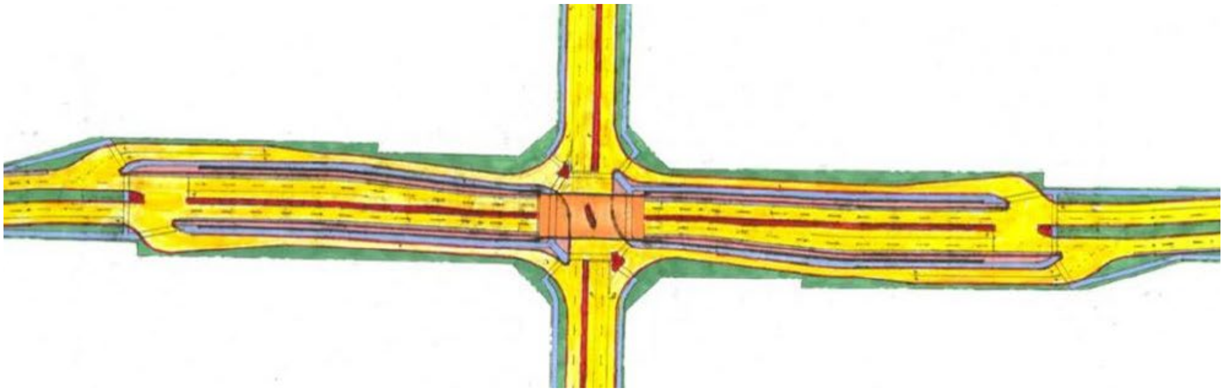


Figure 27. Grade-separated intersection with single-point left turns on top and MUT left turns on bottom (56).

Inspired by Eyler, one can generate a matrix of feasible grade-separated intersection designs by using different left turn techniques on the top and bottom levels. While there are well over ten different ways to make a left turn from one street to another, a research project sponsored by NCDOT (51) boiled the list down to seven ways that could apply to grade-separated intersections:

1. Diamond—a direct left turn past the bridge;
2. Single-point—the two left turns from one roadway are made in front of each other on or under the bridge;
3. Contraflow—the two left turns from one roadway pass to the left of each other;
4. CFI—as shown previously in Figure 14, a left turn crosses to the left of an opposing through movement well before the bridge;
5. U-turn then right turn—left-turning vehicles cross the bridge then use a u-turn crossover;
6. Contraflow u-turn then right turn—Like number 5 above except that the two traffic streams heading into the u-turn crossovers pass to the left of each other; and
7. Right turn then u-turn—Like the minor street approach at an RCI.

It is easy to see that the combination of one of these seven left turn methods on top with another on the bottom could mean 49 unique grade-separated intersection designs. Although some of the 49 combinations described above would not make much sense, some would seem to have great promise. Note that the combination of single-point left turns on the top and on the bottom is patented (57); the research project sponsored by NCDOT (57) checked for patents on the other 48 combinations to make sure analysts and designers can use them with no restrictions.

Project teams working on grade separated intersections should keep in mind that there is a wide variety of non-symmetric alternatives available as well. Figure 28 shows one such concept. It has only one loop, so the ROW need is modest, and needs only one full signal, which is on the minor street. All pedestrian crosswalks are signalized. The major street has only one half-signal in each direction so it provides high capacity with perfect progression capability. If project teams are willing to use non-symmetric alternatives with half-signals on the major street there are many outstanding potential designs.

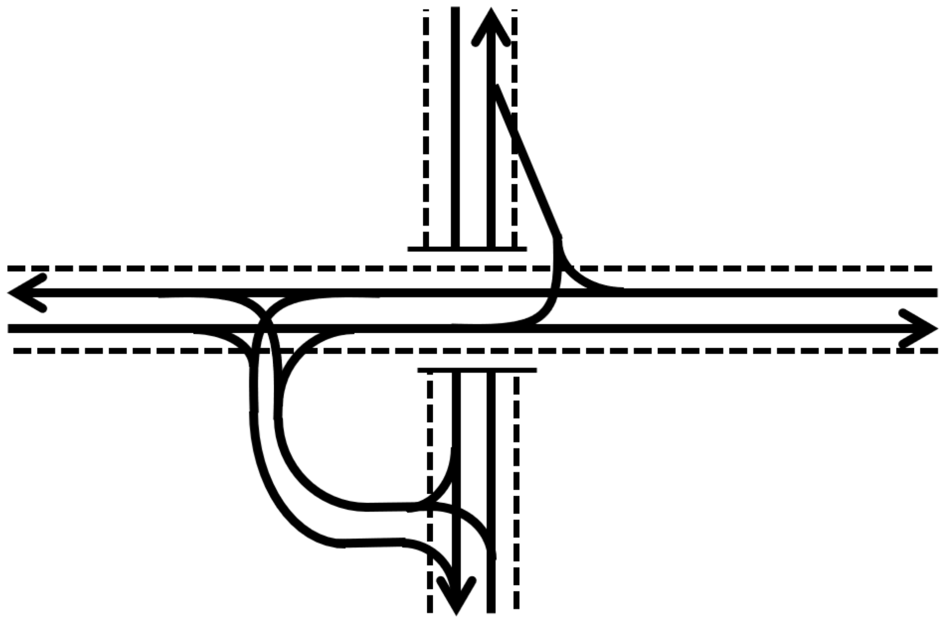


Figure 28. One loop grade separated intersection with one full signal.

INTERCHANGE ALTERNATIVES

Interchange analysts and designers have many factors to consider, but fortunately they have many configurations to choose from. The following paragraphs describe some of the basic interchange configurations and briefly describe their advantages and disadvantages.

Three-Legged

Many of the three-legged interchanges in use connect one freeway to another (also called system interchanges). There are two basic configurations of three-legged system interchange, the trumpet and the three-level, as Figure 29 shows. Trumpets have one left tum on a higher-speed indirect ramp and one left turn on a lower-speed loop ramp, so the lower volume left tum movement is typically relegated to the loop. At three-level interchanges both left turns use indirect ramps. At a three-level interchange, since there are no loop ramps both left turns can have higher design speeds but the construction cost is typically higher than for a trumpet because of the longer and higher bridges. Considering the relative advantages, analysts and designers typically use trumpets in lower-volume rural areas and three-level designs in higher-volume urban areas.

a. Trumpet b. Three-level

Figure 29. Common three-legged system interchanges.

The trumpet is a very efficient and relatively low-cost interchange and thus analysts and designers often use it to connect freeways to other roads (also called service interchanges). Other common designs for three-legged service interchanges include the diamond (see below) and a modified diamond with a roundabout on the top of the "T."

Four-Legged System Interchanges

There is a wide variety of four-legged freeway-to-freeway interchanges in place. Four common designs that are still considered for new interchanges or interchange retrofit projects include the cloverleaf, the single quadrant, the pinwheel, and the four-level as shown in the AASHTO "Green Book" (59). Note that for cloverleaf designs analysts and designers should at least strongly consider collector-distributor roads to avoid weaving areas on the freeway mainline roadways.

A fairly recent four-legged system interchange in North Carolina is the turbine. Figure 30 shows the turbine built at I-85 and I-485 in Charlotte. The turbine has many bridges, but fits in a smaller footprint than some other designs, the bridges are not tall, the ramp speeds can be higher, there are no weaving areas, and there are no left side exits or entrances (60). Thus, the turbine should be considered when projects must include the building or rebuilding of four-legged system interchanges.

Figure 30. Turbine interchange at I-85 and I-485 in Charlotte.

Four-Legged Service Interchanges

At service interchanges, analysts and designers can always use a system interchange design with all merges and diverges. However, that is often a bad idea, for the same reasons listed above that using an interchange design at the meeting of two non-freeways often does not work: it promotes weaving, it promotes high speeds, etc.

Most service interchanges are built using only ten or so concepts. National and state design policies and manuals contain only a few concepts. Diamonds are the most common concept in the US. Cloverleaf concepts with four loop ramps and partial cloverleaf concepts with two loop ramps are also common. Single points, diverging diamonds, and double roundabouts have emerged in the past several decades. However, the menu of service interchange concepts available to planners and designers is much more diverse than these typical ten. At least 15 other concepts have been constructed in the US that are known to the author, and at least ten others have been published.

The objective of this section is to show planners and designers engaged in a build or rebuild project the huge menu of service interchange concepts available to them. The section shows where the ideas for new concepts came from. The section then develops a scoring system so one can quickly screen alternatives to those that fit best in a certain spot. The section goes on to highlight some of the top concepts, including those that rated top overall and those that rated top for efficiency, safety, cost, and pedestrian service. Since several of the common concepts rated very poorly, the takeaway should be that planners and designers involved in building or rebuilding a service interchange should look at a wide range of possibilities before choosing a concept for construction. Service interchanges are too important to just settle for the same old concept.

Left Turns

We developed a large menu of service interchange concepts by first thinking about how left turns could be made at a service interchange. We came up with 14 typical ways a vehicle can make a left turn from the arterial to the freeway, as shown in Figure 31. The spacings referred to in Figure 31 are not arbitrary. A “tight” spacing with ramp terminals 200 feet or so apart gets the ramps off the bridge, so that there is no vehicle storage between terminals and so both terminals are controlled by a single signal. A “standard” spacing of 600 feet or so allows development of full-sized left turn lanes between the ramp terminals which are controlled by independent signals. A “spread” spacing with 1200 feet or so between terminals allows full-sized left turn lanes to begin beyond the bridge and/or allows room for loop ramps. Most of the left turns in Figure 31 should be familiar to most readers with the exception of “l”, which uses slip ramps and appeared at an interchange in the Milwaukee, WI metro area a few years ago and “m”, which appeared at an interchange near St. Augustine, FL recently. The authors then came up with 13 ways a vehicle can make a left turn from the freeway to the arterial, which includes “a” through “m” in Figure 31. Crossing the 14 lefts from the arterial with the 13 lefts from the freeway offered 182 possible interchange concepts. Sketches of all of those revealed that many were unrealistic, but 70 seemed to have potential, including most of those that are common, have been built (as far as we know), or have been published.

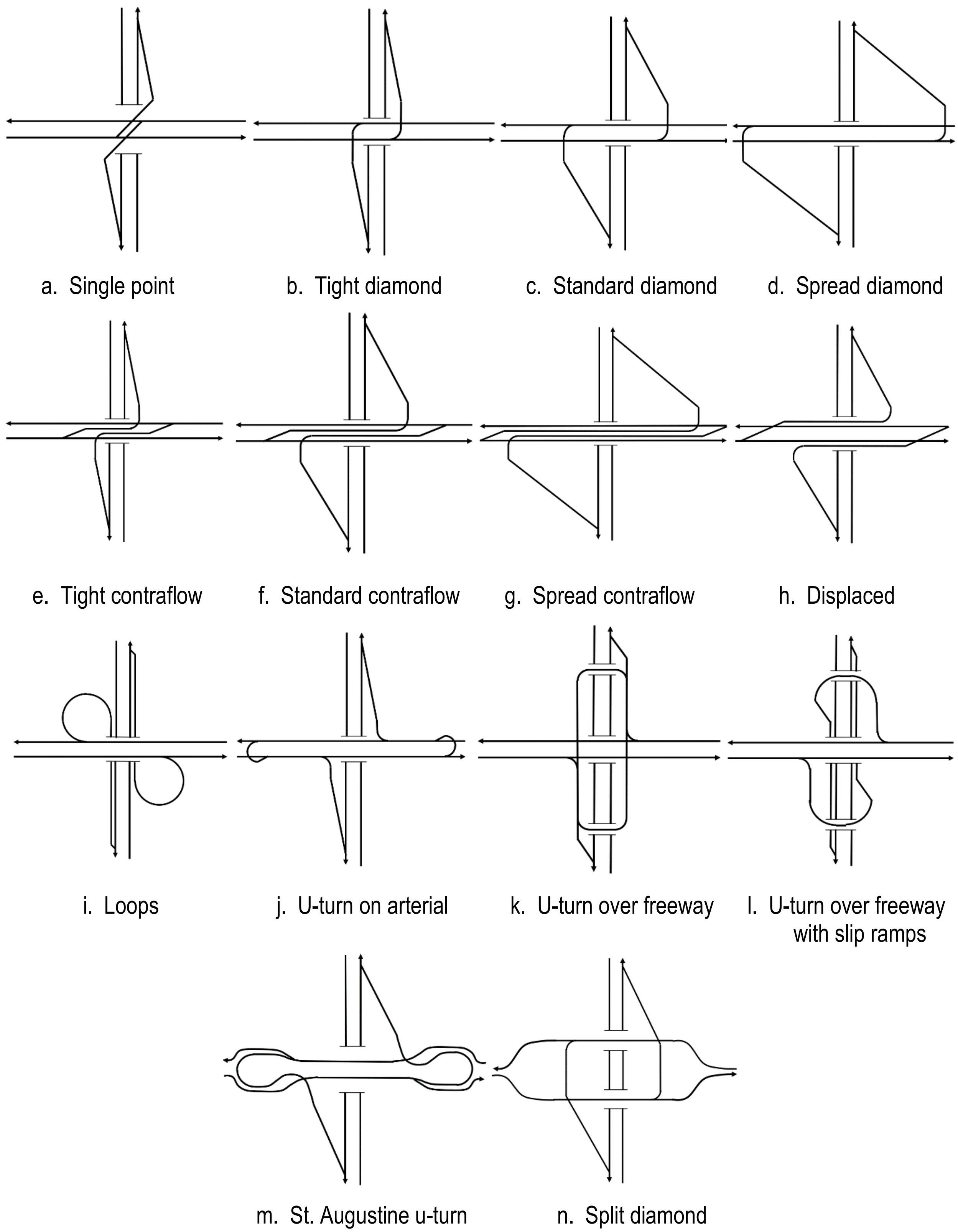


Figure 31. Fourteen feasible ways to make a left turn from the arterial to the freeway at an interchange. Note that the freeway runs top to bottom and the arterial runs side to side in all sketches in this section.

We then added to the menu through a trial-and-error process of looking for hybrids and asymmetrical ideas with potential. The concepts in the 14 by 13 matrix described above were all symmetric, in that the same ramp pattern occurred on each side of the freeway. However, there could be merit in asymmetric concepts with, for example, one loop ramp, three loop ramps, one u-turn crossover, one displaced left turn ramp, etc. We added other ideas such as roundabout concepts, diverging diamond concepts which cross two directions of travel, and three-level concepts that put the arterial through movement on a bridge over the freeway and ramps. Adding 38 promising asymmetric concepts to the 70 concepts from the 14 by 13 matrix led to a menu with 108 concepts. We challenge any reader with a promising new or different concept to contact us: we hope that the menu continues to grow through the years.

Rating System

To make sense of 108 concepts that looked promising, we developed a rating system. The ratings developed from the three basic objectives of most transportation projects, including maximizing the efficiency of vehicles moving through the spot, maximizing safety, and minimizing cost and impacts. Within these general areas, we defined three efficiency categories, four safety categories, and four cost and impact categories:

<u>Efficiency</u>

- Capacity,
- Signal progression,
- Distance travelled,

<u>Safety</u>

- Conflict points,
- Unusual driver maneuvers required,
- Wrong way potential,
- Pedestrian crossing quality,

<u>Cost and impacts</u>

- Bridge size,
- Right of way size,
- Extent along freeway, and
- Extent along arterial.

In each category, we specified a scoring system with 0 being the worst score and 5 being the best score, ensuring that the average score was 2 to 3 in most cases and that there was a wide range of scores. In scoring each concept, we examined a simple line sketch of a general concept rather than a detailed design or a particular application; it is possible that during a detailed process in a particular spot a designer could improve (or worsen) the scores earned by a particular concept. The goals during scoring were fairness and consistency. The 14 by 13 matrix, sketches of all 108 concepts, references to the previously published concepts, scoring criteria, and a spreadsheet of each concept scored in each category are posted at https://connect.ncdot.gov/resources/safety/Pages/Congestion-Management.aspx.

Overall Best Concepts

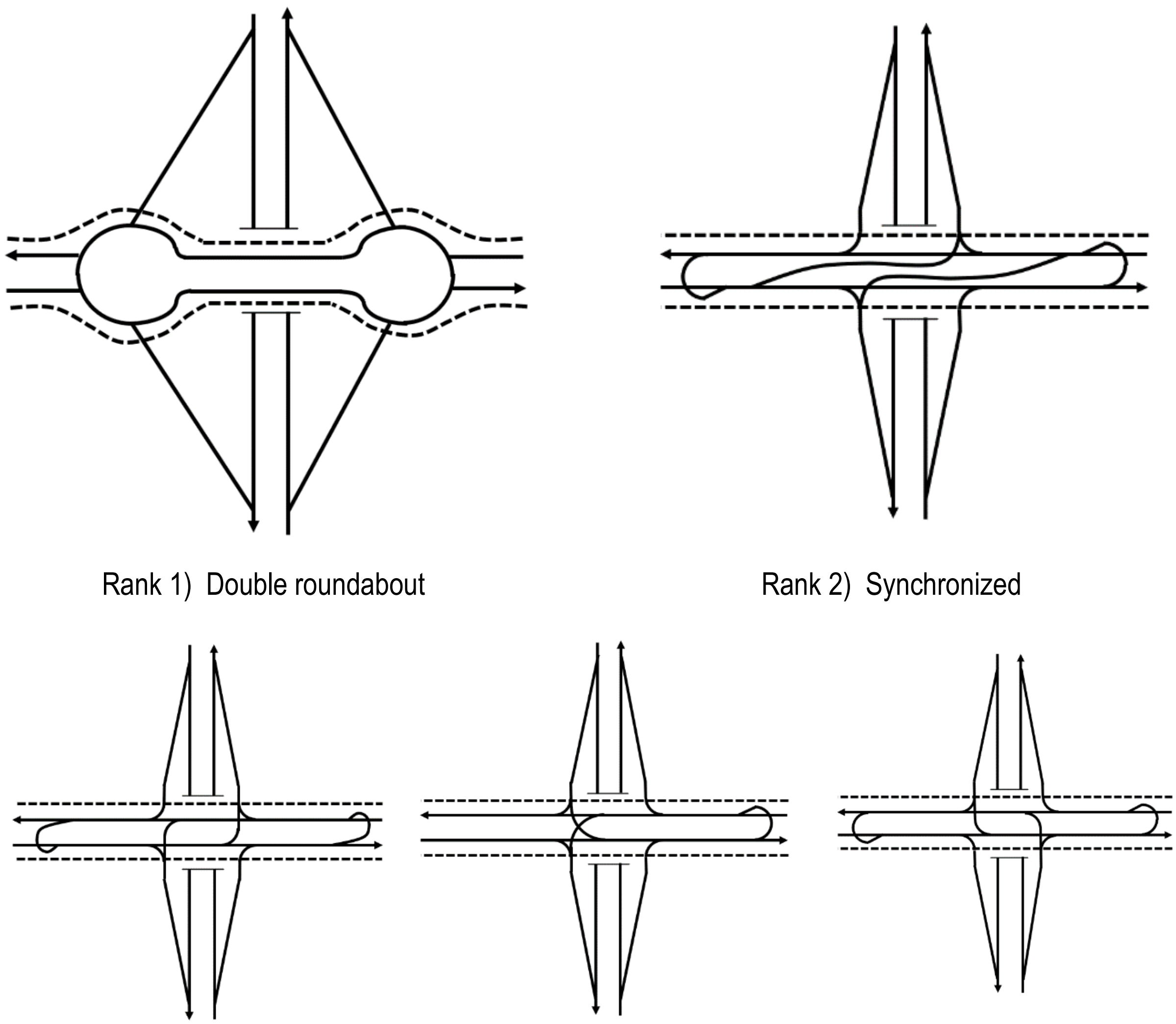
Table 10 shows the ratings for the overall top ten interchange concepts. The top-scoring concept is the relatively common double roundabout, which earned 44 of the possible 55 points and helps illustrate that there is no perfect concept. The double roundabout is a terrific design for safety and cost but is weaker in capacity so its niche is limited. The tight diamond was the other common concept that scored in the top ten overall. The tight diamond presents planners and designers with a clear trade-off of efficiency versus cost, having the lowest capacity of any of the 108 concepts and having top ratings in all four cost categories. In NCDOT projects recently, a trend has emerged whereby project teams are choosing double roundabouts in spots with low traffic demand but some available space, tight diamonds in spots with low traffic demand and minimal available space, and other concepts in spots with higher traffic demands.

Table 10. Ratings of the top ten overall service interchange concepts.

Interchange	History	Capacity	Progression	Distance Traveled	Conflict Points	Unusual Maneuvers	Wrong Way Potential	Pedestrian Quality	Bridge Size	Right of Way Size	Extent Along Freeway	Extent Along Arterial	Efficiency (of 15)	Safety (of 20)	Cost (of 20)	Total (of 55)	Rank (of 108)
Double roundabout	Common	2	5	4	5	5	4	3	5	4	4	3	11	17	16	44	1
Synchronized	Publ.	4	5	3	3	3	4	4	3	5	5	4	12	14	17	43	2
Tight dia., u-turn on art.	New	0	4	3	3	3	4	5	5	5	5	4	7	15	19	41	3
One u-turn	New	1	3	3	3	4	3	3	5	5	5	5	7	13	20	40	4
U-turn on art., tight dia.	New	1	3	3	3	3	3	5	5	5	5	4	7	14	19	40	5
Tight diamond	Common	0	2	5	1	4	3	5	5	5	5	5	7	13	20	40	6
Single roundabout	Rare	2	5	5	5	5	3	3	0	4	4	3	12	16	11	39	7
Superstreet	Publ.	2	5	2	3	4	4	4	4	4	4	3	9	15	15	39	8
Signalized FRE	Publ.	0	5	1	5	2	4	3	5	5	5	4	6	14	19	39	9
Split dia., tight contraflow	New	3	5	4	0	4	3	5	3	4	3	5	12	12	15	39	10

Note that "publ." means that the concept has been published but never built to the author's knowledge.

Figure 32 shows sketches of the high-ranked concepts from Table 10. The synchronized concept was published a few years ago (61) and has been examined by NCDOT during a couple of interchange rehab projects but has never been chosen, mostly due to the difficulty in obtaining room for two u-turn crossovers in built-up areas. However, the synchronized concept scores well in all categories—it does not have any major weaknesses. The superstreet (62) and signalized FRE (63) concepts in Figure 32 are similar to the synchronized concept. Many tight diamond variations scored well, including the two in Figure 32 that combine a tight diamond with u-turns on the arterial. The tight diamond with u-turns on the arterial concepts in Figure 32 scored well in every aspect except capacity. The one u-turn concept does not score as well as the synchronized concept for capacity but requires the agency to find room for only one u-turn crossover. The single roundabout concept in Figure 32 is popular in Europe but rare in the US. The single roundabout concept needs a large bridge, but otherwise performs well in most categories.



Rank 1) Double roundabout

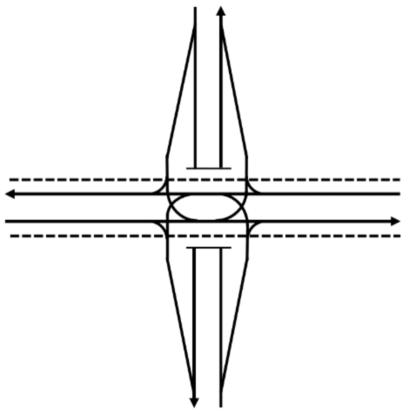
Rank 2) Synchronized

Rank 3) Tight diamond, u-turn

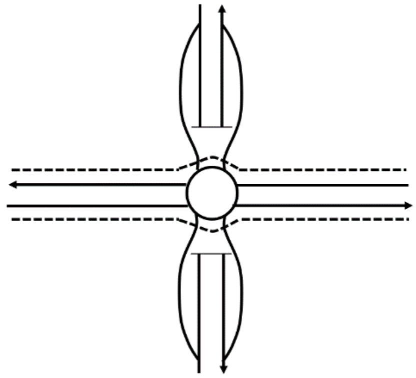
Rank 4) One u-turn on arterial

Rank 5) U-turn on arterial, tight diamond

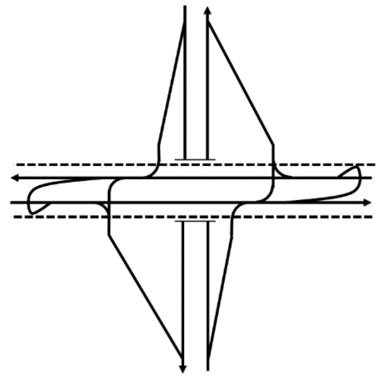
Figure 32. Top ten service interchanges in overall rank.
Dashed lines show walkways in diagrams throughout this section.



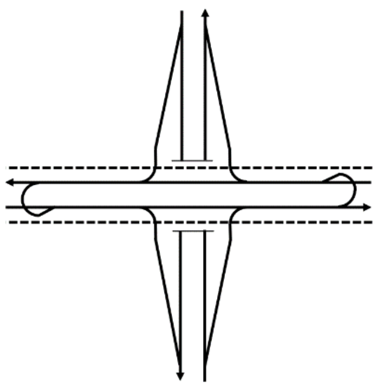
Rank 6) Tight diamond



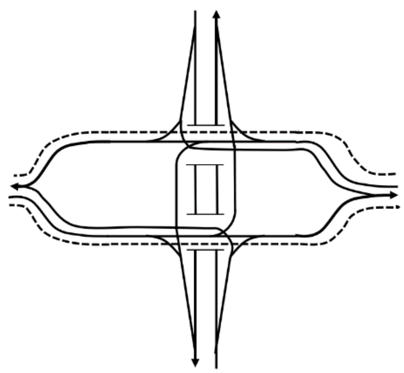
Rank 7) Single roundabout



Rank 8) Superstreet



Rank 9) Signalized FRE



Rank 10) Split diamond, tight contraflow

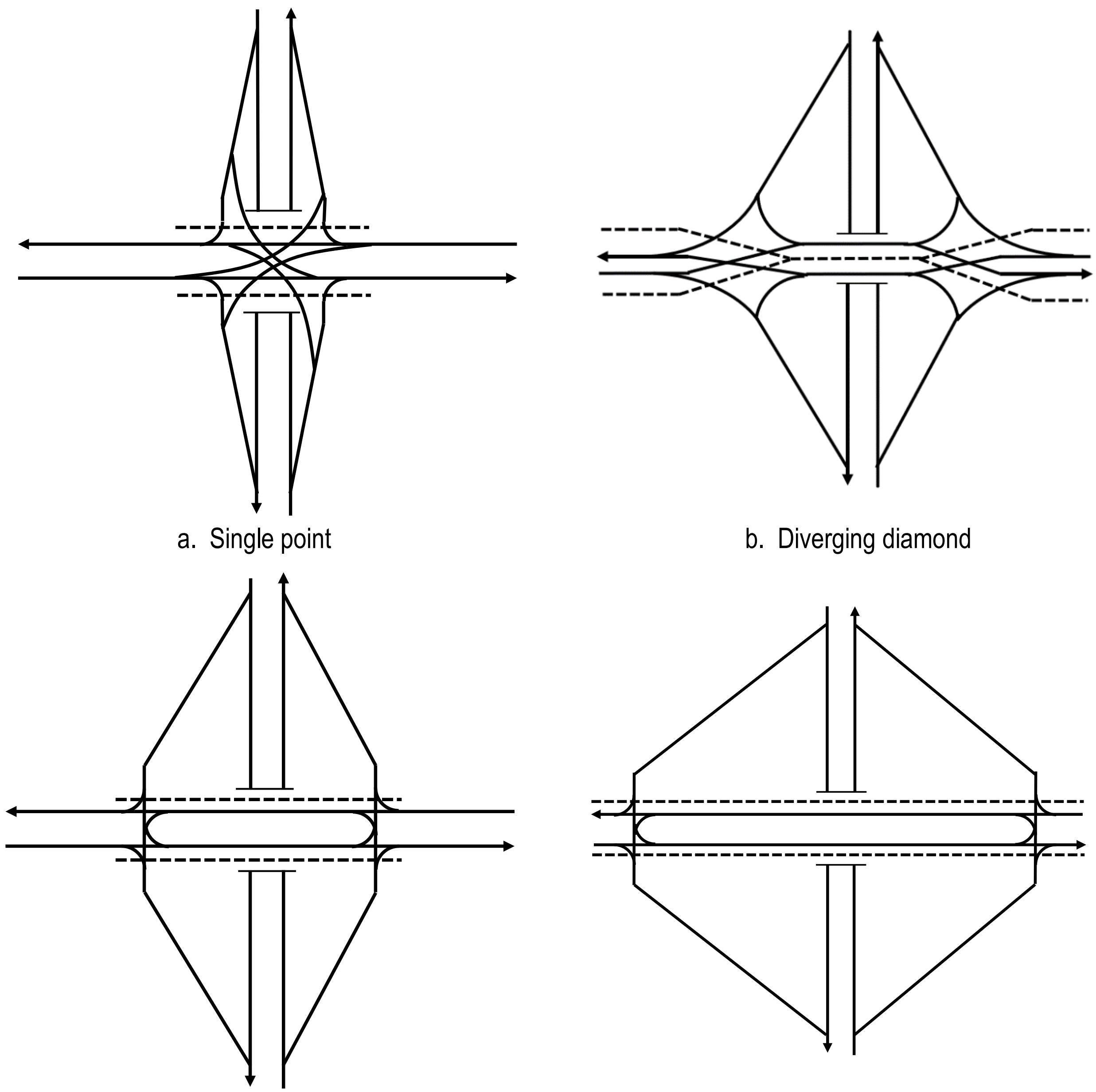
Figure 32. Continued.

Common Concepts

Table 11 shows the ratings of the other common concepts not shown in Table 10 and Figure 33 provides sketches. To explain the "parclo" nomenclature, the parclo B has two loop ramps that serve left turns from the freeway to the arterial, the parclo A has two loop ramps that serve left turns from the arterial to the freeway, and the parclo AB has two loop ramps that are both on one side of the arterial. The parclo B concept scored fairly well and ranked in the upper quartile of concepts overall. It could be costly but also should be relatively safe. The parclo A scored deep in the bottom half of interchanges; it should be just as costly as the parclo B while providing much worse progression and being somewhat less safe. The parclo AB scored even worse overall, with the lowest efficiency score of any of the 108 interchanges. The standard diamond, diverging diamond, and single point scored in the top half of concepts overall. They showed a pattern familiar to many who have worked on interchanges in that the standard diamond and diverging diamond did not score well for efficiency while the single point raised safety concerns. The spread diamond was near the bottom overall, presenting almost no advantage over a standard diamond in any category. Finally, the cloverleaf was overall the third from worst concept scored; at least project teams looking at an existing cloverleaf service interchange can think about a relatively low cost retrofit into something better.

Table 11. Ratings of the common service interchange concepts not shown in Table 10.

Interchange	Capacity	Progression	Distance Traveled	Conflict Points	Unusual Maneuvers	Wrong Way Potential	Pedestrian Quality	Bridge Size	Right of Way Size	Extent Along Freeway	Extent Along Arterial	Efficiency (of 15)	Safety (of 20)	Cost (of 20)	Total (of 55)	Rank (of 108)
Parclo B	4	5	1	3	5	4	3	5	2	2	2	10	15	11	36	21
Standard diamond	1	0	4	1	5	4	4	4	4	4	3	5	14	15	34	36
Diverging diamond	0	1	5	3	2	3	4	5	4	4	3	6	12	16	34	37
Single point	3	3	5	0	3	2	2	0	5	5	5	11	7	15	33	47
Parclo A	4	1	1	3	4	4	2	5	2	2	2	6	13	11	30	77
Parclo AB	1	1	0	1	3	3	5	4	2	5	3	2	12	14	28	93
Spread diamond	1	0	2	1	5	4	4	5	2	3	0	3	14	10	27	99
Cloverleaf	4	5	0	3	3	4	0	5	0	1	0	9	10	6	25	105



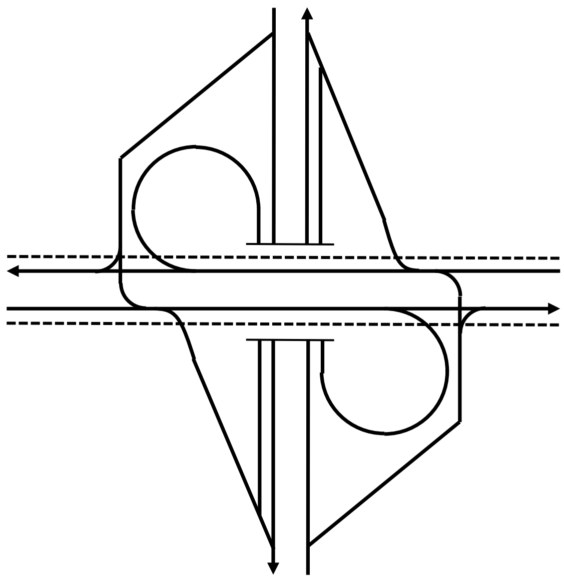
a. Single point

b. Diverging diamond

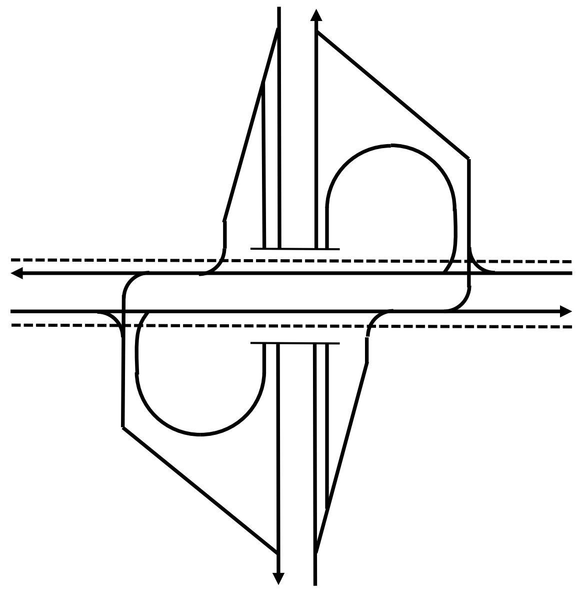
c. Standard diamond

d. Spread diamond

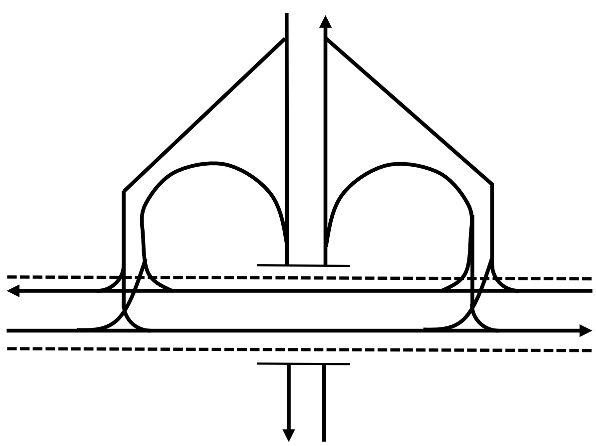
Figure 33. Common four-legged service interchange concepts.



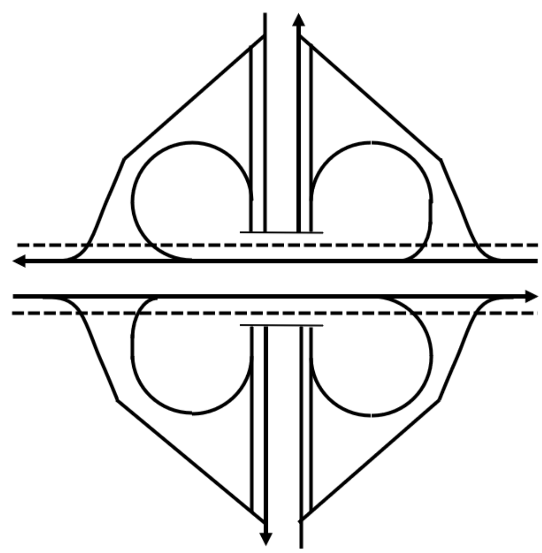
e. Parclo A



f. Parclo B



g. Parclo AB

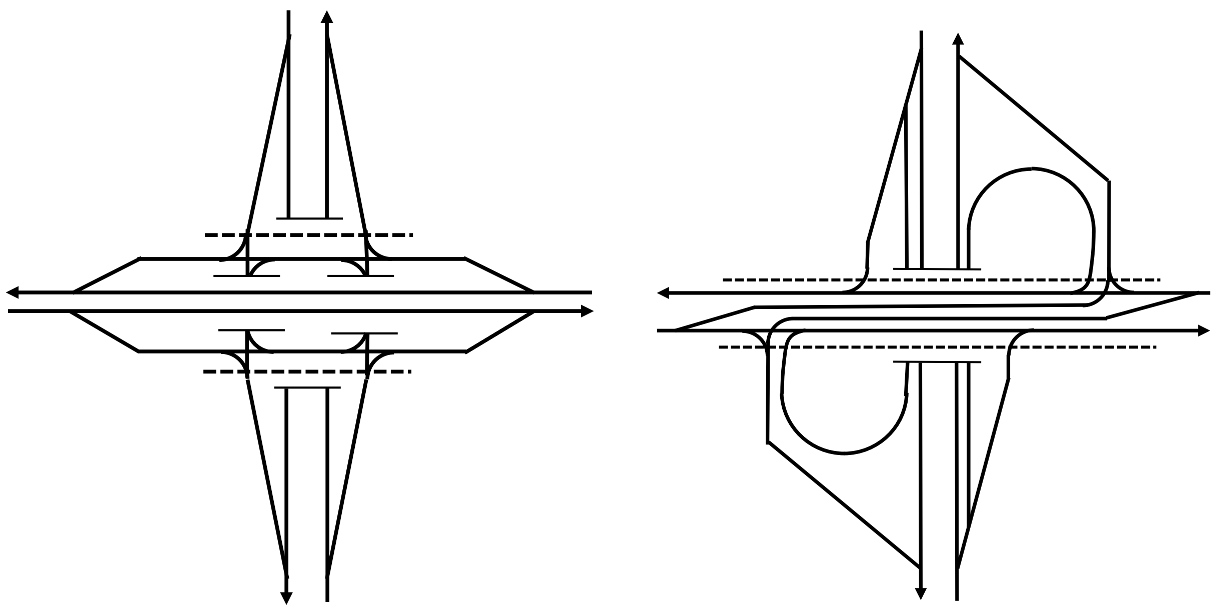


h. Cloverleaf

Figure 33. Continued.

Other Interesting Concepts

The top concepts for efficiency fell into two clusters. First, there were four variations of the three-level concept mentioned earlier that had ratings of 13 to 15 points for efficiency. Figure 34a shows a three-level interchange. Placing the arterial through movements onto their own bridge is an expensive undertaking but pays off in efficiency. Second, there were five interchange concepts that used displaced left turns (i.e., CFIs) and earned 13 or 14 points each for efficiency. Like three-level concepts, displaced left concepts tend to be costly, and sometimes the safety ratings are not stellar, but the displaced left turn ramps add capacity without extra driving distances. Finally, Figure 34b shows a folded interchange, which is an enhancement of a parclo B and scored a 5 for capacity and progression (64). A folded interchange could be a good cloverleaf retrofit.



a. Three-level interchange b. Folded interchange

Figure 34. Interchanges that rated well for efficiency.

Table 12 shows v/c values for some of the interchanges described in this section. The v/c values were calculated using critical lane analysis, for designs with two through lanes in each direction on the arterial and one exclusive turn lane for each movement, for demands of 1200 vph through in each direction on the arterial and 400 vph for each turning movement. Typically, v/c values at interchanges are highly related to demand in a linear fashion such that the pattern seen in Table 12 would also be seen at most demand levels.

Table 12. Example v/c for various service interchanges.

Interchange design	v/c
Parclo A, three-level, folded	0.65
Median u-turn	0.77
Parclo B	0.78
Synchronized	0.79
Single-point urban	0.83
Signalized FRE	0.94
Standard diamond, spread diamond, parclo AB	0.96
Single quadrant	0.97
Diverging diamond	1.03
Tight diamond	1.07

An interesting group of concepts that scored well on safety used u-turns on the arterial. Table 10 and Figure 32 previously described several of those concepts. Figure 3 shows another such concept, with spread diamond left turns from the arterial and u-turns for left turns from the freeway. The concept in Figure 35 earned 15 of 20 points in the safety categories and does not need extra right-of-way for the bulb-outs. Creative use of u-turns could be a way for agencies to retrofit an existing interchange and add safety.

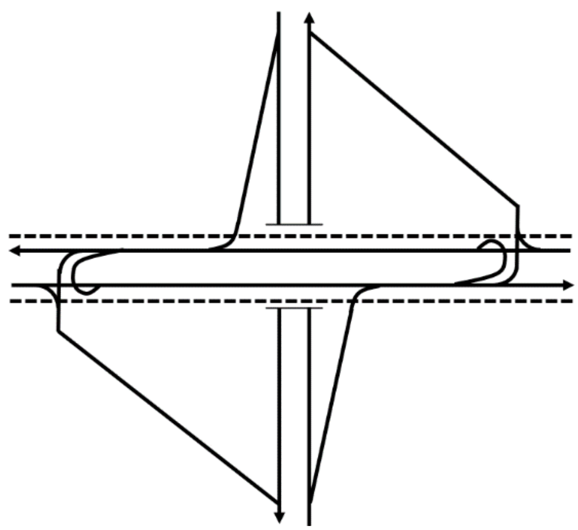
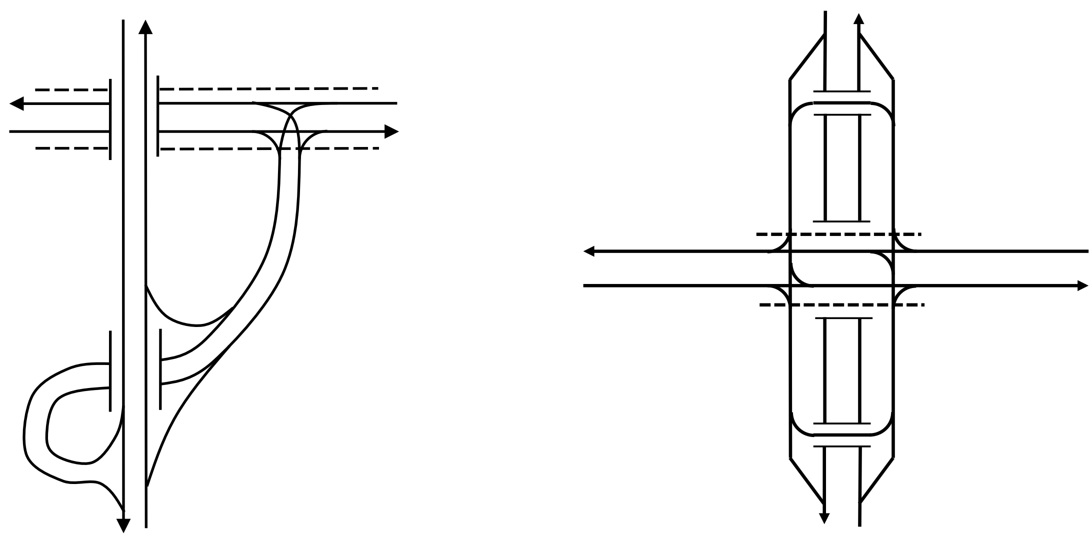


Figure 35. A concept with spread diamond left turns from the arterial and u-turns for left turns from the freeway that rated well for safety.

Top concepts for cost were the roundabout and tight diamond ideas as discussed above. Concepts that rated poorly for cost were those with multiple loop ramps and/or extra bridges.

It is important to highlight concepts that scored well or scored poorly for the quality of the pedestrian movement along the arterial. That score was based on the number of signalized road crossings and the number of unsignalized road crossings (applying judgement as to whether a typical agency would signalize a particular crossing). Twenty-one concepts earned a score of 5 in the pedestrian category. The best concepts for pedestrians were the two single quadrant concepts (with a connector road in one quadrant that serves all eight turning movements), which each have only one signalized crossing. Figure 36a shows the more common single quadrant interchange. A median u-turn interchange like shown in Figure 36b also scored 5 points for pedestrian quality and is common in other states. A number of tight diamond and parclo AB concepts also earned scores of 5 points, with only two signalized crossings each. On the other hand, nine concepts with multiple loop ramps and/or multiple displaced left turn ramps received only 1 point or 0 points for pedestrian movement quality, including the cloverleaf and a concept with three loop ramps that received 0 points and the displaced left interchange that received only 1 point. In areas where pedestrian demands are expected agencies should probably avoid those concepts or build alternate pedestrian paths.



a. Single quadrant interchange b. Median u-turn interchange

Figure 36. A couple interchange concepts that scored well for pedestrian service.

Service Interchange Summary

The objective of this section was to describe a larger menu of service interchange concepts than appears in most design policies and manuals. By thinking first about how left turns can be made, we assembled a menu of 108 service interchange concepts, posted on the Congestion Management website, that have some potential. Ten concepts are common, some have been built only a couple times as far as the authors know, some have only been published, and a majority of the concepts on the menu are new. To make sense of the large menu, we developed a scoring system using 11 efficiency, safety, and cost categories.

Project teams involved in selecting an interchange concept for a new build or rebuild should consult the menu before making a selection. Based on the scores, there is a wide range of performance between the concepts. There are some promising rare, published, or new concepts on the menu that look like they will perform well in most or all of the 11 categories. On the other hand, several of the concepts commonly used in NC and other states scored poorly overall or in some of the categories, indicating room for improvement.

We hope that this section is the beginning of the conversation on the service interchange menu, not the end. Readers with other concepts and other ideas on scoring should contact us. We plan to post regular updates to the menu and scores on the website so that project teams always have a chance to select the best concepts for their spots.

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