Developing, Using, and Improving Tables Showing the Safest Feasible Intersection Design

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Abstract

These days agencies are funding many projects to improve intersections. The traditional intersection transportation improvement program (TIP) project development process does not estimate the numbers of crashes associated with each of the various alternatives however. The lack of attention to safety performance is a shame because in recent years a large library of intersection safety studies has been assembled. To help intersection project teams use the available safety research results more often and effectively, the author assembled tables showing the safest feasible intersection design (SaFID) for each combination of major and minor street size and demand. The tables should prove to be quick and easy to use. The tables are dominated by four designs, including all-way stop control, roundabouts, reduced conflict intersections, and median u-turns. Two-way stop control is never the generally safest choice according to the current literature. A conventional signal only shows up in a small sliver of each table. Project teams should start their investigations of alternatives with a default design that the research shows to be the safest, and then examine other factors that are meaningful in a design decision. If a project team ends up choosing an alternative that is not the safest according to the research, they should have to document why they did that. Starting with consideration of the SaFID should mean that agencies end up building safer intersections.

Introduction

Like many agencies, the North Carolina Department of Transportation (NCDOT) is funding many transportation improvement program (TIP) projects to improve intersections and segments of arterials that contain intersections. The traditional TIP intersection or arterial project development process does not estimate the numbers of crashes that will be associated with each of the various alternatives however. Typically, the project team pulls and examines the crash data for the existing facility, usually concluding that there are too many crashes and thereby justifying some improvement. Also, the designers use the AASHTO "Green Book" (1) or some other policies and standards that are typically based on fundamental physical principles like friction between tires and pavement or sight distances to insure that the new design will meet nominal safety levels. As of this writing nine or so state DOTs have adopted intersection control evaluation (ICE) policies (2), and most of those policies require consideration of empirical safety research results. However, at NCDOT and likely in most of the other non-ICE states, rarely if ever does a TIP project team compare alternatives based on empirical safety evidence.

The lack of attention to empirical safety performance is a shame because 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" (3) 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 is mostly being ignored during project development.

To help intersection project teams use the available CMFs more often and effectively, the author assembled tables showing the safest feasible intersection design (SaFID) for each combination of size and demand on the major and minor streets. The tables 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 have to document why they did that. Starting with consideration of the safest feasible design may mean that agencies end up building safer intersections. The objective of this paper is to show the SaFID tables and provide background on how they were developed. The hope is that once agencies and project team see that using the SaFID tables and the related CMFs is quick and easy they will begin to do so regularly, adopt their policies and procedures accordingly, customize the tables to fit their circumstances, and improve the tables as more research is performed on more designs.

Sources

With two notable exceptions as described below, all the CMFs used to create the SaFID tables are from the CMF Clearinghouse (3). 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 1 shows the references used to assemble the SaFID tables from the Clearinghouse 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.

Table 1. 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	4	0.28	4 and 5
	Conventional signal	0.81	6-10	0.74	8-11
	One-lane roundabout	0.51	12-15	0.16	12
	Unsignalized RCI	0.58	16-18	0.42	16 and 18
Conventional signal	One-lane roundabout	0.74	19	0.45	19
	Two-lane roundabout	0.89	14 and 19	0.54	19 and 20
	Signalized RCI	0.85	21	0.78	21

The author considered two sources of CMFs not in the Clearinghouse in constructing the SaFID tables. First, the FHWA median u-turn (MUT) guidebook (22) contains a thorough review of the extensive safety research on that design, and implies average CMFs for the conversion from a conventional signal to a MUT of 0.85 for all crashes and 0.7 for injury crashes. Second, a 2015 research report for the Utah DOT (23) showed a CMF for all crashes for the conversion of a conventional intersection to a partial continuous flow intersection (CFI) of 0.88. The report did not provide a result for injury crashes. The analysis looks to be of relatively good quality, since it used Empirical Bayes methods on a large sample of crashes from eight sites. The partial CFIs examined in Utah had two left turn crossovers at each site.

The available set of CMFs described above captures most four-legged intersection designs used in the US as of 2020. In the CAP-X tool (24), published by FHWA, the only other four-legged intersection designs listed are full CFI (four left turn crossovers), quadrant, bowtie, and split. None of these is common in the US as of 2020. 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. Overall, with the possible exception of offset intersections, the assertion is that in the list above we have a pretty full set of CMFs for common and feasible at-grade intersection designs.

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

- All-way stop control (AWSC) is viable on two-lane roads with demands less than 7,500 vehicles per day (vpd) on each road, based on extensive North Carolina experience.
- Based on the latest national roundabout guide (25) a single-lane circle can handle up to 25,000 vpd total.
- Based on the latest national roundabout guide (25) a two-lane circle can handle up to 45,000 vpd total.
- Based on the FHWA guidebook (26) a signalized RCI can handle up to 25,000 vpd on the minor street.
- Four-lane minor streets should always be signalized in RCIs, while two-lane minor streets should be signalized at demands ranging from 3,000 to 11,000 vpd based on research conducted for the NCDOT (27).
- Because RCIs have superior signal progression and are not as vulnerable to driver confusion, median u-turn intersections only become feasible at minor street demands above 25,000 vpd.
- Because RCIs have superior signal progression and pedestrian service, continuous flow intersections only become feasible at minor street demands above 25,000 vpd.

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 tables is 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 Tables

Table 2 shows the SaFID table based on all crashes, while Table 3 shows the SaFID table based on injury crashes. Both tables show the safest feasible intersection design based on the available research as described above for any combination of major street and minor street number of through lanes and vehicle demand. The demands are in terms of average annual daily traffic, or AADT, in vehicles per day. The CMF values displayed are for the conversion of a conventional signalized intersection to the design named in the cell.

Table 2. Safest feasible intersection design (SaFID) based on all crashes.

				Minor street									
			Number through lanes:	2				4				6	8
Major street			Low AADT:	0	5,000	7,500	10,000	10,000	15,000	20,000	25,000 and above	Any	Any
Number through lanes	Low AADT	High AADT	High AADT:	5,000	7,500	10,000	15,000	15,000	20,000	25,000			
2	0	7,500	**Safest**	**All-way stop**	**All-way stop**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			CMF	0.4	0.4								
	7,500	10,000	**Safest**	**One-lane roundabout**	**One-lane roundabout**	**One-lane roundabout**	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			CMF	0.7	0.7	0.7							
	10,000	15,000	**Safest**	**One-lane roundabout**	**One-lane roundabout**	**One-lane roundabout**	**One-lane roundabout***	n/a	n/a	n/a	n/a	n/a	n/a
			CMF	0.7	0.7	0.7	0.7						
4	10,000	15,000	**Safest**	**Unsignalized RCI**	**Unsignalized RCI**	**Unsignalized RCI**	**Signalized RCI**	**Signalized RCI**	n/a	n/a	n/a	n/a	n/a
			CMF	0.7	0.7	0.7	0.8	0.8					
	15,000	20,000	**Safest**	**Unsignalized RCI**	**Unsignalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	n/a	n/a	n/a	n/a
			CMF	0.7	0.7	0.8	0.8	0.8	0.8				
	20,000	25,000	**Safest**	**Unsignalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	n/a	n/a	n/a
			CMF	0.7	0.8	0.8	0.8	0.8	0.8	0.8			
	25,000	30,000	**Safest**	**Unsignalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Median u-turn**	n/a	n/a
			CMF	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8		
	30,000 and above		**Safest**	**Unsignalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Median u-turn**	n/a	n/a
			CMF	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8		
6	Any		**Safest**	**Unsignalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Median u-turn**	**Median u-turn**	n/a
			CMF	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
8	Any		**Safest**	**Unsignalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Signalized RCI**	**Median u-turn**	**Median u-turn**	**Median u-turn**
			CMF	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

* One-lane roundabouts are generally feasible if the combined AADT is less than 25,000. If a one-lane roundabout is infeasible a signal is the safest feasible design.

Table 3. Safest feasible intersection design (SaFID) based on injury crashes.

				Minor street									
			Number through lanes:	2				4				6	8
Major street			Low AADT:	0	5,000	7,500	10,000	10,000	15,000	20,000	25,000 and above	Any	Any
Number through lanes	Low AADT	High AADT	High AADT:	5,000	7,500	10,000	15,000	15,000	20,000	25,000			
2	0	7,500	**Safest**	**All-way stop**	**All-way stop**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			CMF	0.4	0.4								
	7,500	10,000	**Safest**	**One-lane roundabout**	**One-lane roundabout**	**One-lane roundabout**	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			CMF	0.4	0.4	0.4							
	10,000	15,000	**Safest**	**One-lane roundabout**	**One-lane roundabout**	**One-lane roundabout**	**One-lane roundabout***	n/a	n/a	n/a	n/a	n/a	n/a
			CMF	0.4	0.4	0.4	0.4						
4	10,000	15,000	**Safest**	**Unsignalized RCI**	**Unsignalized RCI**	**Unsignalized RCI**	**Two-lane roundabout**	**Two-lane roundabout**	n/a	n/a	n/a	n/a	n/a
			CMF	0.5	0.5	0.5	0.5	0.5					
	15,000	20,000	**Safest**	**Unsignalized RCI**	**Unsignalized RCI**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout**	n/a	n/a	n/a	n/a
			CMF	0.5	0.5	0.5	0.5	0.5	0.5				
	20,000	25,000	**Safest**	**Unsignalized RCI**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout****	n/a	n/a	n/a
			CMF	0.5	0.5	0.5	0.5	0.5	0.5	0.5			
	25,000	30,000	**Safest**	**Unsignalized RCI**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout**	**Two-lane roundabout****	**Median u-turn**	**Median u-turn**	n/a	n/a
			CMF	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7		
	30,000 and above		**Safest**	**Unsignalized RCI**	**Two-lane roundabout****	**Two-lane roundabout****	**Two-lane roundabout****	**Two-lane roundabout****	**Median u-turn**	**Median u-turn**	**Median u-turn**	n/a	n/a
			CMF	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.7		
6	Any		**Safest**	**Unsignalized RCI**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	n/a
			CMF	0.5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
8	Any		**Safest**	**Unsignalized RCI**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**	**Median u-turn**
			CMF	0.5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7

* One-lane roundabouts are generally feasible if the combined AADT is less than 25,000. If a one-lane roundabout is infeasible a signal is the safest feasible design.

** Two-lane roundabouts are generally feasible if the combined AADT is less than 45,000. If a two-lane roundabout is infeasible a median u-turn is the safest feasible design.

Agencies and project teams can use Table 2 or Table 3 or both in their policies and project developments. In some cells the tables have the same entry, indicating that a design is generally safest using either all crashes or injury crashes. However, in some cells the two tables have different entries, so agencies and project teams will have to choose which is more important.

Tables 2 and 3 are dominated by four designs, including AWSC, roundabouts, RCIs, and MUTs. With two-lane major streets, AWSC or a one-lane roundabout is generally the safest choice. When the major street has four or more lanes, the RCI is the safest choice for a large swathe of the all-crash table and for a slice of the injury crash table. The multi-lane roundabout covers most of the four-lane major street portion of the injury crash table. A MUT is generally the safest design for all crashes when the minor street demands rise above 25,000 vpd or for injury crashes when the multi-lane roundabout is no longer feasible.

A TWSC design is never the generally safest choice according to the current literature. In other words, there is always a feasible design that has a lower CMF than a TWSC. A conventional signal only shows up in a small sliver of each table, at the very highest demand levels handled with two-lane major and minor streets, where a roundabout is not feasible.

Readers should note that even though the partial CFI did not appear in Table 2, it did not miss by much. The CMF from reference 22 for all crashes for a MUT is 0.85, while the CMF for a CFI from reference 23 is 0.88. Especially at very high demands with six-lane or eight lane roads, a partial CFI may well be a worthy choice for capacity without losing too much safety benefit.

Using the Tables

In view of the stated importance of safety to highway agencies across the US, the author urges those agencies to 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 not be the default designs. There are many reasons why an agency 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 agencies ought to be prepared to say why they did not end up building the safest feasible option. 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 Tables 2 and 3 is out of scope. Tables 2 and 3 apply 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 Tables 2 and 3 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 recent research results pointing out large errors in traffic forecasts (28), the safety results in the Clearinghouse might be some of the stronger models used during an intersection design process, not the weakest.

Intersection project teams should use Tables 2 and 3 early in the process in conjunction with a couple other tools that provide the capability to make quick judgments on different designs. For capacity, the CAP-X tool mentioned above (24) provides the capability to quickly judge which alternatives promise greater efficiency. For the quality of pedestrian and bicyclist service at intersection alternatives, the guidebook from NCHRP project 7-25 should be published in 2020 and should provide a quick but helpful look at any intersection design. Together, the SaFID tables, CAP-X, and the forthcoming NCHRP 7-25 guidebook provide a powerful suite of intersection design filters for early in project development.

Follow-Up Work

Tables 2 and 3 will hopefully prove helpful to intersection design teams, but they could be improved with several types of additional research to become even more helpful. First, more research on some designs already in the tables would be welcome. Tables 2 and 3 rely on only one good CMF for several designs, including, surprisingly, one-lane roundabouts, so more research to confirm previous findings would help. Second, we could use research on designs not considered in these tables, including offset intersections and quadrant intersections, that likely will be considered more often in the next few years. Third, we need research on the validity of combining CMFs, so that project teams can evaluate the safety of hybrid designs. For example, the NCDOT is moving forward with several combinations of CFI and MUT, and the Virginia DOT has one of those combinations under construction. If a design has two CFI left turn crossovers and two MUT u-turn crossovers, would it be accurate to average the existing CFI and MUT CMFs to estimate the safety of the overall design? Fourth, we have no CMFs and almost no safety research on grade-separated intersections (the junction of two non-freeways using a bridge), while many of these relatively high cost solutions are being proposed in North Carolina and elsewhere. Fifth, researchers should begin to derive CMFs for interchanges so an interchange SaFID table may be assembled. Currently, the only interchange form with available high-quality CMFs is the diverging diamond. Finally, work should continue on adequate crash surrogates to help designers estimate the crash potential of novel designs that have not been built yet. A recent paper based on research sponsored by the NCDOT (29) provided a start in this direction by deriving safety predictions based on the numbers of conflict points, the angles of those conflicts, and the vehicle demands at those points, but we clearly need more research before we have a viable product.

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