OPERATIONAL PERFORMANCE OF ALTERNATIVE TYPES OF INTERSECTIONS – A SYSTEMATIC COMPARISON FOR INDIANA CONDITIONS

by
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Paper presented at
the 4th International Symposium on Highway Geometric Design
Valencia, Spain, 5-9 June, 2010

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Topic areas: Basis for design policy/criteria; Operational and safety effects of highway design.

ABSTRACT

The growing traffic volumes and limited capacity of road intersections prompt highway engineers to look for solutions that are more efficient than conventional signalized intersections and less expensive than road interchanges. A number of alternative intersections have been proposed but none of them is universally superior. Guidelines are needed for making good initial selections to limit the number of design alternatives and to reduce the design cost. This paper presents research conducted at Purdue University aimed to developing guidelines to help designers in Indiana and other states in the initial selection process of alternative intersection types.

This study focuses on isolated signalized intersections of busy major and minor roads where capacity problems are likely and conventional intersections might not be the best solution. The study scope includes conventional intersections, roundabouts, median U-turns, far-sided jughandles, near-sided jughandles, and continuous-flow intersections. All the considered types of intersections except roundabouts are signalized.

This paper presents a practical approach based on a classification tree analysis to help designers select promising alternative intersections for given traffic conditions based on capacity, delays, and number of stops. The selected alternatives still have to be considered using other criteria such as cost, right-of-way, and safety. This approach can be applied to develop guidelines for Indiana conditions and for other states that have similar conditions. The paper also may be beneficial to researchers who develop guidelines for other states.

The research results indicate that continuous-flow intersections prevail in most cases over the other studied intersection types. In spite of a short three-second critical gap, the roundabouts turned out to have the lowest capacity among all the studied types of intersections. Traffic operations deteriorate more rapidly at roundabouts with increasing traffic volumes than at other intersections, including conventional ones. Jughandles, near-sided and far-sided, perform better than conventional intersections.

These conclusions are general and may not apply to all conditions. A catalog of scenarios was developed as part of the presented study to help select promising intersection types for specific traffic conditions.

INTRODUCTION

The growing traffic volumes and limited capacity of road intersections are prompting highway engineers to look for solutions that are more efficient than conventional signalized intersections and less expensive than road interchanges. Because left turning maneuvers at an intersection interfere with many other movements, alternative intersections often involve displacement of the left-turn movements from the primary intersection to additional minor intersections. This modification increases capacity but also increases the vehicles' paths and it may increase the number of stops. A number of alternative intersections have been implemented in other countries or recently proposed by other authors; for example, roundabouts, median U-turns, jug-handles, and continuous-flow intersections. All alternative intersections have advantages and disadvantages and no single one is universally superior. Road designers face a difficult dilemma between two options: (1) expensive designing of several alternatives in order to select the best among them and (2) limiting the number of design alternatives at the risk of omitting the best solution. Guidelines are needed to make a good initial selection to limit the number of design alternatives and to reduce the design cost. This paper presents research conducted at Purdue University that aimed to develop guidelines to help designers in the initial selection of alternative intersections types.

This study focused on isolated signalized intersections on busy arterial roads crossing minor roads where capacity problems are likely and conventional intersections might not be the best solution. Several alternative intersection types are included in the scope of the study: conventional intersections, roundabouts, median U-turns, far-sided jughandles, near-sided jughandles, and continuous-flow intersections. The research focus is on identifying effective intersections that can accommodate significant traffic volumes at a satisfactory level of quality. Therefore, all the considered types of intersections, except roundabouts, are signalized.

This paper presents a practical procedure for identifying the most promising alternative intersections for certain traffic conditions based on capacity, delays, and number of stops. This approach was applied to develop guidelines for Indiana conditions. It must be noted that the developed method helps narrow the number of possible solutions to the ones that are promising from the traffic operations point of view. Additional detailed traffic studies are needed, supplemented with consideration of the available right of way. These studies could include a cost-effectiveness analysis, a safety analysis, and other studies appropriate to assist in the selection of the best design solution.

The results can be used in states that have conditions similar to Indiana. The paper may benefit also those researchers in other states who develop their own guidelines. The next section will summarize the studied alternative intersections. The following sections present the research methodology and discuss the results and the application procedure.

STUDIED ALTERNATIVE INTERSECTIONS

This section only highlights the treatment of turning movements at the studied intersections and the operational consequences. A more detailed discussion of these consequences can be found in Tarko et al (2008).

A **conventional intersection** is an intersection where all movements are direct. Increasing demand at conventional intersections slowly degrades their performance. Conventional intersections with direct left turns can serve only a limited number of vehicles with strong conflicting through-movements.

A **continuous-flow intersection (CFI),** sometimes called the **crossover-displaced left-turn** intersection**,** provides ramps left of the arterial and the cross street upstream of the main intersection to handle left turning movements from the arterial and the cross street. A partial CFI only has two ramps on the major roadway, which typically is the arterial.

Figure 1 demonstrates how left- and right-turning vehicles from Major Street (1a) and Minor Street (1b) would traverse the intersection. The major advantage to this design is that through traffic and traffic using the left turn ramp can move during the same signal phase without conflicts. The signals at the ramps should be coordinated with the primary intersection signal so through arterial traffic does not stop more than once. A continuous-flow intersection can provide significant savings in delay, can reduce queue length and the average number of stops, and may add additional capacity when compared with a conventional intersection design with left-turn pockets (Hummer and Reid, 2000). Under balanced volumes, the advantages of a continuous-flow intersection with respect to a conventional intersection are greatest with high left turn volumes and overcapacity conditions (Goldblatt et al., 1994). In terms of pedestrian operations, the service time for any pedestrian at a continuous-flow intersection can be accommodated within two cycle lengths (Jagannathan and Bared, 2005).

The **jughandle** intersection uses ramps diverging to the right side of the arterial to accommodate the left and right turns from the arterial. There are two types of jughandle ramps. The first type uses a forward ramp (called here a near-sided ramp), as shown in Figure 2; and the second is a reverse ramp (called here a far-sided ramp), as shown in Figure 3. The near-sided jughandle can accommodate light to moderate left turn movements on the major road. Under heavy volumes, the queue spillback from the primary intersection might block the termini of the jughandle ramps. The far-sided jughandle can be used to accommodate heavier left turns but a greater right-of-way is needed. Even with an increase in travel distance for left turns, the far-sided jughandles might operate at a lower average delay than at conventional intersections (USDOT, 2004).

The **Median U-turn (MUT)** intersection requires a motorist to use a crossover in the median located downstream of the primary intersection in order to turn left (Figure 4). Right turns proceed as usual. A true median U-turn intersection does not allow bi-directional crossovers as they have the possibility of interlocking (Jagannathan, 2007). Median U-turns can be implemented on the major road (studied here), the minor road, or both. A median U-turn with a crossover controlled by a signal would only work in states which allow a left turn on a red signal on one-way facilities. The location of a crossover is a tradeoff between the travel time for left turns and the storage capacity for left-turning vehicles. Agencies provide varying recommendations for the location, which range from 400 to 760 feet beyond the primary intersection (Hummer, 1998; AASHTO, 2004; Jagannathan, 2007). When comparing the median U-turn design with a conventional intersection, considerable savings in delay occur when left turn volumes are small and through traffic strong (Bared and Kaisar, 2002; Ourston and Hall, 2003).

Roundabouts allow multiple vehicles to enter the intersection simultaneously from any approach when no conflicting vehicle is present in the circulatory roadway (Figure 5). The entry onto a roundabout is controlled by a yield sign. The Federal Highway Administration (FHWA) Roundabout Guide (Robinson et al., 2000) can help classify and determine roundabout geometrical dimensions based on the desired operational characteristics. Roundabouts improve traffic safety and have the potential to provide improved traffic flow operations at locations with high left-turn volumes, skewed approaches, and conditions with limited queue storage. For multilane roundabouts, special attention to design details is necessary to achieve a successful roundabout design (Rodegerdts et al., 2007). The critical gaps and follow-up times, the two most important driver behavior parameters, are longer in the U.S. than in Europe due to the more conservative nature of U.S. driver behavior (Rodegerdts et al., 2007; Eisenman and List, 2004) This difference makes the roundabouts in the U.S. less effective in handling high traffic volumes.

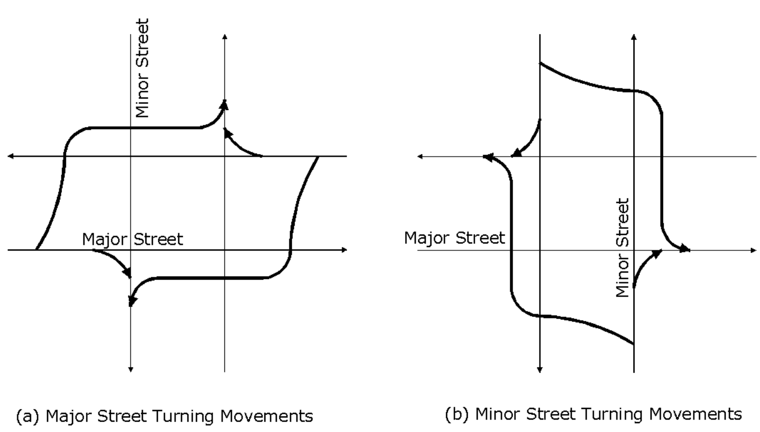


Figure 1 Vehicle Movement at a Full Continuous-flow Intersection

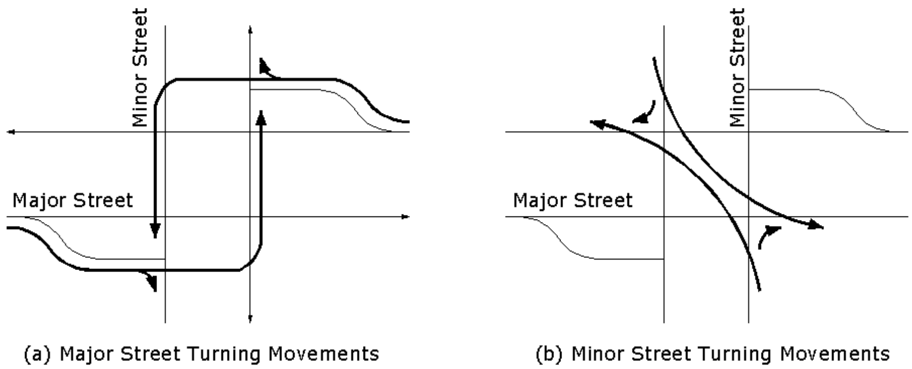


Figure 2 Turning Movements for a Forward-forward Jughandle

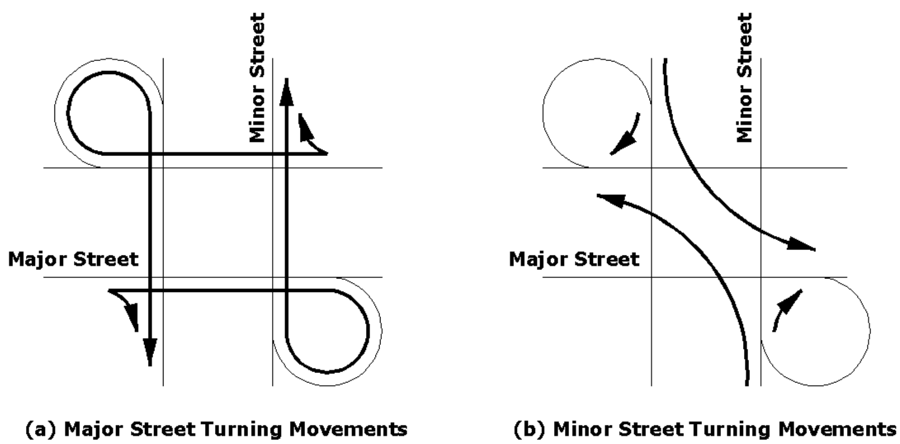


Figure 3 Turning Movements for a Reverse-reverse Jughandle

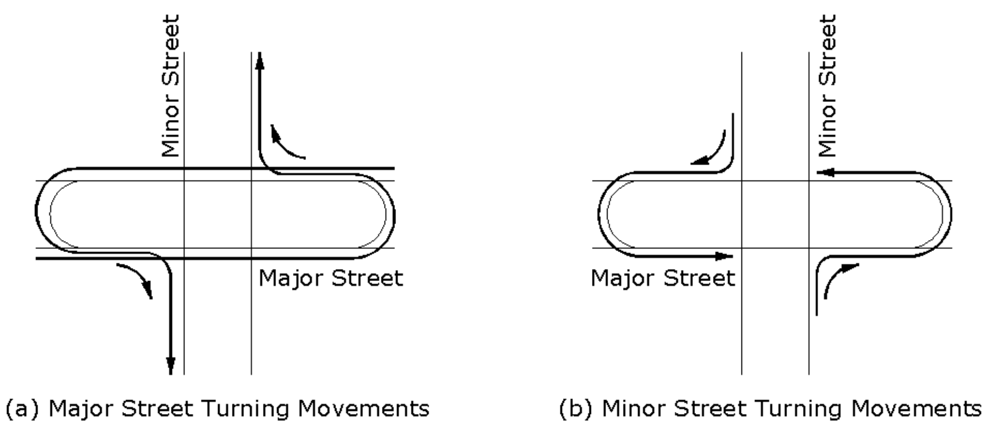


Figure 4 Median U-turn Turning Movements

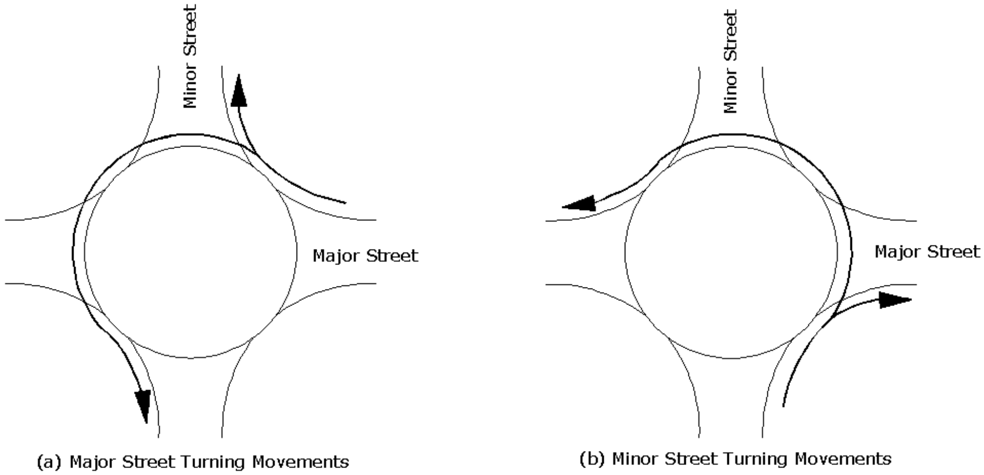


Figure 5 Roundabout Turning Movements - Example

SELECTION OF PROMISING ALTERNATIVES – A CONCEPT

Selection Methods

The most straightforward approach to designing an intersection when several (six here) types of intersections are possible includes advancing the design of each alternative to the point that a modeling tool such as microsimulation can be used to determine which of the considered alternatives provides the best traffic performance. The best alternative is selected for technical design.

The above approach is both simple and expensive. It would be less expensive if a designer selects upfront only two or three alternatives. To be able to do so, the designer needs useful knowledge. Such knowledge may take the form of a collection of *scenarios* with well defined traffic conditions and corresponding performance measures for all the considered alternative types of intersections. The designer would have to find a scenario in which the traffic conditions best match the design conditions and thereby learn from the available information which intersection types meet the performance criteria.

A second approach is a more advanced version of the previous one. Instead of using all the scenarios, data mining would be performed on the scenarios beforehand to group them by similarity in traffic performance. This beforehand analysis would be conducted only once to reduce the number of scenarios and to simplify the selection task. The selection task would be limited to identifying a class of scenarios that correspond to the design traffic conditions and the intersections included exhibit a satisfactory traffic performance. The intersection types included in this class would be selected.

The last approach is a combination of the two previous methods. The selection process ends when a proper class of scenarios is found and two or three intersection types are identified based on this class. It may happen that such a class does not exist or does not provide a conclusive answer. In this case, the designer must resort to the first approach.

Selection Criteria

Selection criteria are another important matter. It should be noted that the proposed method focuses on the operational aspects of design. Nevertheless, additional factors, such as cost or environmental impact, can be considered after the fundamental requirement of satisfactory traffic operations is addressed with the selected alternatives. The situation where traffic performance must be jeopardized due to challenging local conditions (context-sensitive design) is not discussed here, although it can be easily addressed by early consideration of the environmental and economic factors.

Operational criteria include two distinct conditions:

(1) None of the traffic movements or approaches should operate below a certain minimum standard. The Indiana Department of Transportation (INDOT) uses a set standard for intersection approaches as the average delay not higher than 80 seconds. This delay corresponds to the capacity threshold for signalized intersections and exceeding this value is equivalent to a capacity failure.
(2) Lowest possible average intersection delay (and average number of stops), given local conditions, is desirable.

Selection Procedure
A selection procedure emerges from the above selection methods and criteria.

1. (1) Identify scenarios that match the design conditions.
2. (2) Check if the alternative intersection types included in the scenario meet the minimum performance standard.
3. (3) If step (2) identifies more than two or three alternatives, then select from that group the smaller number of alternatives with the superior intersection delay (and/or number of stops).

GENERATING SCENARIOS

Generation of a set of scenarios and their classification was conducted in two phases. First, simulation experiments were performed to generate a collection of scenarios including their traffic conditions and estimated measures of effectiveness (MOE). Then, these scenarios were analyzed by a classification tree technique to group the scenarios by traffic performance.

Simulation Experiments

Development of a collection of scenarios required microsimulation. Although some of the alternative intersection types have been implemented, others have not. Furthermore, field measurements of traffic characteristics and performance at existing intersections are prohibitively expensive if conducted at many locations. Another problem is the lack of comparison of various design alternatives for the same traffic conditions.

For the above reasons, the VISSIM model (PTV_Vision, 2007) was selected and calibrated to Indiana conditions. Tarko et al (2008) describe the field measurements and calibration of VISSIM, including the adjustment of the saturation flow rate at signalized intersection, through the CC1 parameter and properly set speeds. For roundabouts, the critical gaps and follow-up times were estimated at Indiana roundabouts in Carmel near Indianapolis, Indiana USA, where 40 roundabouts have been built over the last twenty years.

Six intersection types were evaluated under the same traffic conditions in 72 simulation scenarios. Each simulation scenario ran for one hour. Among the evaluated intersections are (terms in parenthesis are labels used in the results presentation) conventional intersection (CONV), continuous-flow intersection (CFLW), jughandle far-sided (JHFS), jughandle near-sided (JHNS), median U-turns (MUT), and roundabout (RNDB).

Each intersection was evaluated in two areas: rural and urban. Urban conditions were represented in the simulation by a saturation flow rate of 1,900 veh/h/lane, two percent of heavy vehicles, and a speed limit of 30 mph for two-lane approach roadways (both directions) and 45 mph for four-lane approach roadways (both directions). Rural conditions were represented in the simulation by a saturation flow rate of 1,700 veh/h/lane, five percent of heavy vehicles, and a speed limit of 55 mph for two-lane approach roadways (both directions) and 60 mph for four-lane approach roadways (both directions).

For each area type (urban, rural), three configurations of lanes were considered: (1) four-lane road crossing a four-lane road (4x4); (2) four-lane road crossing a two-lane road (4x2); and (3) two-lane road crossing a two-lane road (2x2). For each lane configuration, three scenarios of left turns were evaluated: (1) 10 percent on major and ten percent on minor road (10/10); (2) 10 percent on major road and twenty percent on minor road (20/10); and (3) 20 percent on major road and 20 percent on minor road (20/20). Each lane configuration with specific left-turn scenarios was evaluated under 12 cases of traffic split and traffic load. Table 1 is a summary of all the scenarios evaluated.

Table 1 Simulation Scenarios in VISSIM

Intersection Type	**Area Type**	**Lane Configuration**	**Left-turn Scenarios**	**Traffic Split and Load Scenarios**
• Conventional (CONV) • Continuous-flow Intersection (CFLW) • Near-sided Jughandle (NSJH) • Far-sided Jughandle (FSJH) • Median U-turn (MUT) • Roundabout (RNDB)	• Urban • Rural	• 4x4 • 4x2 • 2x2	• 10/10: Major Rd 10% Minor Rd 10% • 10/20: Major Rd 10% Minor Rd 20% • 20/20: Major Rd 20% Minor Rd 20%	Intersection Split • 55/45 (balanced) & • 70/30 (unbalanced) Directional Split • 55/45 (balanced) & • 70/30 (unbalanced) Traffic Load Critical Degree of Saturation: 50%, 65%, 90%,
Number of cases: 6	**2**	**3**	**3**	**2x2x3=12**

The total number of scenarios was 6x2x3x3x12 =1,296. An additional 36 scenarios were simulated for the continuous-flow intersections in an urban scenario with the traffic load factor of 1.0 (3 lane configurations x 3 left-turn scenarios x 2 intersection splits x 2 directional splits). Therefore, the total number of scenarios was 1,332. One-hour simulation was repeated four times, giving a total simulation time of 5,328 hours. Six scenarios were removed from the analysis due to a large overload that caused excessively long simulation runs that interrupted the experiments before their completion.

Before running the simulation in VISSIM, Synchro was used to determine the optimal signal timing for the assumed geometry and traffic conditions. Due to the time constraints and the massive simulation scale, we had to apply a pre-timed signals operation. After building the proper networks in Synchro to reflect the presence of one primary and two secondary intersections, the signal timing was obtained by optimizing the splits and cycle lengths for each node individually, followed by optimizing the network cycle lengths and network offsets.

The procedure for a simulation run was as follows:

1. Import volumes to Synchro appropriate for the case.
2. Optimize signal timings for the Synchro network (one or multiple nodes).
3. Enter signal timing in VISSIM controller window (one or multiple node).
4. Enter approach volumes in VISSIM through the vehicle input module.
5. Enter turning percentage in VISSIM through routes.
6. Run four simulations in VISSIM for the same scenario.

The collected measures of effectiveness were total delay, stop delay, and average number of stops per vehicle.

1. The average delay on the busiest intersection approach includes the effect of the control, traffic queues, and the additional distance covered by indirect left-turning movements. Based on the HCM recommendations, an average delay larger than 80 seconds indicates Level of Service F and the shortage of capacity.
2. The average delay at the intersection represents the overall level of service at the intersection and can be used to compare different design alternatives.

3. The average number of stops can be used as an additional measure of performance following the belief that driver perception of traffic quality is affected not only by the delay but also by the number of stops.

All performance measures were recorded along the movement paths, which started 3,000 feet upstream of the intersection and ended downstream of the intersection where the vehicles reached their desired speeds. The selected upstream distance was sufficiently long enought to contain the longest queue and the deceleration distance of vehicles joining the queue.

Simulation Results

The simulation results are presented for each intersection type in Table 2. It is obvious that a roundabout is the worst performing type of intersection, followed by a conventional intersection. On the other hand, the continuous-flow intersection is the best performer. This conclusion is supported by almost all the MOEs.

The variability of the MOE values is considerable, which gives a basis to claim that the generated sample was sufficiently diversified and included scenarios that properly represent cases with satisfactory and unsatisfactory performance. This sample was further analyzed using the classification tree method described in the next section.

Table 2 Summary of simulated measures of performance by intersection type

Measure of Performance	Statistic	Alternative Intersection Type					
		CONV	CFLW	JHFS	JHNS	MUT	RNDB
Number of scenarios	Count	211	251	216	216	216	216
Intersection volume (veh/h)	Min	1214	1214	1214	1214	1214	1214
	Average	2955	3194	2968	2968	2968	2968
	Max	6218	6909	6218	6218	6218	6218
Average intersection delay (s)	Min	20.5	6.1	16.7	19.0	19.3	7.9
	Average	54.7	31.5	45.3	43.9	46.9	92.8
	Max	230.7	153.6	173.8	185.1	332.6	394.8
Average approach delay (s)	Min	22.4	19.1	18.1	20.5	20.8	10.0
	Average	70.0	51.4	59.7	61.7	69.1	219.1
	Max	302.1	269.0	321.2	363.6	462.4	948.1
Average movement delay (s)	Min	34.0	43.4	36.6	50.2	61.3	10.5
	Average	167.0	100.5	130.9	149.4	133.0	248.4
	Max	581.1	424.8	615.5	625.6	799.8	955.3
Average stops/vehicle	Min	0.61	0.45	0.44	0.58	0.48	0.11
	Average	1.13	0.82	0.89	0.98	1.07	4.35
	Max	4.60	3.58	3.55	3.90	7.57	21.48
Approach capacity failure	Proportion	0.302	0.144	0.278	0.250	0.241	0.537
Movement capacity failure	Proportion	0.542	0.428	0.472	0.454	0.491	0.546

CLASSIFICATION OF SCENARIOS

Method

The classification tree method was used to group the 1,326 scenarios into as many homogenous classes as possible. For example, a class is homogenous (or pure) if all the included intersections exhibit capacity shortages. Another pure class may include only scenarios where intersections have sufficient capacity. These classes are defined by conditions on traffic volumes, number of lanes, area type, etc. Usually, only impure classes can be obtained that mix intersections with and without capacity shortage. The classification method used attempts to minimize the *impurity* of classification. The impurity measure used in our study involves the so-called Gini Index:

$$GI(t) = \sum_{i \neq j} p(i \mid t)\, p(j \mid t)$$

where:

t = group or class index,

i,j = indices representing capacity shortage (i) and sufficient capacity (j),

$p(i|t)$ = proportion of case i in class t.

The impurity of class t is calculated as the product $N_t/N \cdot GI(t)$, where N_t is the number of scenarios in class t and N is the total number of scenarios (1326). The final classification is reached through sequential splitting of the initial set of scenarios into smaller classes until splitting is no longer possible (too small groups or no impurity reduction). In each split, the current class is divided according to a condition which reduces the impurity to the maximum extent. The impurity reduction, called *improvement* is calculated as:

$$\frac{N_t}{N} \cdot GI(t) - \frac{N_{t1}}{N} \cdot GI(t_1) - \frac{N_{t2}}{N} \cdot GI(t_2)$$

where t_1 and t_2 indicate the two new sub-classes obtained by splitting class t.

A similar process of splitting can be performed for intersection delay to obtain homogeneous classes. In this case, a class is homogenous if all included intersections have the same average delay. In reality, pure classes are difficult to obtain; and, instead, the splitting attempts to increase the class homogeneity by minimizing the variance of delay inside the class. The improvement accomplished by splitting class t into two sub-classes t_1 and t_2 is measured with the reduction in the scaled variance:

$$\frac{N_t}{N} \cdot s_t^2 - \frac{N_{t1}}{N} \cdot s_{t1}^2 - \frac{N_{t2}}{N} \cdot s_{t2}^2$$

where s^2 is the variance and subscripts t, t_1, and t_2 indicate class t and sub-classes t_1 and t_2.

If unbound, the splitting process tends to generate too many classes. Therefore, an appropriate stopping rule is needed. One option is to continue splitting as long as the impurity improvement is considerable, but this approach poses an inherent problem with setting the threshold value. A threshold that is too low generates an excessive number of nodes while a threshold too high may prevent identification of important classes. For that reason, some researchers prefer to develop a large classification tree with a liberal stopping rule and then prune the developed tree as needed (Breiman et al., 1998). So far, the most frequent rule of pruning is the minimal cost complexity rule. Under this criterion, the complexity for any sub-tree of the developed tree is measured by the number of terminal nodes. Assuming a penalty for a terminal node and under certain additional conditions, the total cost complexity is minimized. The size of the pruned tree can be controlled with the penalty value (Breiman et al., 1998).

A number of techniques exist for performing classification tree analysis. The best known are Classification and Regression Tree (CART), Quick, Unbiased, Efficient, and Statistical Tree (QUEST), Chi-square Automatic Interaction Detection (CHAID), and Quadratic Discriminant Analysis (QDA) (Breiman et al., 1998; SPSS, 2004). QUEST handles only categorical variables while both the CART and CHAID techniques can deal with scalar variables. The CART technique was selected for its ability to handle scalar variables.

The significance of a variable (intersection volume, number of lanes, percent of left turns, etc.) for the classification of scenarios is measured using *normalized importance*. The importance of a variable is the sum of all improvements that have been or could be accomplished in each class by using this variable, divided by the importance of the most significant variable, and expressed in percents.

The overall predictive accuracy of a tree model can be estimated by the risk estimate and its standard error. For categorical dependent variables, the risk estimate is the proportion of cases incorrectly classified after adjustment for prior probabilities and misclassification costs (SPSS, 2004).

Results

Approach Capacity Shortage

INDOT considers an intersection as having capacity failure when one or more approaches reach level of service F (average approach delay higher than 80 seconds). Some agencies may have a more stringent criterion based on delays of traffic movements rather than approaches. Due to the limited space, only the approach-based capacity analysis is presented. Table 3 presents the classes of scenarios defined by the corresponding conditions, including traffic volume ranges, type of area, number of traffic lanes, and types of intersections in the class. Each class also has an estimated risk of capacity shortage, which is simply the proportion of scenarios that have insufficient approach capacity within the class. For example, the first class, with 57 scenarios, is defined by an intersection volume within the range of 1,214-2155 veh/h; an approach volume on the major road in the range of 468-1597; and a roundabout. For these conditions, there is no risk of capacity shortage (risk=0.0, pure class). The classes shown in Table 3 were generated by CART to maximize either the proportion of scenarios with the capacity shortage or the proportion of scenarios with sufficient capacity. Four classes have a risk of capacity shortage not exceeding 0.10 that include total of (57+560+12+180) = 809 scenarios out of 1,326, which is 61 %. There are also three classes with a high risk of capacity shortage (more than 0.85) that represent altogether (64+150+28) = 242 scenarios, or 18 % of all the studied scenarios. The remaining classes are not conclusive about the risk.

Table 3 allows making several statements about the tendencies in the risk of capacity shortage in relation to the traffic volume, number of traffic lanes, and types of studied intersections. Roundabouts do not experience major capacity problems regardless of the number of traffic lanes and distribution of traffic (assuming it remains in the range investigated in this research) for traffic volumes not exceeding 2,200 veh/h. Roundabouts connecting two four-lane roads can accommodate 2,800 veh/h without major delay problems. These conclusions are valid for Indiana conditions, and more precisely, for the Carmel area where drivers are familiar with roundabouts. It must be noted that the critical gap in this area is three seconds, which is in between European countries (two seconds) and U.S. average conditions (four seconds).

Table 3 Classes of Scenarios for Shortage of Approach Capacity

Class Size	Intersection Volume (veh/h)	Major Road Busier Approach Volume (veh/h)	Minor Road Busier Approach Volume (veh/h)	Area Type		Number of Lanes on Minor Road	Intersection Type						Risk of Approach Capacity Shortage
				Urban	Rural		CONV	CFLW	JHFS	JHNS	MUT	RNDB	
57	1214 - 2155	468 - 1597										X	0.00
560	1214 - 2776	468 - 1597					X	X	X	X	X		0.07
12	2155 - 2776	468 - 1597				4						X	0.00
42	2155 - 2776	468 - 1597				2						X	0.64
180	2776 - 4765	468 - 1597				4	X	X	X	X	X	X	0.10
64	2776 - 4765	468 - 1597				2	X					X	0.86
30		1597 - 2660	706 - 765	X			X		X	X	X	X	0.20
36	2782 - 3053	468 - 1597				2		X	X	X	X		0.35
107	3053 - 4765	468 - 1597				2		X	X	X	X		0.72
33	3363 - 5100	1597 - 2660						X					0.21
27	5100 - 6909	1597 - 2660						X					0.70
150		1597 - 2660	765 - 1539				X		X	X	X	X	0.93
28		1597 - 2660	706 - 765		X		X		X	X	X	X	1.00

Other types of intersections may experience excessive delays when volume approaches 2,800 veh/h, but this risk is low (0.07). All the studied types of intersections, including roundabouts, may accommodate as many as 4,800 veh/h if both the crossing roads have four lanes. The risk of capacity shortage is 0.10. Conventional intersections and roundabouts fail at such high volumes if any of the crossing roads have two traffic lanes.

Only continuous-flow intersections can accommodate total traffic volumes up to 5,100 veh/h, but the risk of approach capacity shortage is 0.20. This type of intersection is not adequate for volumes higher than 5,100 veh/h (risk of capacity shortage is 0.70).

Three types of intersections: near-sided jughandle, far-sided jughandle, and median U-turns exhibit similar performance from the point of view of capacity shortage. They all are present in the same classes.

Table 4 Classification Rules for Intersection Delay

Class Size	Intersection Volume (veh/h)	Minor Road Left Turn (%)	Number of Lanes on Major Road	Number of Lanes on Minor Road	Intersection Type						Intersection Average Delay (s)
					CONV	CFLW	JHFS	JHNS	MUT	RNDB	
342	1214-2155				X	X	X	X	X	X	22.5
329	2155-2776				X	X	X	X	X	X	35.8
120	2776-3751			4	X	X	X	X	X		26.6
39	2776-3751			2		X					33.0
118	2776-3751			2	X		X	X	X		63.8
12	2776-3751		2							X	186.8
18	2776-3751		4	2						X	116.1
24	2776-3751		4	4						X	58.1
51	3751-6909									X	208.9
126	3751-5496			4	X	X	X	X	X		49.5
53	3751-5496			2		X	X	X			71.3
28	3751-5496			2	X				X		132
22	5496-6909	10			X	X	X	X	X		75.6
12	5496-6909	20				X					78.3
32	5496-6909	20			X		X	X	X		148.8

Average Intersection Delay

The two selected measures of effectiveness (MOE) for evaluating the performance of alternative intersections were average intersection delay in sec/veh and average number of stops per vehicle. Only the results for intersection delay are presented and discussed. The classes of scenarios obtained based on the intersection average delay are presented in Table 4.

The results indicate a large variability of delays across the obtained classes. As in the case of capacity shortage, three types of intersections (near-sided jughandle, far-sided jughandle, and median U-turns) exhibit many similarities as they appear together in seven classes. Only in one class do the two jughandles appear without the median U-turns. Furthermore, there is no considerable difference among all the intersection types if the intersection volume is low and does not exceed 2,800 veh/h.

The performance of roundabouts deteriorates quickly with volume increases and is much worse than other intersection types when the intersection volume is moderate (2,800 – 3,800 veh/h). The performance of intersection types other than roundabout is still comparable if both the crossing roads have four lanes. Continuous-flow intersections outperform other types of intersections when the minor road has only two lanes.

Roundabouts exhibit an average delay larger than other types of intersection at moderate traffic volumes (2,800 – 3,800 veh/h) and where both the crossing roads have four lanes. The average delay, slightly less than 60 seconds, may be acceptable by some jurisdictions if other benefits of roundabouts such as improved safety are considered.

Under heavy intersection traffic volumes between 3,800 and 5,500 veh/h, all the studied solutions are comparable (except roundabouts) where both crossing roads have four lanes. In other lane configuration cases (2x2 and 4x2), the continuous-flow intersections and the two jughandles perform better than the conventional intersections and median U-turns.

Under very heavy traffic volumes exceeding 5,500 veh/h, the continuous-flow intersections are considerably more efficient than other types, but capacity shortage is quite likely.

Significance of Variables

The normalized importance of all significant variables for classification of scenarios was compared. CART totals all the values of improvement over all the classes and normalizes the obtained values with the largest value. The variable with the highest sum of improvements is scored 100 and other variables have lower scores.

Table 5 illustrates the importance of the predictor variables along with their normalized importance. Intersection volume is the most important variable for classification of scenarios by approach capacity (almost 100%) and by intersection delay. A heavier approach volume on the main road is the most significant covariate for classifying scenarios by approach capacity. Surprisingly, the intersection type is not important for classifying scenarios by capacity failure, but it is important for delay-based classification. The higher importance of the number of lanes on a minor road than on a major road is an interesting result.

APPLICATION OF THE RESULTS

This paper presents the results of applying the classification tree to a generated set of design scenarios. General guidance could be derived from these results as discussed in the previous sections. It seems that roundabouts may not be the best alternative where the main task is to deal with heavy volumes and risk of congestion although it works well under lower volumes. The performance of conventional intersections tends to deteriorate more rapidly than other types of intersections (except roundabouts whose performance deteriorates even sooner). The jughandles and median U-turns exhibit similar performance under most conditions and they can be ranked between conventional intersections and continuous-flow intersections. Continuous-flow intersections are undoubted winners in terms of capacity and average delay.

Table 5 Importance of Independent Variables in CART Model

Independent Variable	Approach Capacity		Intersection Delay	
	Importance	Norm. Imp.	Importance	Norm. Imp.
Intersection volume (veh/h)	0.157	99.8	923.3	100.0
Main road busier approach volume (veh/h)	0.157	100.0	613.9	66.5
Crossing road busier approach volume (veh/h)	0.086	54.9	531.7	57.6
Main road less busy approach volume (veh/h)	0.083	52.7	502.8	54.5
Crossing road less busy approach volume (veh/h)	0.065	41.3	554.7	60.1
Number of traffic lanes on major road	0.015	9.7	102.5	11.1
Number of traffic lanes on minor road	0.058	36.9	195.5	21.2
Intersection type	0.029	18.6	808.3	87.5
Truck percentage	0.018	11.5	2.0	0.2
Urban/rural area	0.018	11.5	2.0	0.2

The above summary indicates only the general tendencies in the results. A designer needs to select the most promising alternative solutions for specific design conditions. Using general knowledge may not always work. The performed classification of the simulated scenarios was intended to help identify alternatives that are promising than others for the design conditions. This objective was only partially accomplished. The obtained conditions and corresponding alternative types of intersections with performance evaluations are presented in Table 3 and Table 4. These results may help in some cases but yield inconclusive results in other cases. Therefore, our team has developed a catalog of simulated scenarios which can be used by designers (Tarko et al, 2008).

Figure 6 contains one page from this catalog. The traffic conditions of the scenario are listed at the top of the page. A designer needs to find a scenario which is the closest to the design conditions. Once found, the included graphs present the busiest approach delay as a function of intersection volume and for all the studied intersection types. In the presented example, the roundabout becomes overloaded at 1,950 veh/h while the far-sided jughandle at 2,700 veh/h. The conventional, median U-turns, and near-sided jughandle perform similarly while the continuous-flow intersection is the most effective alternative.

CONCLUDING REMARKS

Several new or relatively new intersection types have been investigated in this paper to develop guidelines to help designers select the most promising ones and reduce design cost. Field measurements in Indiana provided data to calibrate parameters of the microsimulation model VISSIM: (1) saturation flow rates important for capacity and delay at signalized intersections, and (2) critical gaps and follow-up times important for traffic operations at unsignalized intersections. The calibrated VISSIM together with Synchro was utilized to conduct more than 5,300 hours of simulation for 1,326 scenarios. All the studied types of intersections, except roundabouts, were signalized to determine how much the capacity can be increased when intersections alternative to conventional ones are used with optimal signal settings yielded by Synchro. The analysis was limited to isolated intersections with one major and one minor road.

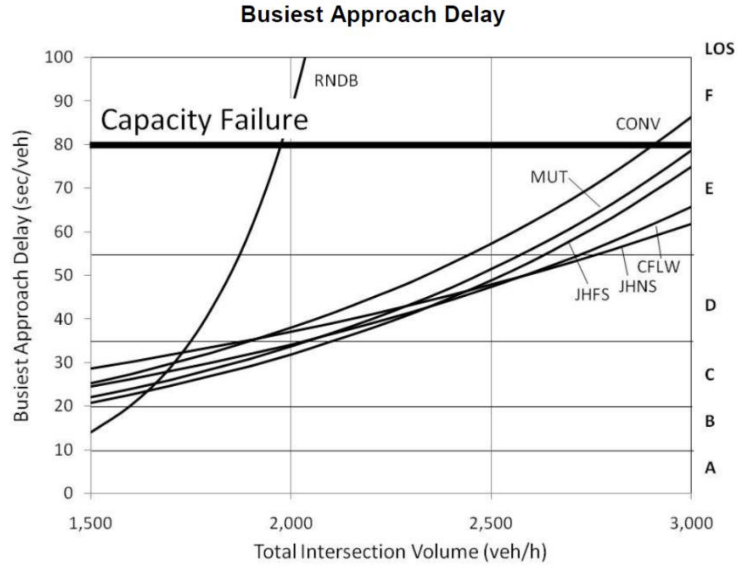
A method called *classification tree* was applied to identify groups of scenarios that exhibit similar performance measured with the risk of capacity shortage and with the average intersection delay. Roundabouts were found to offer the lowest capacity (volume at which average approach delay reached 80 seconds). On the other hand, continuous-flow intersections were found to be the most efficient in the majority of the tested scenarios. Median U-turns and jughandles were proven to provide better traffic performance than conventional intersections.

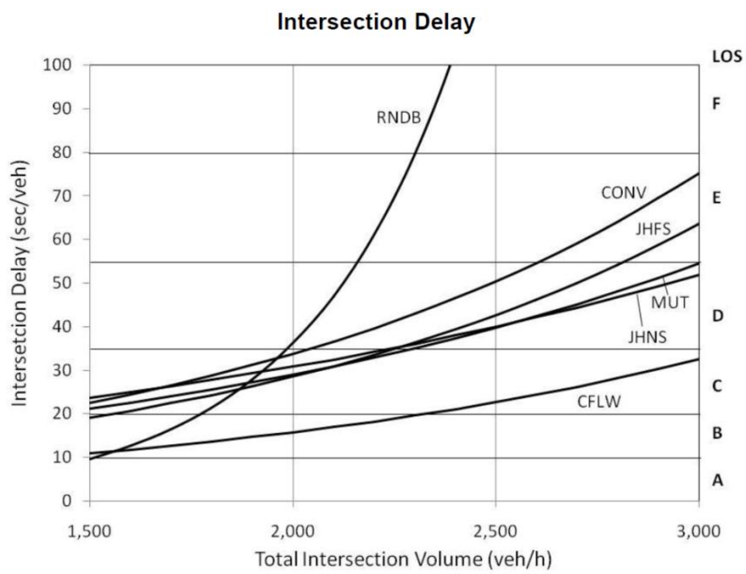
These general findings do not provide sufficient guidance for specific traffic conditions. A catalog of scenarios were developed to provide more detail and precise evaluation of the six intersection alternatives. A designer would find a scenario which is closest to the design conditions and then determine, using a set of graphs and tables, which of the six intersection types offers sufficient capacity and exhibits the lowest or at least an acceptable average delays level. The average numbers of stops per vehicle are also available for each scenario.

The presented analysis focuses on the operational considerations in selecting design alternatives. The developed tool is meant to narrow the number of possible alternatives to a smaller number, let us say, two. These promising alternatives may be a good starting point for a preliminary alternative-based design. This design process should include a detail traffic analysis complemented with additional analyses pertaining to costs, available right-of-way, local design standards, drivers' expectations, environmental impacts, and safety. Only a comprehensive design study may yield a final solution that satisfies all design criteria.

The developed guidelines can be useful not only to Indiana designers but also to other states with comparable conditions. The presented methodology of developing guidelines may be found helpful in developing similar design tools for other states.

Location	**Urban**	Intersection Split	**55/45**	Major Road Left Turns	**10 %**
Through Lanes	**2x2**	Directional Split	**70/30**	Minor Road Left Turns	**20 %**





Stops Per Vehicle

DESIGN	Total Intersection Volume (veh/h)		
	1360	1760	2450
CONV	0.71	0.77	1.17
CFLW	0.66	0.72	0.88
JHFS	0.62	0.68	0.94
JHNS	0.73	0.79	1.07
MUT	0.71	0.76	1.10
RNDB	0.22	0.51	7.90

Figure 6 Example page from the *Guidelines for Using Intersection Alternative Designs in Indiana*
(Tarko et al, 2008)

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