# DETERMINATION OF INTERSECTION CONTROL TYPE USING THE HCM 2000

Samuel K Ahiamadi and Zong Z. Tian,

## ABSTRACT

Selecting an intersection control type can be a complex process because of the many factors involved. Any process which can ease the preliminary selection of the control type before detailed designs is thus helpful. Volume to capacity (v/c) ratio, level of service, average control delay and queue length are important factors for determining an intersection control type when using the Highway Capacity Manual (HCM) 2000. Following the procedure of an earlier research effort which used the 1994 HCM, the 2000 HCM in combination with other tools was used to develop new guidelines for intersection control selection. The guidelines mainly consist of three tables developed by modifying the traffic volume criteria included in the Signal Warrants contained in the Manual of Uniform Traffic Control Devices (MUTCD). These tables were developed using either the intersection level of service, average intersection control delay or the average intersection queue length as the performance measure to obtain an optimal intersection control type.  The results indicated that roundabouts can accommodate a wide range of traffic volume conditions with better performance than other intersection control types. Signals are best used when the traffic volume is very high. Average intersection control delay and average intersection queue length appeared to be good predictors when determining intersection controls knowing the major and minor street volumes.

*Keywords: Level of Service (LOS), intersection control, control delay, queue, HCM*

# INTRODUCTION

The selection of an intersection control is often a dilemma that traffic engineers face during the construction of new roadways or when upgrading existing intersections because of the many issues involved. This decision is usually complicated when many factors need to be balanced to come up with a rational recommendation. Hence any tools that can aid the process are of practical values to the traffic engineering field.

Marek et al (1997) (*1*) developed a series of graphs based on the 1994 Highway Capacity Manual (HCM) as a guide for traffic engineers to determine an intersection type. The graphs included three intersection types namely two-way stop control (TWSC), all-way stop control (AWSC) and signalized intersections. They used the warrants for traffic signal control as a guide for volume considerations and produced the graphs based on intersection Level-of-service (LOS), intersection average delay and intersection queue. The graphs were easy to use since it only needed the total major street traffic volume and the higher minor street traffic volume similar to the MUTCD (adopted after the MUTCD 1988).

Since 1995, roundabouts have gained acceptance in most U.S. States and also been successful at a variety of intersections (both urban and rural roads). Currently, there are over 1500 modern roundabouts in the U.S. (*2*) and the number keeps growing rapidly. Interestingly, not all the roundabouts built currently are located at new intersections, a large number have been constructed at locations previously controlled with TWSC, AWSC or traffic signal. With the inclusion of modern roundabouts as an intersection control options, the selection of the best intersection control type has been further complicated since designers have one more option to consider. Roundabouts have been gaining acceptability in most places due to their ability to improve safety, reduced delay and stops. On-going research continues to reveals the benefits of roundabouts in the US; consequently, it is almost a standard to consider roundabouts as a first choice in most counties.

The earliest version of the 2000 HCM, (*3*) Chapter 17 Part C for roundabouts did not contain sufficient information, consequently in 2006, there was an update to Part C after further research had been conducted on the performance of roundabouts in the US (*4*). However after the printing of this report, a lot of research on roundabouts has been done and result published including the following; Reports No. FHWA-RD-00-067-Roundabouts: An Informational Guide (*5*), NCHRP 572-Roundabouts in the United States (*6*), NCHRP 3-65-Applying Roundabout in the United States (*7*). There is still on-going researches like the NCHRP 3-65A which is due to come out in 2010. A lot of research has also been carried out by groups and in individual both in the in the US and elsewhere and have produced very good results concerning the design parameter like LOS and control delay at roundabouts Akcelik, 2009(*8*), Peterson et al (*9*), Kennedy and Taylor (*10*). Several States have also developed guidelines for roundabouts examples are Florida (*11*), Maryland (*12*), Wisconsin (*13*), Arizona (*14*), Iowa (*15*), California (*16*) etc. The 2009 edition of the Manual of Uniform Traffic Control Devices (MUTCD) (*17*) has improvements over the 1988 edition regarding the Traffic Signal Control Warrant 1. The traffic volume combinations however remained the same.

For practitioners to make the best choice of traffic control options available for use at any intersections roundabouts should be one of the options mainly because of the safety advantages that come with a good design. Considering the above discussion, there is therefore the need to develop an easy procedure for selecting the appropriate intersection control before going into detailed design. The primary objective of this research paper is to develop of a set of Tables that will assist in the preliminary determination of the best intersection control option when the traffic volumes for the major and minor streets are known. This research effort was conducted, using mainly the 2000 HCM and 2009 MUTCD with an input from the HCM 2010, to incorporate roundabouts into a decision making tool similar to the one developed earlier by Marek et al (*1*).

# CONTROLLING MEASURES OF EFFECTIVENESS FOR TRAFFIC CONTROL TYPES

The HCM 2000 analysis can be used for making decisions in planning, designing and operating transportation facilities. The methods in HCM are used for estimating performance measures for assessing alternative actions and together with other factors as necessary, they can assist in deciding which of the alternative being compared is most appropriate for the particular situation.

The 2000 version of the HCM has been expanded in scope with a total of 31 chapters as against 14 chapters that were in the 1994 HCM. Chapter 16 and chapter 17 discuss signalized intersections and unsignalized intersections respectively. In addition to the new topics that have been introduced the scope and content of existing chapters have been expanded to cover more topics because more research is now available. The chapter 17 which deals with unsignalized intersection now has a part C which covers roundabouts.

## Signalized Intersections

From the HCM 2000, the LOS for signalized intersections is evaluated on the basis of control delay per vehicle which is measured in second per vehicle. The average control delay per vehicle for a given lane group is given by the equation 1 (*16*)

$$d = d_1(PF) + d_2 + d_3 \qquad (1)$$

Where

*d = control delay per vehicle(s/veh)*
*$d_1$ = uniform control delay assuming uniform arrivals (s/veh)*
*PF = uniform delay progression adjustment factor, which accounts for effects of signal progression*
*$d_2$ = incremental delay to account for effect of random arrivals and oversaturation queues*
*$d_3$ = initial queue delay*

Uniform control delay ($d_1$) is defined by the equation 2 below

$$d_1 = \frac{0.5C\left(1-\frac{g}{C}\right)^2}{1-\left[min(1,X)\frac{g}{C}\right]} \qquad (2)$$

Where

*C = cycle length (s)*
*g = effective green time for lane group (s)*
*X = v/c ration or degree of saturation for lane group*

Incremental delay ($d_2$) is defined by the equation 3

$$d_2 = 900T\left[(X-1) + \sqrt{(X-1)^2 + \frac{8kIX}{cT}}\right] \qquad (3)$$

Where

*T = duration of analysis period (h)*
*k = incremental delay factor that is dependent on controller settings*
*I = upstream filtering /metering adjustment factor*
*c = lane group capacity (veh/h)*
*X = lane group v/c ration or degree of saturation*

The initial queue delay ($d_3$) only becomes significant in situations where a residual queue from a previous time period causes an initial queue to occur at the start of the analysis period. This is so since additional delay is experienced by vehicles arriving in the analysis period since the initial queue must clear first. The procedure is extended to analyze delay over multiple periods should the queue persist.

## Two-Way Stop Control

For TWSC, both gap acceptance and empirical models have been developed to describe the operations at such intersections. The procedures discussed in the current HCM 2000 are based on the gap acceptance model developed and refined in Germany (*18*). The LOS is not defined for the intersection as a whole but for each minor movement and is determined from the computed control delay. The average control delay for any particular minor movement is a function of the capacity of the approach and the degree of saturation. The analytical model used to estimate the control delay (d) is shown below in equation (4) and assumes that the demand is less than capacity for the analysis period (*16*).

$$d = \frac{3600}{C_{m,x}} + 900T\left[\frac{V_x}{C_{m,x}} - 1 + \sqrt{\left(\frac{V_x}{C_{m,x}} - 1\right)^2 + \frac{\left(\frac{3600}{C_{m,x}}\right)\left(\frac{V_x}{C_{m,x}}\right)}{450T}}\right] + 5 \qquad (4)$$

Where

*d = control delay (s/veh)*
*$v_x$ = flow rate for movement x (veh/h)*
*$c_{m,x}$ = capacity of movement x (veh/h) and*
*T= analysis time period (h) (T=0.25 for 15-min period)*

The equation above varies slightly from what was used in the 1994 HCM, in that a constant 5 s/veh has been introduced to account for the deceleration of vehicles from free flow speed to the speed of vehicle in queue and the acceleration of vehicles from the stop line to the free-flow speed.

## All-Way Stop Control

AWSC analyzes each intersection approach independently. The approach under study is the subject approach while the opposing and conflicting approaches create conflicts with vehicles on the subject approach. The AWSC intersections operate in either a two-phase or four-phase patterns, based on the complexity of the intersection geometry. The LOS is based on the control delay. The threshold values are the same as that for the TWSC. The control delay (d) can be computed from the equation 5 below (*16*)

$$d = t_s + 900T\left[(x-1) + \sqrt{(x-1)^2 + \frac{h_d x}{450T}}\right] + 5 \quad (5)$$

Where

*d = average control delay (s/veh)*
*x = degree of utilization ($vh_d/3600$)*
*$t_s$ = service time (s)*
*$h_d$ = departure headway (s) and*
*T = length of analysis period (h)*

## Roundabouts

The section on roundabouts was introduced and updated (*4*) as part of the Chapter 17 which discusses unsignalized intersections in the HCM 2000. The gap acceptance approach is adopted for analysis or roundabout. Critical to this approach are the critical gap and follow-up time for vehicles using the roundabout. The analysis of individual legs of the roundabout are carried out exclusive of the others because the general assumption is that the performance of each leg of a roundabout can be analyzed independently of the other legs. The NCHRP 572 discusses roundabout into greater detail than the HCM 2000. The recommended control delay model (d) is given by the equation 6 below. The recommended LOS criteria are the same as those used for unsignalized intersections. The LOS for a roundabout is determined from the computed or measure control delay for each lane. The LOS is not defined for the intersection as a whole.

$$d = \frac{3600}{c} + 900T\left[\frac{v}{c} - 1 + \sqrt{\left(\frac{v}{c} - 1\right)^2 + \frac{\left(\frac{3600}{c}\right)\frac{v}{c}}{450T}}\right] \quad (6)$$

Where

*d = average control delay (s/veh)*
*c = capacity of subject lane (veh/h)*
*T = time period (h:T=1 for 1-h analysis, T=0.25 for 15-min analysis)*
*V = flow in subject lane (veh/h)*

## Determining Intersection Control Type

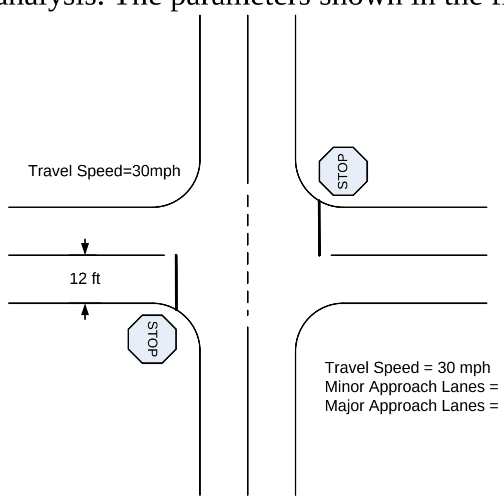
Choosing an appropriate control type for any intersection involves integrating information from several sources. Three documents most readily used by traffic engineers are the HCM, MUTCD, the Traffic Engineering Handbook (TEH) (*19*) produced by the Institute of Transportation Engineers (ITE). In addition to these documents, several good commercially available computer software for analyzing intended intersection type. They enable us obtain data that forms the basis for comparison. Information like traffic signal warrants, LOS analysis, accident data and public opinion are obtained before deciding on the intersection control type. The LOS criteria in the 2000 HCM is shown in the Exhibits 16-2 for signalized intersection, Exhibits 17-2 for TWSC, Exhibit 17-22 for AWSC and Exhibit 17-43 for roundabouts. Table 1 tabulates the different intersection controls and the LOS definitions by delay threshold.

**TABLE 1 Level of Service Definition for Vehicles Based on Delay**

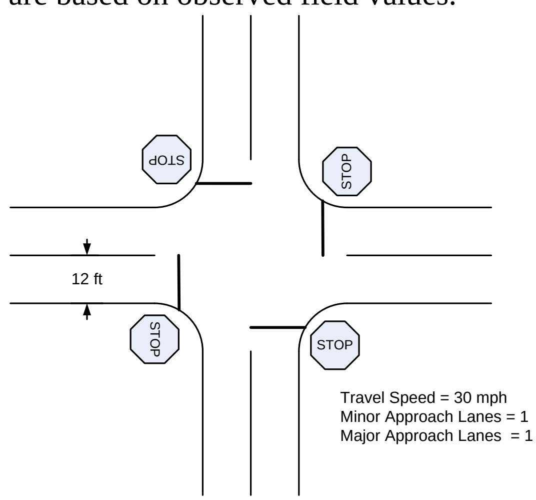
| Level of Service | Control Delay per Vehicle in Second (s) | | |
|---|---|---|---|
| | Signal | Roundabouts | AWSC/ TWSC |
| A | d ≤ 10 | d ≤ 10 | d ≤ 10 |
| B | 10 < d ≤ 20 | 10 < d ≤ 20 | 10 < d ≤ 15 |
| C | 20 < d ≤ 35 | 20 < d ≤ 35 | 15 < d ≤ 25 |
| D | 35 < d ≤ 55 | 35 < d ≤ 50 | 25 < d ≤ 35 |
| E | 55 < d ≤ 80 | 50 < d ≤ 70 | 35 < d ≤ 50 |
| F | 80 < d | 70 < d | 50 < d |

## RESEARCH PROCEDURE

For the purpose of comparing the analysis in chapters 16 and 17 of the HCM 2000 a generic intersection was used (adopted from Marek et al (*1*)) and modified to include parameters for roundabouts. Figures 1, 2 and 3 show the characteristics for the generic intersection used for the analysis. The parameters shown in the figures are based on observed field values.




TWSC




AWSC

**FIGURE 1 Characteristics of a Generic Intersection (TWSC and AWSC)**

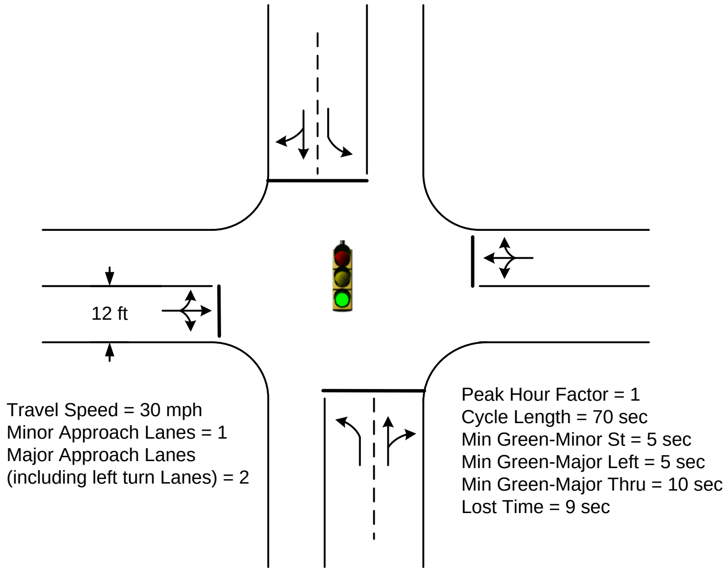



**FIGURE 2 Characteristics of a Generic Intersection (Signalized)**

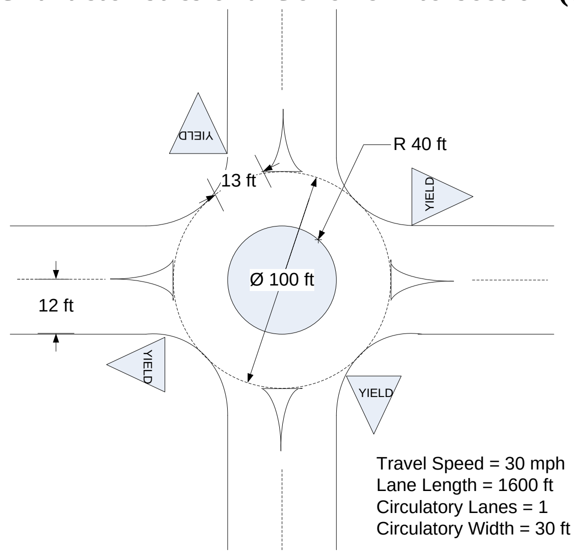



**FIGURE 3 Characteristics of a Generic Intersection (Roundabout)**

Using Table 4C-1, Figures 4C-1, Figures 4C-2, Figures 4C-3, and Figures 4C-4 from the MUTCD, the major street approach volume ranged from 100-1800 vehicles per hour (veh/hr) and the minor street approach volume from 100-1000 veh/hr. The volume table was developed with increments of 100 for both the major and minor street approach volumes giving a total of 135 volume combinations. The volume splits used for this analysis follows the earlier research (*1*) and is shown in the Table 2.

**TABLE 2 Intersection Volume Split**

| Direction | Total Split | Left Split | Thru Split | Right Split |
|---|---|---|---|---|
| **Major Street** | % | | | |
| Major 1 | 50 | 10 | 75 | 15 |
| Major 2 | 50 | 15 | 70 | 15 |
| **Minor Street** | % | | | |
| Minor 1 (subject) | 70 | 20 | 40 | 40 |
| Minor 2 | 30 | 25 | 50 | 25 |

To obtain the LOS and average intersection delay, SYNCHRO software version 6 was used to analyze the TWSC, AWSC and signalized intersections and SIDRA Intersection software version 5.0 was used to analyze the roundabout. The SYNCHRO HCM report values were used in the analysis. For the signalized intersections, the splits were optimized prior to obtaining the LOS and delays values. The results from SYNCHRO and SIDRA were deemed to be comparable because both programs are designed using the average control delay for obtaining LOS and delay as shown in the HCM 2000.

## RESULTS AND DISCUSSION

Six tables were developed using the results obtained from analyzing the intersection data in Table 2. The tables are divided into two types, Group1 (G1) and Group 2 (G2). The G1 tables were obtained from comparing the results obtained for TWSC, AWSC, Roundabout and Signal and shown in Tables 4a, 5a, and 6a while G2 tables compared results for TWSC, AWSC and Signalized control and shown in Tables 4b, 5b and 6b.

Table 3 is an example of the calculation and analysis process. This table describes how the various control types vary in terms of performance when the volume combinations are altered for the four intersection control types. The best control type is chosen after comparing the four control types before selecting the best performance indicator value.

The tables developed are based on the performance indicators used. The intersection LOS and average control delay were obtained from the intersection analysis software used (SYNCHRO and SIDRA Intersections). The intersection queue by definition is computed as a product of the control delay (hours/vehicle) and total intersection volume (vehicle/hour). So for this case, the total intersection volume was multiplied by the average intersection delay resulting in the total intersection delay. The tables produced display the control type that produced the best performance for a given volume based on the performance indicators being measured. “T” was used to represents TWSC, “A” for AWSC, “R” for roundabouts and “S” for signalized control types.

**TABLE 3 Sample Calculations for Selecting Optimal Control Type**

| TYPE 1: Optimal Intersection Control Based on LOS | | | | | | |
|---|---|---|---|---|---|---|
| Major St Vol (vph) | Minor St Vol (vph) | TWSC LOS | AWSC LOS | Roundabout LOS | Signal LOS | Optimal Control Type |
| 700 | 200 | C | B | A | A | R, S |
| 700 | 300 | D | B | A | B | R |
| 700 | 400 | E | C | A | B | R |
| 700 | 500 | E | C | A | B | R |

| TYPE 2: Optimal Intersection Control Based on Average Control Delay | | | | | | |
|---|---|---|---|---|---|---|
| Major St Vol (vph) | Minor St Vol (vph) | TWSC LOS | AWSC LOS | Roundabout LOS | Signal LOS | Optimal Control Type |
| 700 | 200 | 5.2 | 11.8 | 5.5 | 9.1 | T |
| 700 | 300 | 9 | 14.2 | 5.9 | 12.1 | R |
| 700 | 400 | 13.4 | 15.2 | 6.3 | 14.1 | R |
| 700 | 500 | 18 | 18.3 | 6.7 | 16.2 | R |

| TYPE 1: Optimal Intersection Control Based on Average Queue Length | | | | | | |
|---|---|---|---|---|---|---|
| Major St Vol (vph) | Minor St Vol (vph) | TWSC LOS | AWSC LOS | Roundabout LOS | Signal LOS | Optimal Control Type |
| 700 | 200 | 1.3 | 2.95 | 1.38 | 2.28 | T |
| 700 | 300 | 2.5 | 3.94 | 1.64 | 3.36 | R |
| 700 | 400 | 4.01 | 4.64 | 1.93 | 4.31 | R |
| 700 | 500 | 6 | 6.1 | 2.23 | 5.4 | R |

**TABLE 4 Optimal Intersection Control Based on Level of Service**

Comparing TWSC, AWSC, RA and Signals

| Total Major Street (veh/hr) | Highest Minor Street Volume (veh/hr): 70 | 140 | 210 | 280 | 350 | 420 | 490 | 560 | 630 | 700 |
|---|---|---|---|---|---|---|---|---|---|---|
| 100 | TARS | | | | | | | | | |
| 200 | TARS | ARS | | | | | | | | |
| 300 | ARS | ARS | AR | | | | | | | |
| 400 | ARS | ARS | AR | R | | | | | | |
| 500 | ARS | ARS | R | R | R | | | | | |
| 600 | ARS | RS | R | R | R | R | | | | |
| 700 | RS | RS | R | R | R | R | R | | | |
| 800 | RS | RS | R | R | R | R | R | R | | |
| 900 | RS | RS | R | R | R | R | R | R | R | |
| 1000 | RS | R | R | R | R | R | R | R | R | R |
| 1100 | RS | R | R | R | R | R | R | R | R | R |
| 1200 | RS | R | R | R | R | R | R | R | RS | R |
| 1300 | RS | R | R | R | R | R | R | R | RS | RS |
| 1400 | RS | R | R | R | R | R | R | RS | R | RS |
| 1500 | RS | R | R | R | R | R | R | RS | RS | S |
| 1600 | RS | R | R | RS | R | R | RS | RS | S | RS |
| 1700 | RS | R | R | RS | R | RS | S | RS | S | S |
| 1800 | RS | R | R | RS | RS | RS | RS | S | S | S |

(a)

Comparing TWSC, AWSC and Signals

| Total Major Street (veh/hr) | Highest Minor Street Volume (veh/hr): 70 | 140 | 210 | 280 | 350 | 420 | 490 | 560 | 630 | 700 |
|---|---|---|---|---|---|---|---|---|---|---|
| 100 | TAS | | | | | | | | | |
| 200 | AS | AS | | | | | | | | |
| 300 | AS | AS | A | | | | | | | |
| 400 | AS | AS | A | AS | | | | | | |
| 500 | AS | AS | AS | AS | AS | | | | | |
| 600 | AS | AS | AS | AS | S | S | | | | |
| 700 | S | S | AS | S | S | S | S | | | |
| 800 | S | S | S | S | S | S | S | S | | |
| 900 | S | S | S | S | S | S | S | S | S | |
| 1000 | S | S | S | S | S | S | S | S | S | S |
| 1100 | S | S | S | S | S | S | S | S | S | S |
| 1200 | S | S | S | S | S | S | S | S | S | S |
| 1300 | S | S | S | S | S | S | S | S | S | S |
| 1400 | S | S | S | S | S | S | S | S | S | S |
| 1500 | S | S | S | S | S | S | S | S | S | S |
| 1600 | S | S | S | S | S | S | S | S | S | S |
| 1700 | S | S | S | S | S | S | S | S | S | S |
| 1800 | S | S | S | S | S | S | S | S | S | S |

(b)

## TABLE 5 Optimal Intersection Control Based on Average Control Delay

**Comparing TWSC, AWSC, RA and Signals**

| | Highest Minor Street Volume (veh/hr) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Total Major Street (veh/hr) | 70 | 140 | 210 | 280 | 350 | 420 | 490 | 560 | 630 | 700 |
| 100 | T | | | | | | | | | |
| 200 | T | R | | | | | | | | |
| 300 | T | TR | R | | | | | | | |
| 400 | T | T | R | R | | | | | | |
| 500 | T | T | R | R | R | | | | | |
| 600 | T | T | R | R | R | R | | | | |
| 700 | T | T | R | R | R | R | R | | | |
| 800 | T | TR | R | R | R | R | R | R | | |
| 900 | T | R | R | R | R | R | R | R | R | |
| 1000 | T | R | R | R | R | R | R | R | R | R |
| 1100 | T | R | R | R | R | R | R | R | R | R |
| 1200 | T | R | R | R | R | R | R | R | R | R |
| 1300 | T | R | R | R | R | R | R | R | R | R |
| 1400 | R | R | R | R | R | R | R | R | R | R |
| 1500 | R | R | R | R | R | R | R | R | S | S |
| 1600 | R | R | R | R | R | R | R | S | S | S |
| 1700 | R | R | R | R | R | R | S | S | S | S |
| 1800 | R | R | R | R | R | S | S | S | S | S |

(a)

**Comparing TWSC, AWSC and Signals**

| | Highest Minor Street Volume (veh/hr) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Total Major Street (veh/hr) | 70 | 140 | 210 | 280 | 350 | 420 | 490 | 560 | 630 | 700 |
| 100 | T | | | | | | | | | |
| 200 | T | T | | | | | | | | |
| 300 | T | T | T | | | | | | | |
| 400 | T | T | T | T | | | | | | |
| 500 | T | T | T | T | S | | | | | |
| 600 | T | T | T | T | S | S | | | | |
| 700 | T | T | T | T | S | S | S | | | |
| 800 | T | T | T | S | S | S | S | S | | |
| 900 | T | T | S | S | S | S | S | S | S | |
| 1000 | T | T | S | S | S | S | S | S | S | S |
| 1100 | T | T | S | S | S | S | S | S | S | S |
| 1200 | T | S | S | S | S | S | S | S | S | S |
| 1300 | T | S | S | S | S | S | S | S | S | S |
| 1400 | T | S | S | S | S | S | S | S | S | S |
| 1500 | T | S | S | S | S | S | S | S | S | S |
| 1600 | S | S | S | S | S | S | S | S | S | S |
| 1700 | S | S | S | S | S | S | S | S | S | S |
| 1800 | S | S | S | S | S | S | S | S | S | S |

(b)

## TABLE 6 Optimal Intersection Control Based on Average Queue Length

**Comparing TWSC, AWSC, RA and Signals**

| | Highest Minor Street Volume (veh/hr) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Total Major Street (veh/hr) | 70 | 140 | 210 | 280 | 350 | 420 | 490 | 560 | 630 | 700 |
| 100 | T | | | | | | | | | |
| 200 | T | R | | | | | | | | |
| 300 | T | TR | R | | | | | | | |
| 400 | T | T | R | R | | | | | | |
| 500 | T | T | R | R | R | | | | | |
| 600 | T | T | R | R | R | R | | | | |
| 700 | T | T | R | R | R | R | R | | | |
| 800 | T | TR | R | R | R | R | R | R | | |
| 900 | T | R | R | R | R | R | R | R | R | |
| 1000 | T | R | R | R | R | R | R | R | R | R |
| 1100 | T | R | R | R | R | R | R | R | R | R |
| 1200 | T | R | R | R | R | R | R | R | R | R |
| 1300 | T | R | R | R | R | R | R | R | R | R |
| 1400 | R | R | R | R | R | R | R | R | R | R |
| 1500 | R | R | R | R | R | R | R | R | S | S |
| 1600 | R | R | R | R | R | R | R | S | S | S |
| 1700 | R | R | R | R | R | R | S | S | S | S |
| 1800 | R | R | R | R | R | R | S | S | S | S |

(a)

**Comparing TWSC, AWSC and Signals**

| | Highest Minor Street Volume (veh/hr) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Total Major Street (veh/hr) | 70 | 140 | 210 | 280 | 350 | 420 | 490 | 560 | 630 | 700 |
| 100 | T | | | | | | | | | |
| 200 | T | T | | | | | | | | |
| 300 | T | T | T | | | | | | | |
| 400 | T | T | T | T | | | | | | |
| 500 | T | T | T | T | T | | | | | |
| 600 | T | T | T | T | T | S | | | | |
| 700 | T | T | T | T | S | S | S | | | |
| 800 | T | T | T | S | S | S | S | S | | |
| 900 | T | T | S | S | S | S | S | S | S | |
| 1000 | T | T | S | S | S | S | S | S | S | S |
| 1100 | T | T | S | S | S | S | S | S | S | S |
| 1200 | T | S | S | S | S | S | S | S | S | S |
| 1300 | T | S | S | S | S | S | S | S | S | S |
| 1400 | T | S | S | S | S | S | S | S | S | S |
| 1500 | T | S | S | S | S | S | S | S | S | S |
| 1600 | S | S | S | S | S | S | S | S | S | S |
| 1700 | S | S | S | S | S | S | S | S | S | S |
| 1800 | S | S | S | S | S | S | S | S | S | S |

(b)

Comparing Tables 4 (a, b) to Tables 6 (a, b) reveals several new and interesting patterns which are quite different from the earlier study (*1*). With both groups, that AWSC had no application as the optimal intersection choice when using the average intersection control delay and average intersection queue length as the performance criteria. There is however some limited use when LOS is considered but that is even confined to major street volume of less than 600 veh/hr and minor street volumes of 350 veh/hr combination.

Tables 4a and 4b show the best intersection control type using LOS as the performance indicator for the given volume combination. Table 1 shows that the LOS thresholds are not defined for unique values, but defined over a range of delay values. Thus using LOS as the indicator, it is not very apparent which traffic control type is best for very low volume and very high volume combinations used in the tables. Table 4a also show a wide range of traffic volume combinations where roundabout give the best LOS. For the Table 4b where roundabout is not considered, it can be seen that the AWSC becomes competitive for low volumes on both the major and minor street. For both Tables 4a and 4b, the AWSC and TWSC do not show an area where they are uniquely applicable as the best choice. The roundabout and Traffic signal are best for medium to high volume traffic combination at the intersection.

Table 5 (a, b) shows the best intersection control using average intersection control delay as the performance indicators. Table 5 shows a more defined option than the Table 4. This can be attributed to the fact that, average control delays have unique values as opposed to the range used in determination of LOS. For the Table 5a, one can clearly see the regime where a TWSC, Roundabout and Signalized controls would best be used as against the Table 4a where the user has a combination of the control types presented. For the Table 5, it is also observed that the AWSC did not show up. When the raw data was critically examined, it was noticed that, but for the presence of, roundabouts and signalized controls, the AWSC would have had a unique regime for intersections with volumes slight higher than the section of the table showing TWSC. The delays obtained in these instances were a shade higher than those obtained for the signalized controls, but because the signalized presented the optimum solution, that was chosen. When roundabouts are considered, it can be clearly seen that they can perform well over a wide range of traffic volumes with minimal delays compared to the other types of control. This phenomenon partly explains why certain states are changing some signalized intersections to roundabouts as they tend to perform better over a wide range of volume changes compared to other intersection control types. However, at very high traffic volumes, the signalized intersection is still the best control type that gives the minimum delay.

Table 6 (a, b) shows the best intersection control type using average intersection queue length as the performance indicator. The intersection queue length is derived from the product of the average intersection control delay and the total intersection traffic volume. The table follows closely the pattern for the Table 5. For Table 6a, the regime for the TWSC, roundabouts and signalized controls are well defined. For Table 6b, the two controls, TWSC and Signalized were the only ones that showed up just as observed in Table 5b. Table 6 also show roundabout performing best as the intersection control type with the minimal queue over a wide range of volume combination.

From the Tables 4, 5 and 6, it can be said that by using the volume combination alone, a preliminary selection of an intersection control type can be obtained. Coupled with the engineering judgment of the traffic engineers, this tool can serve a useful purpose in the field as well, since they can be consulted to make quick decision. These tables also confirmed the delay reductions that come about with the introduction of modern roundabout into the road network, as they are proving to be very versatile when traffic volume varies rapidly at intersections. Additional advantages are reduction of queues on at intersections and improved safety at intersections which hitherto have been known to be prone to accidents and also as a speed calming measure in most communities. The tables produced here can find a variety of uses with practitioners. They can serve as a quick reference for field use for intersection and also as a quick method for determining the best traffic control (preliminary) type at an intersection. As always, further engineering studies like life cycle cost, safety analysis etc will have to be conducted before finally accepting and designing the control type for an intersection.

## CONCLUSIONS

The HCM 2000 uses average control delay as the measure of the LOS and intersection delay for both the signalized and unsignalized intersections, as opposed to the 1994 HCM where average stop delay per vehicle was used for signalized intersections and total delay was used for unsignalized intersections. The HCM 2000 approach allow for direct comparison of the various intersection LOS without any modification to the result.

Guidelines were developed using the HCM 2000 and other analysis tools for determining optimal intersection types based on selected performance measures: control delay, queue, and LOS. A series of tables were derived for easy use by traffic engineers given the traffic volume conditions of an intersection. The details of the guidelines were included in Tables 4, 5 and 6.

Average intersection control delay and average intersection queue length appeared to be better performance indicators for selecting intersection control types compared to LOS. Roundabouts showed superior performance over a wide range of traffic volume combinations compared to other intersection control types although signalized intersections are still better options when the traffic volumes are high (e.g., given the actual volume range).

This study is limited to intersections with single-lane approaches. However, it can be easily expanded to multi-lane cases.

**Samuel Kofi Ahiamadi**, Graduate Research Assistant, Center for Advanced Transportation Education and Research (CATER), Department of Civil and Environmental Engineering, University of Nevada, Reno, TEL: (775) 784-6195, skahiamadi@yahoo.com

**Zong Z. Tian,** Associate Professor, P.E, Center for Advanced Transportation Education and Research (CATER), Department of Civil and Environmental Engineering University of Nevada, Reno, TEL: (775) 784-1232, zongt@unr.edu

# REFERENCES

1 Marek, J.F., M. Kyte, Z., Tian, K. Lall, K. Voigt, Determining Intersection Traffic Control Using the 1994 Highway Capacity Manual, *ITE Journal*, December, 1997
2 Rodegerdts, L., A. Cibor, A. Pochowsk, Status of Rounadbout in North America, *National Roundabout Conference*, Kansas City Missouri, 2008.
3 Highway Capacity Manual, *TRB, National Research Council*, Washington D.C., 2000
4 Highway Capacity Manual, Proposed Draft, Chapter 17, Part C, 2006
5 Robinson, B. W., L, Rodegerdts, W. Scarbrough, W. Kittelson, R. Troutbeck, W. Brilon, L. Bondzio, K. Courage, M. Kyte, J. Mason, A. Flannery, E. Myers, J. Bunker, G. and Jacquemart, "*Roundabouts: An Informational Guide"*, Report No. FHWA-RD-00-067, Washington, DC: USDOT, FHWA, June 2000.
6 Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, B. Brilon, N. Wu, B. Persaud, C Lyon, D. Harkey, D. Carter, "*Roundabouts in the United States"*, NCHRP Report 572, Transportation Research Board. 2007
7 Kittelson & Associates, Inc NCHRP 3-65: *Applying Roundabouts in the United States*
8 Akcelik, R, Evaluating Roundabout Capacity, Level of Service and Performance, *ITE Annual Meeting*, 2009
9 Peterson R.W, S.J.Lewis, F.J. Fugal, R.D. Lancaster, "Modelling Roundabout: Lessons learned in Idaho" *National Roundabout Conference*, Kansas City Missouri. 2008,
10 Kennedy, D. R., K. M. Taylor, Estimating Roundabout Performance Using Delay and conflict Opportunity Crash Prediction, *National Roundabout Conference*, Vail, Colorado, 2005
11 Florida Department of Transportation "*Florida Roundabout Guide*" 1996
12 State of Maryland Department of Transport, State Highway Administration, "*Roundabout Design Guidelines*", 1995
13 Wisconsin Department of Transport. "*Facilities Development Manual*", Chapter 11, Section 26, April 2008
14 Lee, J. C., B.B. Kidd, B. Robinson, W. and Scarbrough, *Roundabouts: An Arizona Case Study and Design Guidelines*, Final Report 545. Phoenix, AZ: Arizona Department of Transportation, July 2003.
15 Hallmark, S., H.N. Isebrands, "Planning Level Guidelines for Modern Roundabouts"-Iowa Department of Transportation, *Technical Memorandum Nov 2008, CTRE project 06-255*, Iowa State University
16 Tian, Z., F. Xu, L Rodegerdts, W. Scarbrough, B. Ray, W. Bishop, T.C. and Ferrara, ., "*Roundabout Geometric Design Guidance*", Federal Report # F/CA/RI-2006/13, California Department of Transportation, 2007.
17 *Manual of Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition, Washington DC:, US Department of Transportation, *Federal Highway Administration*
18 Brilon, W., M. Grossmann, Aktualisiertes Berechnungsverfahren fur knoptenpunkte ohne Lichtsignalanlagen. Forschung Strassenbau and Strassenverkehrstechnik, Heft 596, 1991
19 Kraft, W. H., (ed.), *Traffic Engineering Handbook* -6th Edition, Institute of Transportation Engineers, ITE 2009