Saturation Headways at Stop-Controlled Intersections

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Capacity analysis procedures for stop-controlled intersections require saturation headways or related parameters as inputs. Unfortunately, no data base currently exists for these parameters, including critical gaps and follow-up times for two-way stop-controlled (TWSC) intersections and saturation headways for all-way stop-controlled (AWSC) intersections, for conditions found in the United States. The results of a set of recent measurements of these parameters are reported, and several important issues are explored: (a) how are the critical gap and follow-up gap measured at a TWSC intersection and what is the relationship between them? (b) what is the saturation headway (i.e., follow-up gap) for a TWSC intersection? (c) what is the effect of turning movements on the saturation headway at an AWSC intersection? and (d) should other cases be considered, in addition to the standard four cases, when measuring the saturation headway at an AWSC intersection? For TWSC intersections, a relationship was found between the critical gap and the follow-up time. In addition, the importance of the directional movement of the major street vehicle terminating a gap as it affects the critical gap was determined. A new set of categories was developed for saturation headway cases for AWSC intersections, and the importance of the movement direction of the subject approach vehicle on the saturation headway was determined.

The basic parameter used to estimate capacity at a signalized intersection is saturation headway. Ideal saturation headway is the difference in the passage time at the intersection stop line between two consecutive vehicles once the queue is moving in a stable manner. The 1985 *Highway Capacity Manual* (HCM) (*1*) notes that the saturation headway is "estimated as the constant average headway between vehicles which occurs after the 6th vehicle in the queue and continues until the last vehicle in the queue clears that intersection." Field measurements must consider the start-up lost time, or that time at the beginning of the green phase that is required for the queue to begin to move. The capacity procedures given in Chapter 9 of the HCM provide a standard value for the ideal saturation headway of 2.0 sec/veh, which yields an ideal saturation flow rate of 1,800 vehicles per hour (vph) of green. The procedure provides adjustments to this ideal value to consider the effects of intersection geometry, opposing traffic flow, signal timing parameters, and pedestrian flows.

The capacity analysis procedure for unsignalized intersections is given in Chapter 10 of the HCM. A new version of Chapter 10 is planned for release in 1994, with an improved procedure for two-way stop-controlled (TWSC) intersections based on a capacity methodology developed by Siegloch and described by Brilon et al. (*2*). The chapter also includes a procedure for estimating the capacity of an all-way stop-controlled (AWSC) intersection based on *Transportation Research Circular 373* (*3*).

Both of the capacity procedures for stop-controlled intersections use the concept of saturation headway. The TWSC intersection procedure is defined in terms of the critical gap and the follow-up gap. The critical gap is the minimum time gap in the major traffic stream needed by a minor stream vehicle to merge into or travel through the major stream. The follow-up gap is the minimum headway between the first vehicle and the second vehicle, and subsequent vehicle pairs, as they enter the same major stream gap, when a continuous queue exists on the minor street approach. In effect, the follow-up gap is the saturation headway for the minor traffic stream when the conflicting major stream flow is zero.

Table 10-2 in the new version of Chapter 10 gives critical gaps ranging from 5.0 sec for major stream left-turning traffic to 6.5 sec for minor stream left-turning traffic. Follow-up gaps range from 2.1 sec for left-turning traffic from the major street to 3.4 sec for left-turning traffic from the minor stream. The capacity on the minor stream approach, based on Siegloch's work, is a function of the major stream flow rate (v_c), the critical gap (t_g), and the follow-up gap (t_f). The capacity equation is given in Equation 1.

$$c_p = \frac{3,600}{t_f}\, e^{-v_c t_0/3,600} \tag{1}$$

One of the problems with this procedure, however, is that it has not been validated with data collected from sites in the United States. Data in Table 10-2 were measured first in Germany and then slightly modified on the basis of studies of critical gap for a very limited number of sites in the United States. None of these U.S. studies attempted to measure the follow-up gap and assumed only the fixed relationship between the critical gap and the follow-up gap given in Equation 2:

$$t_g = 0.6\, t_f \tag{2}$$

A further complication is the inherent difficulty in measuring the critical gap. The HCM defines the critical gap as the median time headway between two successive vehicles in the major street traffic stream that is accepted by drivers in a subject movement that must cross or merge with the major street flow. Several researchers [e.g., Kittelson and Vandehey (*4*)] have pointed out the difficulty in using this definition. In fact, the formulation of the Siegloch equation is based on a very specific description of the gap acceptance process that may yield estimates of the critical gap that are different from those produced by the HCM definition. According to the Siegloch formulation, one vehicle will accept a major stream gap that is greater than the critical gap but less than the sum of the critical gap and the follow-up gap. Two vehicles will use a gap that is greater than the sum of the critical gap and the follow-up gap but less than the sum of the critical gap and twice the follow-up gap. To

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measure the critical gap in this way, a continuous minor stream queue is required. Brilon et al. recommend the use of either the maximum likelihood technique or Ashworth's method if a continuous queue is not present on the minor street approach (*5*).

The AWSC intersection capacity procedure is based on a set of four saturation headways, each defined according to the conditions faced by the subject approach driver. Table 10-5 in the new version of Chapter 10 gives values of 3.5 sec/veh when the subject vehicle is faced with neither opposing nor conflicting stream vehicles and 9.0 sec/veh when the subject vehicle is faced with both opposing and conflicting approach vehicles. Table 1 presents the saturation headway from Table 10-5 of the new version of Chapter 10.

The capacity of an approach is based on the mix of traffic conditions faced by the subject approach driver and is defined in terms of the volume proportions of each of the intersection approaches. The capacity of an approach varies from 1,100 vph when the subject driver faces no opposing or conflicting vehicles to 525 vph when the subject driver faces a continuous queue of vehicles on both the opposing and conflicting approaches.

The four headway cases given in Table 1 do not consider directly the effects of turning traffic. The Case 2 headway, which is a subject vehicle faced by an opposing vehicle and no conflicting vehicles, does not consider the effects of the interaction of one or both of the vehicles turning and not traveling straight through the intersection. The value of 5.5 sec given in Table 1 is assumed to cover the range of combinations that actually make up Case 2: for example, pairs of through vehicles with no turning conflicts, one through vehicle opposed by a left-turning vehicle, one through vehicle opposed by a right-turning vehicle, and so on. Although the capacity equation given in the new version of Chapter 10 does provide an adjustment for turning movements, it is based only on the overall proportions of turning movements and not on the microscopic or vehicle-by-vehicle interactions that actually reflect the impedance resulting from turning vehicle conflicts.

STUDY OBJECTIVES

The purpose of this paper is to report on a study of saturation headway measurements made at stop-controlled intersections in order to explore several questions raised in the previous discussion; these issues include the following:

1. How are the critical gap and follow-up gap measured at a TWSC intersection? What is the relationship between the follow-up gap and the critical gap?
2. What is the saturation headway (i.e., follow-up gap) for a TWSC intersection?
3. What is the effect of turning movements on the saturation headway at an AWSC intersection?
4. Should other cases be considered, in addition to the standard four cases, when measuring the saturation headway at an AWSC intersection?

This paper also investigates one other issue important in the formulation of the capacity analysis procedure for TWSC intersections. The gap acceptance mechanism that is the basis for the TWSC intersection capacity analysis procedure assumes a priority among the various traffic streams at a TWSC intersection. Traffic streams assumed to conflict with each minor stream movement are identified, and the degree of conflict is specified. For traffic on the stop-controlled approach, right-turning vehicles arriving from the left on the major street are weighted by a factor of 0.5, indicating that although this group of major street vehicles affects the operation of the minor street traffic, the effect is less than that for the through major street traffic. However, the factor of 0.5 is based not on empirical data but on judgment only. This paper provides a procedure that may help to validate this relationship.

DATA COLLECTION AND REDUCTION METHODS

Data were collected at two sites for this study, at one AWSC intersection site and one TWSC intersection site. The AWSC intersection site is located in suburban westside Portland, Oregon. It has four legs with a single lane on each approach. One video camera was used to record traffic flow through the intersection. The camera was located so that all vehicles entering the intersection could be viewed and so that the queue activity on one approach could be viewed also. The TWSC intersection site is located in Pullman, Washington. It is a T-intersection, with two lanes (one each for left-turning and right-turning vehicles) on the stop-controlled approach. The major street has single lanes on each approach. One camera was used to record traffic operations, again recording all vehicle movements through the intersection as well as the queue activity on the stop-controlled approach. Since a continuous queue was present only for the minor street left-turn approach, only this movement was used for the analysis described later in this paper.

Vehicle passage times through the conflict point at the intersection were recorded using the Traffic Data Input Program (*6*) operating on an IBM-compatible personal computer. While observing the videotape of traffic traveling through the intersection, the pro-

TABLE 1 Saturation Headway Data for AWSC Intersections

Condition	Mean Saturation Headway, sec/veh			
	Case 1	Case 2	Case 3	Case 4
All data	3.5	5.5	6.5	9.0
Single lane approach sample sites	3.9	5.6	6.5	9.0
Multi lane approach sample sites	1.5	4.3	6.3	9.3

Notes:
Case 1: Subject vehicle does not face either opposing or conflicting vehicles.
Case 2: Subject vehicle faces only an opposing vehicle.
Case 3: Subject vehicle faces only conflicting vehicles.
Case 4: Subject vehicle faces both opposing and conflicting vehicles.

gram operator presses a key to record the desired events. The events of interest include the passage times of all vehicles as well as the times that each vehicle on the subject stop-controlled approach enters the end of the queue, arrives at the stop line, and enters the intersection. This effort produces a raw data file for each of the two intersections.

For the TWSC intersection, the raw data file was used to create a second file with the following variables for each subject approach (minor street left-turning) vehicle: the time that the vehicle entered the queue, the time that the vehicle arrived first in line at the stop line, the time that the vehicle left the stop line, and the passage times through the intersection of each higher-priority vehicle seen by the minor stream vehicle. This latter information was used to construct the gaps that were accepted and rejected by the minor stream vehicle and the pair of higher-priority vehicles that defined the beginning and end of each gap. A third data set was also created on the basis of the number of minor stream vehicles using each major traffic stream gap. Only data that were collected during the existence of a continuous queue on the minor street were used in creating the data sets.

For AWSC intersections, the raw event data file was used to create a record for each vehicle on the subject stop-controlled approach that included the following variables: the time that the vehicle arrived in the queue, the time that the vehicle arrived first in line in the queue, the time that the vehicle entered the intersection, and a list of opposing and conflicting vehicles that entered the intersection since the departure of the previous subject approach vehicle. This latter information allowed the determination of the saturation headway as well as conditions faced by the subject approach driver. Only those subject approach vehicles that were a part of a continuous queue were included in the data base.

TWSC INTERSECTION DATA ANALYSIS

Determination of Critical Gap and Follow-Up Gap

Gap acceptance theory defines the critical gap and the follow-up gap in a clear manner. Figure 1 illustrates these definitions for a critical gap of 5.0 sec and a follow-up gap of 2.5 sec. The theory states that one minor stream vehicle will use a gap that is greater than the critical gap and less than the sum of the critical and the follow-up gaps. As stated previously, the follow-up gap is just the saturation headway for the minor stream, since each time the major stream gap increases by the follow-up gap, one additional minor stream vehicle can be absorbed into the major traffic stream. The primary requirement for this mechanism to be used as the basis for field measurements is that the minor stream must have a continuous queue.

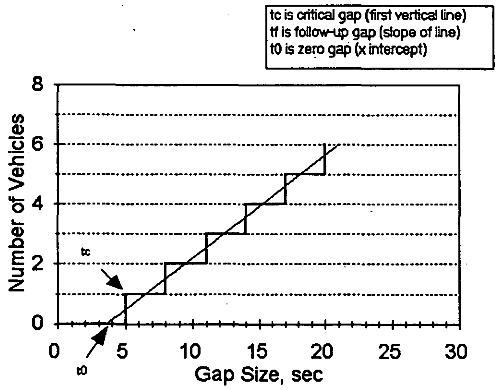

FIGURE 1 Gap acceptance mechanism.

Table 2 presents the range of major stream gap sizes used by various numbers of left-turning minor stream vehicles at the TWSC intersection used for this study during periods of continuous queueing on the minor stream approach. Figure 2 shows a plot of the individual gap sizes versus the number of vehicles using each gap. The mean gap size for each vehicle number is also shown. These mean values are used to estimate a regression line, whose parameters are then used to estimate the various gap parameters.

In Table 2 some of the vehicles-per-gap cells included only a few observations, even two or fewer. The regression line was plotted using the data for a range of one vehicle to four vehicles per gap, cells that included three or more observations. This line is shown in Figure 3. Several parameters of interest can be derived from the equation that forms the basis for the line. The follow-up gap is the reciprocal of the slope of the line. The zero gap is the x-intercept. The critical gap is the zero gap plus half the follow-up gap.

The parameter estimates that were developed from the regression line are as follows:

Gap	*Estimate (sec)*
Zero	3.0
Follow-up	3.3
Critical	4.7

Two comparisons can be made with respect to these parameters. In this case, the follow-up gap is equal to 0.70 of the critical gap. This compares with the value of 0.60 assumed in the current version of Chapter 10 of the HCM and a computed value of 0.52 using data provided in the new version of Chapter 10. The saturation flow rate, the reciprocal of the follow-up gap, is 1,090 vph. This compares with a value of 1,060 vph from the new version of Chapter 10.

Effect of Major Stream Right-Turn Vehicles on Critical Gap and Follow-Up Gap

Table 10-3 in Chapter 10 of the HCM gives the traffic streams that have priority over each minor traffic stream at a TWSC intersection. The table further describes the manner in which these conflicting volumes are to be summed in order to provide an estimate of the total conflicting volume faced by a given subject traffic stream. For example, the conflicting volume for the left-turning traffic on the minor traffic stream includes half of the major street right-turning volume from the left. The use of the one-half in this term has been justified as follows: although the minor stream left-turning traffic does not have to share intersection space with the major stream right-turning traffic arriving from the left, it is affected by this stream. But it is often difficult to know if a major stream vehicle will indeed turn right even if it has so indicated with its turn signal. This uncertainty means that the major stream right-turning movement does affect the behavior of the minor stream left-turning traffic. Using only half of this traffic volume recognizes the fact that the effect is not as great as that for the through major stream traffic. Again, the value of one-half is based on judgment only.

Data collected in this study allow the development of a procedure for the quantification of this effect. For the left-turning minor

TABLE 2 Number of Vehicles Accepting Gaps of Various Sizes

Number of Vehicles Using Gap	Mean Gap, sec	Standard Deviation	Maximum Value, sec	Minimum Value, sec	Obs
1	5.93	2.26	11.10	1.43	85
2	10.05	2.38	14.28	4.28	27
3	13.93	2.62	19.88	11.42	10
4	15.08	4.42	18.89	8.89	3
5	23.04	4.15	27.19	18.89	2
6	28.24	-	28.24	28.24	1
7	-	-	-	-	0
8	46.91	-	46.91	46.91	1

Note:
1. Obs is the number of observations.
2.The data shown in this table are for the left turning traffic from the minor street.

traffic stream vehicles, each gap that was accepted is classified into one of two categories: the first category includes those gaps that are terminated by a major street right-turning vehicle from the left; the second category includes all other gaps accepted by these left-turning minor stream vehicles. Table 3 shows a clear difference between these two cases. When a gap is terminated by a major stream right-turning vehicle from the left, more minor stream vehicles are likely to use a gap of a given size. This is also indicated in the size of the critical gap for these two cases. If a gap is terminated by a major stream right-turning vehicle from the left, the critical gap is estimated to be 3.2 sec. For all other gap termination combinations, the critical gap is estimated to be 50 percent higher, or 4.8 sec.

The significance of this relationship is more clear when the capacity equation is examined further. The issue under consideration here can be stated mathematically as follows. If t_{c1} is the overall critical gap for all minor stream left-turning vehicles (regardless of the conflicting vehicle that terminates the gap) and if t_{c2} is the critical gap for minor stream vehicles when the gap is terminated by a major street right-turning vehicle from the left, the correct adjustment to the conflicting volume equation is given by α in Equation 3:

$$\alpha\, v_{RT}\,(t_{c1} - 0.5\, t_f) = v_{RT}\,(t_{c2} - 0.5\, t_f) \qquad (3)$$

where α is currently given as 0.5 in the HCM procedures, v_{RT} is the major street right-turning volume approaching from the left, and each side of Equation 3 is the exponent in the Siegloch capacity equation. If t_{01} and t_{02} are the zero gaps for the two cases described earlier, this relationship can be simplified by solving for t_{01} in terms of t_{02}, as given in Equation 4.

$$t_{02} = \alpha\, t_{01} \qquad (4)$$

In this case, α is equal to 1.3 divided by 2.8, or 0.46. This is nearly equal to the factor of 0.5 now used in the conflicting volume equation. This method can be used to check the assumptions of conflicting volume used for other minor stream movements as given in Figure 10-3 of the HCM.

AWSC INTERSECTION DATA ANALYSIS

The new version of the HCM Chapter 10 describes a capacity analysis procedure based on a set of conditions faced by drivers on the

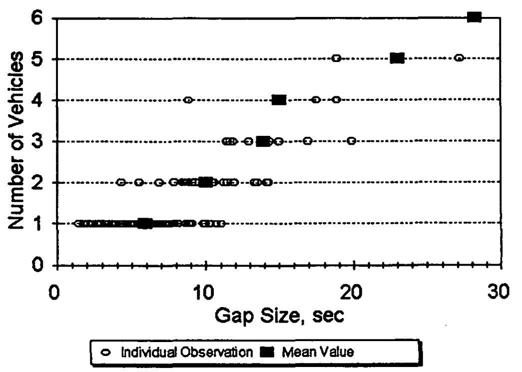

FIGURE 2 Gap size versus number of vehicles using gap (individual observation and mean value).

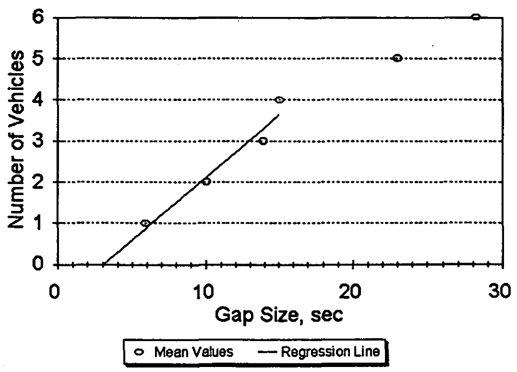

FIGURE 3 Gap size versus number of vehicles using gap (mean values and regression line).

TABLE 3 Effect of Vehicle Movement Terminating Accepted Gap

Vehicle Movement Terminating Accepted Gap	Mean Gap Size for Various Number of Vehicles Using Gap, sec			t_c, sec
	1 Vehicle	2 Vehicles	3 Vehicle	
Major street RT vehicle from the Left	4.9	9.6	12.2	3.2
All other major street vehicles	6.7	10.4	14.4	4.8

subject approach. The four cases, along with the saturation headways measured for each, are described in Table 1.

Although these data led to a more comprehensive capacity analysis procedure than was previously available, the procedure does have some obvious limitations. Most important, the four cases provide only a very simplified classification of the conditions actually faced by the subject approach driver. Case 2, for example, is the condition in which the subject approach driver is faced by a driver on the opposing approach. The turning movements of either driver, clearly important factors in the resulting saturation headway, are not considered.

Saturation headway data were collected for one approach of an AWSC intersection to determine if there were subsets of these four basic cases that could be established so that the capacity estimation procedure given in Chapter 10 could be improved. For each subject approach vehicle that was a part of a continuous queue, the saturation headway was measured and the conditions faced by the driver were identified, including the turning movement directions for all vehicles.

Two separate series of tests were conducted. First, for each of the four cases, the effect of the direction of the subject approach vehicle was determined. Second, subsets of Cases 3 and 4 were identified and tested.

Effect of Subject Approach Vehicle Movement

Table 4 gives a summary of the saturation headway data for each of the four cases according to the directional movement of the subject approach driver. The difference-in-means test was used to determine if there was a significant difference between the mean value of the saturation headway as a function of the turning movement direction of the subject vehicle. Since there was a small number of left-turning vehicles in each case, only through and right-turning vehicles could be compared.

The difference-in-means test compares the mean and standard deviation for two samples, with the hypothesis that the two samples are drawn from the same population. The null hypothesis (that the saturation headways for the through and right-turning vehicles are from the same population) for Cases 3 and 4 can be rejected at a confidence level of 0.99. The null hypothesis can be rejected for Cases 1 and 2 at a 0.95 level. Thus it can be concluded that the directional movement of the subject vehicle has an effect on the saturation headway.

Table 5 presents the computed capacities using the saturation headways for the through and right-turning movements for each of the four cases. Separation of the saturation headways by turning movement results in considerably different capacity estimates, with capacity differences ranging from 27 to 50 percent between the through and the right-turning movement capacities. Since the capacity equation now includes only an additive factor to account for turning movements, some future adjustment clearly is required so that a more accurate estimate of approach capacity is available.

Consideration of Case Subsets

Another way of improving the AWSC intersection capacity procedure is to determine if the four cases can be divided into subsets that better reflect the conditions faced by the subject vehicle. For example, Case 3 states that the subject vehicle is faced by vehicles on the conflicting approach and not on the opposing approach. But this case can include one or two conflicting vehicles, one from the left and one from the right, or both.

Several subsets were considered for Cases 3 and 4 to determine if additional cases are justified. Table 6 presents these subsets. Table

TABLE 4 Effect of Turning Movement Direction on AWSC Intersection Saturation Headways

Case	Mean, sec			Standard Deviation			Observations			Test Statistic
	LT	TH	RT	LT	TH	RT	LT	TH	RT	
1	1.6	3.0	2.1	0.03	1.52	0.97	2	14	37	2.13
2	3.2	4.2	2.8	-	1.53	1.25	1	14	12	2.49
3	6.6	6.3	4.9	2.71	1.43	1.83	4	57	25	3.37
4	8.2	7.9	6.2	2.44	2.10	1.91	15	164	25	4.11

Note: The test statistic is computed using the difference in means test.

TABLE 5 Effect of Turning Movement on Approach Capacity of AWSC Intersection

Case	Headway, sec		Capacity, veh/hr		Percent Difference
	TH	RT	TH	RT	
1	3.0	2.1	1200	1714	+43
2	4.2	2.8	857	1286	+50
3	6.3	4.9	571	735	+29
4	7.9	6.2	456	581	+27

7 shows the saturation headways that were measured for each of the six subsets. Tables 8 and 9 give the difference-in-means test statistics that resulted in the comparisons between the subsets. Several conclusions can be made with respect to the data presented in these tables.

First, there is no statistically significant difference between Cases 3a (5.1 sec) and 3b (5.6 sec). That is, from the standpoint of the subject approach driver, it makes no difference if a conflicting vehicle approaches from the left or the right, as long as there is only one conflicting vehicle.

But there is a significant difference between Case 3a or 3b and Case 3c (6.8 sec). Thus if one conflicting vehicle is present on both the left and the right approaches, the saturation headway for the subject vehicle is different, in this case longer, than if the subject vehicle were faced by only one conflicting vehicle.

There are also some differences in the three Case 4 subsets. Similar to the results for Cases 3a and 3b, there does not appear to be a significant difference between the Case 4a and 4b subsets (6.8 and 6.9 sec). But there are differences between the subsets of Cases 4a and 4b and of Case 4c (8.4 sec). Thus, even though the direction of approach on the conflicting approach does not make a difference, the number of conflicting vehicles is significant.

Future versions of the capacity model for AWSC intersections should consider more than just the four cases now included. This paper has shown that at least two additional cases are warranted.

SUMMARY AND CONCLUSIONS

The results of a study of the saturation headway and related data for stop-controlled intersections have been presented. Data collected from one TWSC intersection and one AWSC intersection have been used to illustrate several important aspects about the saturation headway, and thus the capacity, of these two types of intersection.

For TWSC intersections,

- The theoretical definitions of the critical gap and the follow-up gap that underlie gap acceptance theory were described, and values for the two parameters were computed on the basis of data collected at the study site. The relationship between these two parameters was given.
- The importance of the directional movement of the major stream vehicle terminating a gap was illustrated for gaps that were rejected and accepted by minor stream left-turning vehicles. The

TABLE 6 Subsets for Saturation Headway Cases

Subset	Description
3a	One conflicting vehicle from the right
3b	One conflicting vehicle from the left
3c	One conflicting vehicle from both the left and the right
4a	One conflicting vehicle from the left and one opposing vehicle
4b	One conflicting vehicle from the right and one opposing vehicle
4c	One conflicting vehicle from both the left and right, and one opposing vehicle

TABLE 7 Saturation Headways for Subsets for AWSC Intersections

Subset	Mean Headway, sec	Standard Deviation	Observations
3a	5.1	1.60	31
3b	5.6	1.38	20
3c	6.8	1.67	36
4a	6.9	1.62	32
4b	6.8	1.57	62
4c	8.4	2.39	82

TABLE 8 Test Statistics for Case 3

	Case 3a	Case 3b	Case 3c
Case 3a	-	-1.115	-4.149
Case 3b	1.115	-	-2.864
Case 3c	4.149	2.864	-

TABLE 9 Test Statistics for Case 4

	Case 4a	Case 4b	Case 4c
Case 4a	-	-0.229	-3.85
Case 4b	0.229	-	-4.777
Case 4c	3.85	4.777	-

technique described here allows a quantification of the conflicting vehicle equations now given in Figure 10-3 of the HCM.

For AWSC intersections,

- The effect of the turning movement direction of the subject approach vehicle on the saturation headway was determined to be significant. This effect must be considered in future versions of the capacity equation.
- The classification of the four basic saturation headway cases for AWSC intersections into a new set of subsets was described, and a series of statistical tests were used to identify the new categories that could be justified. The effect on the approach capacity was illustrated.

Each of the factors should be considered in greater depth as the capacity procedures for stop-controlled intersections are modified and improved. The results described here may provide some guidance on some of the specific changes that should be considered.

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