A Further Investigation on Critical Gap and Follow-Up Time

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ABSTRACT

The 1997 update to the *Highway Capacity Manual* (HCM) includes a new set of critical gap and follow-up time values calibrated based on the U.S. conditions. This paper is to present the detailed investigation on various factors affecting the critical gap and follow-up time, so that users can have a better understanding of the recommended critical gap and follow-up time values. The investigation was based on the comprehensive database established during the NCHRP 3-46 project, Capacity and Level of Service at Unsignalized Intersections.

The paper first identified various factors that might affect critical gap and follow-up time, such as intersection geometry, traffic movements, vehicle type, speed limits, and delay. Step-wise regression technique was then applied to identify the significance of these various factors. The relationship between critical gap and follow-up time values was also investigated.

It was found that the major factors affecting critical gap and follow-up time include intersection geometry, vehicle type, approach grade, and traffic movements. While an independent set of follow-up time values were recommended, the follow-up time to critical gap ratio was found to be approximately 0.60, which had been reported in previous studies. The newly recommended set of critical gap and follow-up time values formed the basis for the procedures for two-way stop-controlled intersections included in the 1997 update to the HCM and the 2000 HCM.

1. INTRODUCTION

The 1997 update to the *Highway Capacity Manual* (HCM) includes new procedures for estimating capacity and level-of-service (LOS) at two-way stop-controlled (TWSC) intersections (TRB 1997). One of the significant components of the update is a new set of critical gap and follow-up time values, calibrated based on the U.S. conditions.

Previous studies have concluded that the maximum likelihood method is one of the most promising methods for estimating critical gap (Brilon and Koenig 1997). General guidelines on how to apply the maximum likelihood methodology to measure critical gap have been documented in previous studies (Troutbeck 1992; Tian et al. 1999). The maximum likelihood methodology provides critical gap measurements based on the maximum rejected gap and the accepted gap for each driver, and the critical gap estimated by such a method represents an average value of all the drivers observed. As for the follow-up time, it can normally be measured directly from the field (Kyte et al. 1996). Follow-up time can be measured for individual vehicles whenever two consecutive vehicles in a queue discharge from a minor stream. The average follow-up time value is obtained from individual measurements.

The critical gap and follow-up time measured using the above methodology represent average traffic and intersection geometry conditions. As a result, the capacity and delay estimates based on these general critical gap and follow-up values also reflect average conditions. It is important to know how critical gap and follow-up time might vary based on various traffic and geometry conditions, so that more accurate capacity and delay estimates can be obtained based on specific conditions.

An extensive database was established during the NCHRP 3-46 project, Capacity and Level of Service at Unsignalized Intersections (Kyte et al. 1996). The database included measurements of critical gap and follow-up time at more than 40 TWSC intersections in 5 geographical regions (Southwest – California State, Southeast – Alabama State, Central – Wisconsin State, Northwest – Oregon State and Washington State, and Northeast – New York State) throughout the United States. The paper is intended to address the detailed analysis of various factors that might affect critical gap and follow-up time. These factors include geographical region, intersection geometry, traffic movements, vehicle type, speed, delay, etc. Step-wise regression was applied to identify the significance of these various factors. Analyses were also conducted to examine individual gap characteristics in microscopic level, and to investigate a previously reported ratio of 0.60 between follow-up time and critical gap values (Brilon 1988).

2. REGRESSION ANALYSIS ON CRITICAL GAP

The investigation of the factors that affect the critical gap was conducted using linear regression. Such an analysis is somewhat a macroscopic level analysis because the analysis was based on the average critical gap obtained from observing a number of drivers. For the purpose of the analysis, a macroscopic database was established. The database includes measurements of critical gap values as well as the associated attributes from more than 40 TWSC intersections throughout the United States. In order to increase the sample size, the entire intersection data was divided into several sub-sections if a significant number of minor stream drivers were observed. For example, if more than 200 minor street vehicles were observed in a 2-hour period, the critical gap can be measured for both the entire time period and for each 15-minute time period, which would yield a total of 9 critical gap values from a single site.

A step-wise regression technique was applied in the analysis. The first step was to identify the variables which might affect the critical gap. Regression was then conducted by including or excluding certain variables. Variance analysis was then conducted to compare the statistics of the regression equations for both cases when a variable was included or excluded. The variance analysis determines whether the variable has significant impact on the critical gap. The significance level was set at 5 percent level. By repeating the same process, the variables which had significant impact on critical gap can then be identified. The following section illustrates an example of how this process was conducted.

2.1 The Independent Variables

The independent variables considered in the regression analysis are described below.

t_c	the mean critical gap measured for a minor stream movement using the maximum likelihood method
R_{NE}	a dummy variable which has the value of 1 if the site is in the Northeast region and 0 otherwise
R_{NW}	a dummy variable which has the value of 1 if the site is in the Northwest region and 0 otherwise
R_{CE}	a dummy variable which has the value of 1 if the site is in the Central region and 0 otherwise
R_{SE}	a dummy variable which has the value of 1 if the site is in the Southeast region and 0 otherwise
R_{SW}	a dummy variable which has the value of 1 if the site is in the Southwest region and 0 otherwise
N_L	a variable which has the value of 1 if the intersection has 3 legs, and 0 if 4 legs
M_{maj}	a dummy variable that has the value of 1 if the site is Multi-lane and 0 otherwise.

A multi-lane site usually has more than two through lanes on the major street for both directions. For one way on the major street with two lanes, the site is defined as multi-lane for minor street left- and right-turn movements, but as single lane for minor street through movement. A multi-lane site usually requires traffic of a particular movement traveling on more than one lane, and only the vehicles on the conflicting lane are considered when measuring the critical gap.

V_{ML}	traffic volume from the left side on the major street
V_{MR}	traffic volume from the right side on the major street
R_{PL}	percentage of right turn movement on the major street from the left
R_{PR}	percentage of right turn movement on the major street from the right
S_{maj}	posted speed limit on the major street (mph)
T_{TL}	a dummy variable that has the value of 1 if there is a two-way left turn lane on the major street and 0 otherwise

D_{SL}	distance of the nearest upstream signalized intersection on the left side (mile)
D_{SR}	distance of the nearest upstream signalized intersection on the right side (mile)
G	approach grade at the location of the stop line
θ	a variable which has the value of 1 if the minor street intersects with major street at a small angle (less than 45 degrees) and 0 otherwise
d	average delay for those minor stream vehicles during the period of critical gap measurement (sec/veh).

Other factors which may affect the critical gap include the city size and intersection location (rural vs. urban). Due to limited information, these variables were not included in the regression analysis

2.2 Possible Influence of the Region Variables

Data were collected at 5 geographical regions: Southwest (SW), Southeast (SE), Central (CE), Northeast (NE) and Northwest (NW). The significance of the variable of geographical region was determined by only allowing this variable to enter the regression process. The resulted regression equations are given below.

Major Street Left Turn

$$t_c = 4.28 - 0.51 R_{NE} - 0.62 R_{CE} \quad (1)$$

The R^2 value was 0.123 and the root mean square (RMS) of the residual was 0.70. Other variables were not significant at the 5 percent level.

Minor Street Left Turn

$$t_c = 5.33 + 2.84 R_{NE} + 1.12 R_{SE} + 1.36 R_{CE} + 0.69 R_{NW} \quad (2)$$

The R^2 value was 0.470 and the RMS of the residual was 0.92.

Minor Street Through

$$t_c = 5.99 + 1.77 R_{NE} \quad (3)$$

The R^2 value was 0.378 and the RMS of the residual was 1.06.

Minor Street Right Turn

$$t_c = 5.48 + 1.93 R_{NE} + 0.77 R_{SE} - 0.67 R_{CE} \quad (4)$$

The R^2 value was 0.275 and the RMS of the residual was 1.23.

It is clear that the geographic region variable does not have a consistent influence. Although the NE region was represented in all the equations, the sign was not always consistent. It was concluded that the region variable should not be included in further analysis.

Using the same technique, other variables were examined on their significance level. For example, the variables considered in the regression analysis for the minor street left-turn movement included:

- the number of legs, N_L,
- multi-lane or single-lane major street, M_{maj},
- approach grade, G,
- major road volume from the left, V_{ML},
- major road volume from the right, V_{MR},
- existence of a two-way left-turn lane on the major street, T_{TL},
- the percentage of right vehicles on the major street from the left, R_{PL}, and from the right, R_{PR}, and
- delay, d.

Through the regression analysis, the following equations for the critical gap were developed for the four turning movements:

Major Street Left Turn: No variables showed at the 5 percent significance level. Only the multi-lane factor M_{maj} showed at 10 percent significance level.

$$t_c = 4.3 - 0.31M_{Maj} \qquad (5)$$

Minor Street Right Turn: Equation (6) was obtained with all the variables in the equation at 5 percent significance level.

$$t_c = 6.27 + 0.82M_{Maj} - 0.0345R_{PL} - 0.38N_L + 0.123G - 2.43\theta \qquad (6)$$

Minor Street Left Turn: Equation (7) was obtained with all the variables at 5 percent level.

$$t_c = 6.79 - 0.0216R_{PL} - 0.72N_L + 0.22G - 1.03T_{LT} \qquad (7)$$

Minor Street Through Movement: Equation (8) was obtained with all the variables at 5 percent significance level.

$$t_c = 4.91 + 0.0611R_{PR} + 0.104(S_{maj} - 30) \qquad (8)$$

The results of the variance analysis of the above regression equations are given in Table 1.

TABLE 1 Results of Variance Analysis for Different Regression Equations

Source	Degree of Freedom	Sum Squares	Mean Square	F-Test
Major Street Left Turn				
Regression	1	1.99	1.99	3.37
Residual	85	45.37	0.53	
Total	86	47.36		
R^2	0.042			
Minor Street Right Turn				
Regression	5	140.73	28.15	36.59
Residual	127	97.69	0.77	
Total	132	238.42		
R^2	0.459			
Minor Street Right Turn				
Regression	5	78.96	15.79	16.78
Residual	121	113.88	0.94	
Total	126	192.84		
R^2	0.409			
Minor Street Through				
Regression	2	25.30	12.65	13.49
Residual	23	21.58	0.94	
Total	25	46.88		
R^2	0.409			

To summarize the regression analysis results, the following points were reached:

- Some of the factors which have significant effect on the critical gap were identified. These factors include: multi-lane or single lane on the major street, the existence of a two-way left-turn lane, the percentage of right turn vehicles on the major street, the number of legs of the intersection, the grade of the minor stream approach, and the turn angle of the minor street approach.

- The resulted regression equations reflected how the various factors affect the critical gap, and they can be used to estimate the critical gap based on certain conditions.

3. MICROSCOPIC ANALYSIS

The investigation of the effect of some of the factors was also conducted in a somewhat microscopic level, which includes the following:

- the effect of vehicle delay
- the effect of heavy vehicles
- the effect of directional traffic volume distributions on the major street
- the relationship between critical gap and follow-up time

Some of the methodologies and results are discussed below.

3.1 The Effect of Delay on Critical Gap

Intuitively, minor stream vehicles experiencing longer delays might seek shorter gaps, therefore, driver's critical gap might be different under various traffic flow conditions. However, the regression analysis indicated that the vehicle delay is not a significant factor affecting critical gap. One reason might be that the database included in the regression analysis covered many sites with various site geometry and traffic flow characteristics, and the compounded effects due to other variables might have diminished the effect of the delay variable. In order to investigate whether the vehicle delay has any effect on critical gap, the study was focused on the sites with similar geometric conditions. Two sites of similar geometric conditions and high number of observations were selected for the analysis. The high number of observations allowed us to divide the entire time period into smaller time periods to obtain high number of critical gap samples. Figure 1 illustrates the critical gaps measured for each time period and the associated average vehicle delay during that time period.

It can be observed from Figure 1 that with the increase of delay, the critical gap tends to decrease. For the two particular sites analyzed, the driver's critical gap is about 5.5 seconds when the average delay is short (less than 40 sec/veh). As condition changes and drivers experience longer delays, they may use a reduced critical gap. It is unclear, however whether drivers would continually reduce their critical gap or whether they would evaluate the traffic conditions while in the queue or awaiting at the head of queue. In either case, the outcome is the same. Drivers use shorter critical gap at higher flow (and hence delay) conditions.

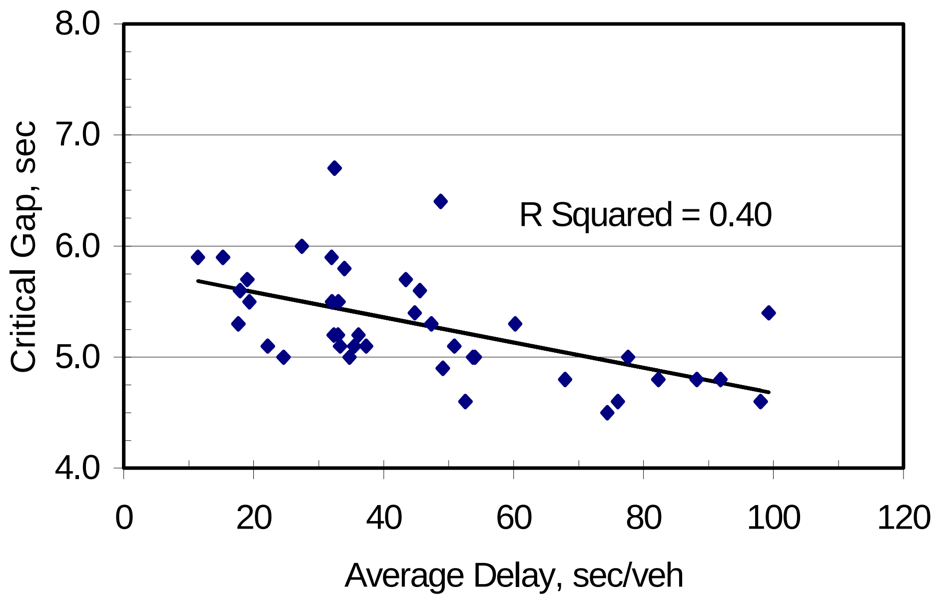

FIGURE 1 Effect of vehicle delay on critical gap.

3.2 The Effect of Heavy Vehicles on Critical Gap and Follow-Up Time

In this study, heavy vehicles or trucks refer to those automobiles other than passenger cars and light pick-up trucks. Since critical gap estimation requires a certain number of observations on the minor stream vehicles, it was difficult to acquire enough information to estimate critical gap for heavy vehicles or trucks for each site. For conducting this analysis, the gap events associated with heavy vehicles were extracted from each site and then aggregated based on intersection geometry type and movement type. Similarly, the gaps associated with passenger cars were also extracted and aggregated by intersection geometry type. The maximum likelihood method was then applied to estimate the critical gap for heavy vehicles and passenger cars of all the sites. Table 2 shows the critical gap estimates for both trucks and passenger cars using this approach. The statistics for trucks were also included indicating the sample size and variations. It can be observed that the critical gaps for heavy vehicles were significantly higher than those for the passenger cars, and large variations also existed among heavy vehicles.

The follow-up times for heavy vehicles were also calculated and the results are summarized in Table 3. Since follow-up time is the minimum headway between two consecutive vehicles in a minor stream, the measurement of a follow-up time involved time events associated with both the leading and the following vehicles. A follow-up time classified as for heavy vehicles was when at least one vehicle in the pair was a heavy vehicle, i.e., either the leading vehicle or the following vehicle or both were heavy vehicles. Table 3 also lists the results measured for passenger cars. The measurements were grouped based on intersection geometry types and vehicle movement types. It can be observed that the follow-up times for heavy vehicles were consistently higher than those for the passenger cars. Typically, the follow-up times for heavy vehicles were about 1 second higher than those for the passenger cars.

TABLE 2 Critical Gap for Trucks

Geometry	Movement	t_c -Truck	S.D.	Obs.	t_c - Car
3-Leg, Single Lane	LT	7.2	2.9	166	6.0
	RT	6.0	2.3	65	5.2
4-Leg , Single Lane	LT	7.6	2.1	58	7.1
	TH	6.3	2.9	24	6.4
	RT	6.7	3.0	37	5.9
3-Leg, Multi-Lane	LT	9.0	2.1	9	7.2
	RT	9.4	3.8	104	6.9
4-Leg, Multi-Lane	LT	9.0	4.5	13	7.4
	TH	9.5	6.3	17	7.6
	RT	8.2	2.7	25	6.8
All	Major LT	5.5	3.3	22	4.1

Note: LT = Minor Street Left Turn, TH = Minor Street Through, RT = Minor Street Right Turn, Major LT = Major Street Left Turn; S.D. = Standard Deviation; Obs. = Number of Observations.

TABLE 3 Follow-Up Time for Trucks and Passenger Cars

Geometry	Movement	t_f - Truck	S.D.	Obs.	t_f - Car	S.D.	Obs.
3-Leg, Single Lane	LT	4.4	1.6	82	3.5	1.3	2760
	RT	3.1	1.4	13	3.1	1.4	549
4-Leg , Single Lane	LT	2.2	2.1	18	4.0	1.5	551
	TH	4.7	0.8	5	4.1	1.4	259
	RT	5.1	2.2	11	4.0	1.8	181
3-Leg, Multi-Lane	LT	4.0	1.2	27	3.4	1.2	808
	RT	4.0	1.2	26	3.3	1.2	758
4-Leg, Multi-Lane	LT	4.4	1.1	17	3.3	1.5	331
	TH	4.8	0.0	1	3.7	1.4	60
	RT	4.3	1.1	5	3.4	2.4	71
All	LT	4.4	1.6	144	3.5	1.3	4450
	TH	4.7	0.7	6	4.0	1.4	319
	RT	4.2	1.6	55	3.3	1.4	1559
	Major LT	3.1	0.8	33	2.2	0.8	551

Note: LT = Minor Street Left Turn, TH = Minor Street Through, RT = Minor Street Right Turn, Major LT = Major Street Left Turn; S.D. = Standard Deviation; Obs. = Number of Observations.

3.3 The Effect of Vehicle Movement on the Major Street on Minor Street Drivers

It was suspected that the minor street drivers might react differently to different vehicle movement types on the major street. For example, a left turn vehicle from a minor street may have more pressure to accelerate to the desired speed when facing a major street vehicle approaching from the right than from the left. Although a quantitative evaluation of such an effect may be difficult to achieve from the measured critical gap values, we have extracted all the maximum rejected gaps, and classified them by movement type of the ending gap vehicles. As documented in the maximum likelihood procedure, the maximum rejected gap of each vehicle determines the lower boundary of the critical gap value. Therefore, examination on the maximum rejected gap values would suggest similar trends on critical gap. Table 4 shows a group of intersections where the maximum rejected gaps for the minor street left turn vehicles were summarized. The highest maximum rejected gap values were observed when the ending gap vehicles were major street left turns. One explanation could be that drivers are only able to make their decisions on the expected arrival time and not the actual arrival time. Typical deceleration of the major street left turn vehicles resulted in later than expected arrival and hence a larger rejected gap which would have been normally accepted by the minor street driver. Nevertheless, the results in Table 4 clearly indicated that the through movement from the right side always yielded higher maximum rejected gap values than that from the left side. The observation confirmed general experience that the vehicles from the right side usually put more pressure on the minor street driver, where the minor street driver needs to accelerate to the desired speed if he/she decided to enter the intersection.

TABLE 4 Maximum Rejected Gaps by End Gap Movement for Minor Street Left Turn

Site ID	TH Movement From the Left			RT Movement From the Left			LT Movement From the Right			TH Movement From the Right		
	Mean	**S.D.**	**Obs.**	**Mean**	**S.D.**	**Obs.**	**Mean**	**S.D.**	**Obs.**	**Mean**	**S.D.**	**Obs.**
SWT008	3.9	1.7	157	NA	NA	NA	NA	NA	NA	4.0	1.7	240
SWT017	3.7	1.5	192	NA	NA	NA	NA	NA	NA	4.0	1.5	196
SWT018	3.6	1.6	153	NA	NA	NA	NA	NA	NA	4.0	1.7	303
CET306	4.3	2.1	27	NA	NA	NA	NA	NA	NA	4.8	2.1	176
NWT402	3.4	1.9	109	4.0	2.3	123	4.8	2.7	18	4.6	2.1	27
NWT405	3.7	2.0	108	4.0	2.7	117	5.9	2.3	49	3.9	2.0	73
SWT010	3.7	2.1	111	3.7	2.0	183	5.4	2.1	18	4.4	1.7	95
NET209	3.3	2.1	44	3.9	2.2	1	4.3	1.3	4	4.1	1.8	74
Average	3.7	1.9	901	3.9	2.3	424	5.1	2.1	89	4.2	1.8	1184

Note: NA – The movement doesn't exist at the site.

3.4 The Relationship Between Critical Gap and Follow-up Time

Previous studies (Brilon 1988) had reported that a constant ratio of 0.60 exists between follow-up time and critical gap, which was also used in the 1985 *Highway Capacity Manual* (TRB 1985). Such a relationship was examined based on the newly established database used in this study. Figure 2 shows the distribution of the follow-up/critical gap ratio of all the sites studied.

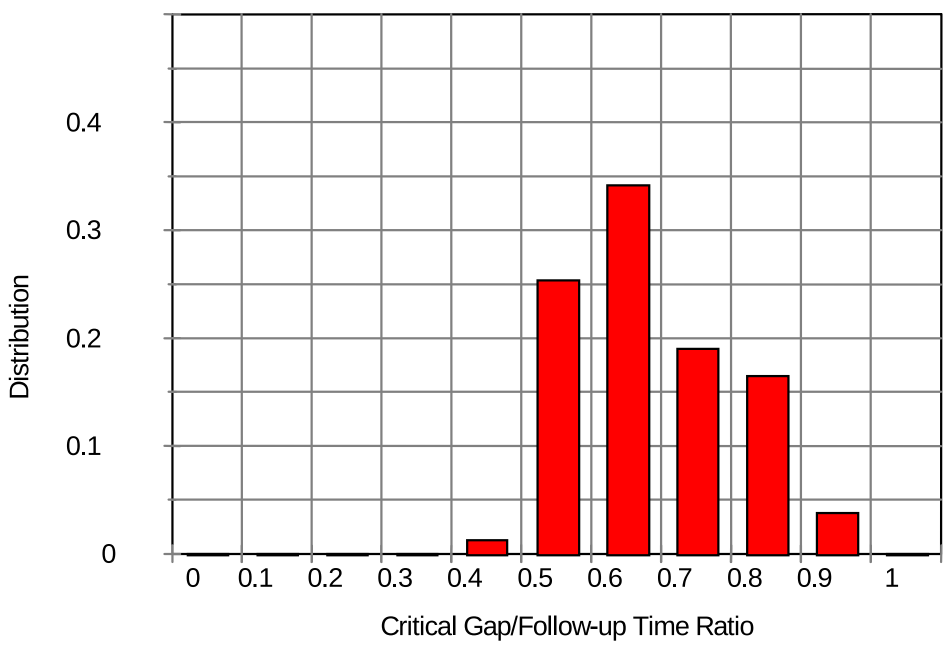

FIGURE 2 Distribution of critical gap/follow-up time ratios.

It can be observed that the ratios of the follow-up time and the critical gap ranged between 0.4 and 0.9 with the majorities around 0.6. This finding partially confirms the results by previous studies (Brilon 1988). It also provides a convenient way to predict the critical gap, since follow-up time can normally be measured from the field. This will enable the professionals to adjust the critical gap and follow-up time values to suit a particular site.

4. CONCLUSIONS AND RECOMMENDATIONS

The paper provides detailed investigations on the various factors that affect critical gap and follow-up time. The investigation was based on the database established during the NCHRP 3-46 project, Capacity and Level of Service at Unsignalized Intersections. Both the step-wise regression analysis and the microscopic analysis were conducted to investigate the potential factors affecting the critical gap and the follow-up time.

General observations of the various factors can be summarized below:

- It was found that the major factors affecting critical gap and follow-up time include intersection geometry (e.g., multi-lane or single lane, 4-leg or 3-leg), approach grade, vehicle type, movement type, and vehicle delay.
- With the increase of major stream volume or minor stream vehicle delay, drivers tend to seek smaller gaps. However, driver's critical gap cannot be reduced to the minimum threshold probably determined by the follow-up time value or the maximum rejected gap value.
- With the increase of the number of lanes on the major street or the number of legs at the intersection, the critical gap tends to increase due to the increase of the difficulty of the movement maneuver.
- With the increase of the approach grade, the critical gap tends to increase.
- With a small turn angle, the movement maneuver is easier comparing to a perpendicular angle or a large angle, and the critical gap tends to decrease.
- Critical gap and follow-up time for heavy vehicles are found to be consistently higher than for passer cars.

Although the regression analysis and the microscopic analysis provided insights on the relationships among various factors, practical engineering judgement still played an important role while recommending the final set of critical gap and follow-up time values. For example, the other two factors, the proportion of right turn vehicles and the existence of two-way left-turn lane, both appeared to be significant in the regression analyses were not included in the final recommendations. Both factors were dealt with specifically in other parts of the capacity analysis procedure, such as the conflicting flow calculation (50% reduction on right turns), and the two-stage gap acceptance process (where a two-way left-turn lane exists).

The newly recommended set of critical gap and follow-up time values are shown in Tables 5 and 6. These recommended values have been adopted as the basis for Chapter 10 of the 1997 update to the *Highway Capacity Manual* and the proposed 2000 HCM.

TABLE 5 Recommended Critical Gap

Geometry	**Single Lane**				**Multi-Lane**			
Movement	MajLT	MinRT	MinTH	MinLT	MajLT	MinRT	MinTH	MinLT
Critical Gap	4.1	6.2	6.5	7.1	4.1	6.9	6.5	7.5
Adjustment Factors	1.0	1.0	1.0	1.0	2.0	2.0	2.0	2.0
Heavy Vehicle	—	0.1	0.2	0.2	—	0.1	0.2	0.2
Grade %	—	—	—	-0.7	—	—	—	-0.7
Three-Leg								

TABLE 6 Recommended Follow-Up Time

Movement	**MajLT**	**MinRT**	**MinTH**	**MinLT**
Follow-up Time	2.2	3.3	4.0	3.5
Adjustment Factors *Heavy Vehicle**	0.9–1.0	0.9–1.0	0.9–1.0	0.9–1.0

* Note: 0.9 = for single lane site; 1.0 = for multilane site.

REFERENCES

Brilon, W. (1988). *Recent Development in Calculation Methods for Unsignalized Intersections in West Germany*, Intersections without Traffic Signals, Springer 1988, pp. 114.

Brilon, W., and Koenig, R. (1997). *Useful Estimation Procedures for Critical Gaps*, Intersections Without Traffic Signals, Portland, Oregon, July 1997, pp. 71.

Kyte, M., Tian, Z., Mir, Z., Hammeedansor, Z., Kittelson, W., Vandehey, M., Robinson, B., Brilon, W., and Troutbeck, R. (1996*). Capacity and Level of Service at Unsignalized Intersections*. National Cooperative Highway Research Program Project 3-46.

Tian, Z., Kyte, W., Vandehey, M., Robinson, B., Kittelson, W., Troutbeck, R.W., and Brilon, W. (1999). *Implementing the Maximum Likelihood Methodology to Measure Driver's Critical Gap*. Transportation Research, Part A 33, pp. 187–197.

Transportation Research Board. (1985). *Special Report 209: Highway Capacity Manual.*, TRB, Washington, D.C.

Transportation Research Board. (1997). *Special Report 209: Highway Capacity Manual.*, 1997 Update, TRB, Washington, D.C.

Troutbeck, R.J. (1992*). Estimating the Critical Acceptance Gap from Traffic Movements*. Queensland University of Technology, March 1992.