Empirical Delay Models for Multi-Lane Two-Way Stop-Controlled Intersections

THE CURRENT PROCEDURE FOR ANALYZING TWO-WAY STOP-CONTROLLED (TWSC) INTERSECTIONS IN THE 2000 EDITION OF THE *HIGHWAY CAPACITY MANUAL* IS LIMITED TO MAJOR STREET APPROACHES OF ONE OR TWO LANES (TWO-LANE OR FOUR-LANE ARTERIALS). THE OBJECTIVE OF THIS STUDY IS TO DEVELOP EMPIRICAL MODELS TO ESTIMATE DELAYS FOR MINOR STREET TRAFFIC AT TWSC INTERSECTIONS ON MULTI-LANE ARTERIALS OF SIX OR EIGHT LANES.

BY HUAGUO ZHOU, PH.D., P.E., LARRY HAGEN, P.E., PTOE, JIAN JOHN LU, PH.D. P.E. AND ZONGZHONG TIAN, PH.D., P.E.

INTRODUCTION

The average delays of minor movements such as left and right turns are important measures of effectiveness for determining the operational performance of two-way stop-controlled (TWSC) intersections. For a TWSC intersection, the stop-controlled approaches are referred to as the minor road approaches. The intersection approaches that are not controlled by stop signs are referred to as the major road approaches.

Minor road approaches usually are driveways or side streets that provide access to business or residential areas. Major road through traffic basically is in a free-flow state, although the vehicles making right and left turns into the driveways or side streets have minor impacts on through traffic speed. Typically, there are no delays for major road through traffic because it passes through unsignalized intersections. The delays of vehicles making left and right turns out of side streets are the main factors for determining the operational performance and level of service of the intersections.

Currently, three types of models are available to estimate minor traffic movement delays at TWSC intersections. However, none of them adequately handle the condition in which the main street contains multi-lane approaches. The three models include the *Highway Capacity Manual* (HCM) procedure, models based on queuing theory and some empirical models based on either field data or computer simulations.[1–8]

In order to complete the delay estimation procedure in HCM, the potential capacities of the minor traffic streams have to be estimated before estimating delays. The HCM capacity analysis procedures at TWSC intersections are based on the gap acceptance models for two-lane or four-lane major roads.

Therefore, the procedure provided by the current HCM could not be used to estimate the delays of right and left turns from a driveway onto arterials of six or more lanes.

This feature presents a methodology to estimate average delays of left- and right-turn movements from a minor street at TWSC intersections onto multi-lane arterials, based on field data obtained from a University of South Florida research project sponsored by the Florida Department of Transportation.

DEFINITION OF DELAY

At TWSC intersections on multi-lane major street arterials, the traffic volumes on the minor street are relatively low, and traffic from the minor street makes two-stage left turns (where a median typically exists) or right turns onto the major road. On multi-lane arterials, wide medians often are available to accommodate one or two vehicles. Major road through traffic generally is in a free-flow state. No delays are incurred for major road through traffic when it passes through unsignalized intersections.

Vehicles making a left turn onto minor streets have to yield to one direction of through traffic on the major road. Vehicles making a right turn onto minor streets have to yield only to pedestrians or bicycles. The delays for these two movements are not studied in this feature because these delays are relatively small compared with the waiting delays of vehicles making left and right turns out of minor streets or driveways.

It is believed that minor street through traffic delays would be similar to those for the two-stage left-turn movement. However, the delays of minor street through traffic are not estimated in this study because very few vehicles were observed to make a through movement at the study sites and there are insufficient observations to develop a reliable estimate.

HCM provides a clear definition of traffic delay. Total delay is defined as the difference between the travel time actually experienced and the reference travel time that would result during base conditions, in the absence of incident, control, traffic, or geometric delay.

One element of total delay, called control delay, is the portion of total delay attributed to control measures, including initial deceleration delay, queue move-up time, stopped delay and final acceleration delay.

In this study, the delay of left and right turns is defined as the control delay, including two parts: stopped delay and queue move-up time measured in the field, and a constant value of 5 seconds per vehicle to account for vehicle deceleration and acceleration delay as defined in the 2000 edition of HCM.

The total average delays of an unsignalized intersection mainly consist of the delays of vehicles making right and left turns out of the minor street approaches. The delays of vehicles making right and left turns onto the minor street are not evaluated in this study. The level of service of a TWSC intersection can be determined by the weighted average delay of vehicles making left and right turns out of the minor streets.

Delay of Left Turns

Based on the definition of the priority of all movements at an unsignalized intersection by HCM, left-turn egress from a driveway or a side street has the lowest priority. On arterials with wide medians that can allow one or more vehicles to stop and wait, the total control delay of a typical left-turn maneuver includes:

- stopping and waiting at the driveway;
- selecting a suitable gap, accelerating across major road through traffic lanes and coming to a stop in the median;
- stopping at the median and waiting for a suitable gap from right-side through traffic; and
- accelerating to the operating speed on the major roadway.

Based on the operational analysis of a left-turn movement, the average control delay of left turns can be defined by the following equation:

$$d_{LT} = t_{L1} + t_{L2} + t_{L3} + 5 \qquad (1)$$

where

d_{LT} = average control delay of left turns (seconds per vehicle (sec./veh))

t_{L1} = average waiting time of left-turn vehicles at the driveway (sec.)

t_{L2} = average waiting time of left-turn vehicles at the median opening (sec.)

t_{L3} = average running time for left-turn vehicles leaving the driveway until stopping at the median.

As specified in HCM, the constant value of 5.0 sec./veh was used to account for the deceleration of vehicles from free-flow speed to the speed of the vehicle in the queue and the acceleration of vehicles from stop line to free-flow speed. The average running time for left-turn vehicles crossing three through lanes (t_{L3}) was included as part of control delay because it can be treated as queue move-up time.

Delay of Right Turns

The average control delay of right turns from a driveway includes:

- the total elapsed time from when a right-turn vehicle stops at the end of the queue until the vehicle departs from the stop line; and
- decelerating to the speed of the vehicle in the queue and accelerating to the operating speed on the major roadway.

To develop a delay model for right-turn movements, the following equation can be used:

$$d_{RT} = t_R + 5 \qquad (2)$$

where

d_{RT} = average control delay of right turns (sec./veh)

t_R = average total elapsed time from when a right-turn vehicle stops at the end of the queue until the vehicle departs from the stop line.

Similar to the control delay for the left-turn movement discussed above, the constant value of 5.0 sec./veh accounts for the deceleration of right-turning vehicles from the minor street free-flow speed to the speed of vehicles in the queue and the acceleration of vehicles from the stop line to free-flow speed on the major street.

Approach Delay

For a typical TWSC intersection, the average approach control delay is defined as the weighted average delay of right and left turns from the minor street.

$$d_A = (d_{RT}{*}v_{RT} + d_{LT}{*}v_{LT})/(v_{RT} + v_{LT}) \qquad (3)$$

where

d_A = average approach control delay at an unsignalized intersection (sec./veh)

d_{RT} = average control delay for right turns (sec./veh)

d_{LT} = average control delay for left turns (sec./veh)

v_{RT} = flow rate for right-turn approach traffic (vehicles per hour (vph))

v_{LT} = flow rate for left-turn approach traffic (vph)

FIELD DATA COLLECTION

In this research, eight sites were selected for data collection in the Tampa Bay, FL, USA area. The study sites were all unsignalized intersections on six-lane arterials. The median on all of these major arterials was a raised curb. The median was wide enough to safely store one or two waiting vehicles. The minor streets had either two lanes (one for the right turn, another for the left turn) or one wide lane with a flared curb so that the two movements did not interfere with each other. The speed limit ranged from 45 to 55 miles per hour.

The eight unsignalized study intersections were as follows:

- Fowler Avenue and 46th Street
- Fowler Avenue and 19th Street
- U.S. 19 and 115th Street
- Bruce B. Downs and Medical Center
- Hillsborough Avenue and Golden Drive
- U.S. 19 and Enterprise Center
- U.S. 19 and Innisbrook Avenue
- Fowler Avenue and 52nd Street

To collect field data, two video cameras were used to monitor vehicles making right turns and turns from the minor street at these unsignalized intersections. One camera recorded vehicle delays at the minor street; another recorded left-turning vehicle delays in the median.

Major road through traffic volumes were collected using automatic traffic counters. Data were collected for two weeks at each site for at least four hours each day, including both peak and non-peak hours. It should be noted that all data were collected during weekday periods between 7:00 a.m. and 6:00 p.m.

While reviewing the videotapes, researchers tracked each vehicle making a right turn or a left turn. The following information was recorded: waiting delay of left turns and right turns at the driveway (defined as t_{L1} and t_R, respectively); waiting delay of left-turning vehicles at the median opening (defined as t_{L2}); running time for left-turning vehicles crossing three through lanes; minor street traffic volumes; and number of vehicles making a left turn into the driveway.

The control delay of right turns and left turns at a driveway can be obtained by recording two events: the time a vehicle enters a queue and the time a vehicle exits the stop line.

The waiting delay for a left turn at a median opening can be measured by recording the time the vehicle stops at the median until it leaves the median. Major road through traffic volumes were directly downloaded to an Microsoft Excel spreadsheet from the traffic counters. All the traffic data were averaged in 5-minute intervals before conducting data analysis.

DATA ANALYSIS

Delay Model for Left Turn

A regression analysis was conducted to develop the left-turn delay model based on the data collected at sites 2 through 7. Left-turn egress was prohibited through installing a restrictive median opening at sites 1 and 8.

The original data at 5-minute intervals were averaged at 15-minute intervals because the latter were found to have better statistical characteristics, such as R-squared value. Additionally, the average delay of left turns at 15-minute intervals is more consistent than at 5-minute intervals because there are more left-turn vehicles at 15-minute intervals. Table 1 illustrates the descriptive statistics of the collected field data.

Table 1. Descriptive statistics of the collected data for delay models.

	Average waiting delay of left turn (sec.)	v_{LT} (vph)	v_{TH} (vph)	v_{LTin} (vph)	SPLIT	Average waiting delay of right turn (sec.)	v_{TH1} (vph)
Mean	50.08	46	4910	80	0.48	17.92	1940
Median	43.96	44	4864	76	0.48	16.95	1896
Standard deviation	29.51	20	636	31	0.04	7.15	447
Sample variance	870.66	381	404785	981	0.00	51	200216
Range	149.83	132	3204	172	0.22	40.73	2414
Minimum	6.68	12	3532	8	0.38	4.53	942
Maximum	156.51	144	6736	180	0.61	45.26	3356
Count	451	451	451	451	451	545	545

Table 2. Regression results of the delay model of left and right turns.

Model	N*	R-square	Variables	Intercept	v_{TH}	v_{LT}	v_{LTin}	SPLIT	v_{TH1}
Left-turn delay	451	0.39	Coefficients	0.87	0.0006	0.01	0.004	-.88	-
			t- statistics	2.38	15.12	8.16	4.95	-1.59	-
Right-turn delay	545	0.43	Coefficients	1.61	-	-	-	-	0.0006
			t- statistics	50.76	-	-	-	-	23.70

* Note: N = number of observations.

The variables that affect the delay of left turns include: the flow rate of two-directional major road through traffic ($v_{TH} = v_{TH1} + v_{TH2}$); split (defined as the proportion of traffic from the left (v_{TH1}) on the major road); the flow rate of left-turn-in traffic from a major roadway (v_{LTin}); and the flow rate of left turn (v_{LT}) from a minor street. The dependent variable (average control delay of left turns) refers to average total waiting delay per vehicle making a left turn during a 15-minute period. The hourly flow rate was obtained by multiplying the 15-minute traffic volume by four.

Many other factors may influence driver behavior and, therefore, affect the delay of left-turning vehicles from minor roads, such as intersection sight distance, storage length on the subject driveway, geometric features on the driveways and the width required to cross from the minor approach to the median.[9] In this study, these geometric features are not included in the final model development because they are similar in all the study sites.

A total of 451 observations at 15-minute intervals were used to estimate the delay model for left turns. Analysis showed that linear and exponential forms were appropriate for describing the relationship. However, the exponential form was found to have better theoretical and statistical characteristics. Past studies have shown that delay will increase dramatically when the conflicting traffic volumes reach a certain amount or the ratio of volume and capacity (v/c) is greater than one.

Regression results are listed in Table 2, where the variables v_{TH}, v_{LT} and v_{LTin} are significant at a 95-percent confidence level. The final developed regression equation was as follows:

$$d_{LT} = 2.4e^{0.0006v_{TH}+0.01v_{LT}+0.004v_{LTin}-0.9SPLIT} + 5 \qquad (4)$$

where

d_{LT} = average control delay of left turns (sec./veh)

v_{TH} = flow rate of major road through traffic (vph)

v_{LT} = flow rate of left turn from a driveway (vph)

v_{LTin} = flow rate of left-turn-in from the major road (vph)

SPLIT = proportion of through traffic flow rate from the left side

$SPLIT = v_{TH1} / v_{TH}$

v_{TH1} = through traffic flow rate from the left side

In Equation 4, the independent variable (*SPLIT*) has a negative sign, which implies that the through traffic flow rate from the right side (v_{TH2}) may have a greater impact on delay than the through traffic flow rate from the left side (v_{TH1}). This can be explained by the fact that when the median space is occupied by other maneuvers, left-turn vehicles must wait at the driveway, even if suitable gaps are available at the upstream through traffic stream.

The intercept refers to the minimum delay of a left turn when the volume approaches zero. The model gave a reasonable intercept value of 2.4 sec., which is close to the start-up lost time (2 to 3 sec.).

Figure 1 shows a group of curves of left-turn delays versus through traffic volumes when the left-turn-in volume is equal to 50 vph and the split is 0.5.

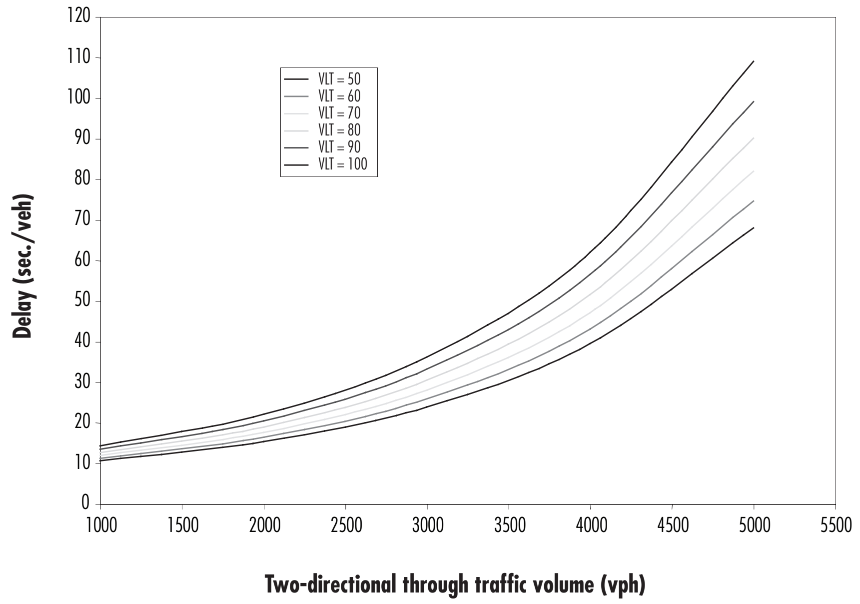
Delay Model for Right Turn

The two variables expected to affect the average delay of right turns are through traffic flow rate from the left side (v_{TH1}) and right-turn flow rate (v_{RT}). However, the regression analysis conducted in this study indicated the right-turn flow rate was not an independent variable that was significant at a 95-percent confidence level. A higher right-turn volume probably would be needed to explore the effect of right-turn flow rate on the average delay.

Field data collected from all eight sites were used to develop the delay model for right turns. Table 1 illustrates the descriptive statistics of the collected data. A total of 545 observations at 15-minute intervals were used to perform the regression analysis.

Figure 2 shows the fitting curve and the original data points for the eight studied sites. Results of the regression analysis are listed in Table 2. The R-squared value of the model was 0.43. The empirical equation for average total delay of right turns was as follows:

$$d_{RT} = 5.0e^{0.0006 v_{TH1}} + 5 \qquad (5)$$



* Note: left-turn-in = 50 vph; split = 0.5.

Figure 1. Average delay of left turn versus through traffic flow rate.

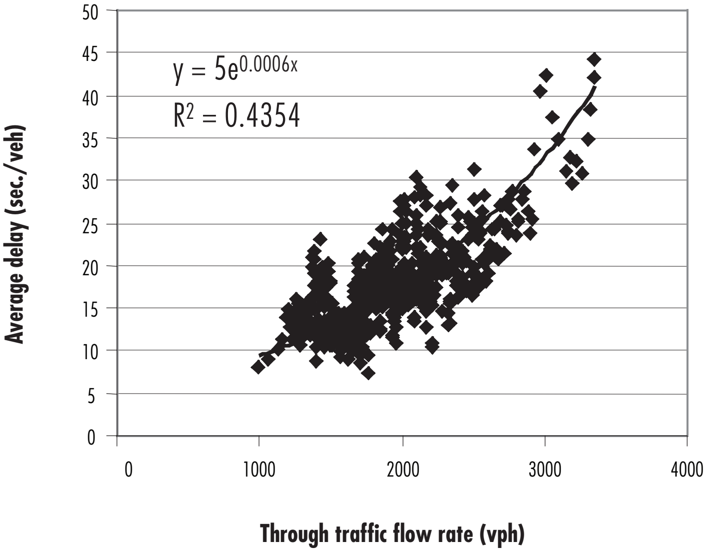


Figure 2. Average delay of right turn versus through traffic flow rate.

where

d_{RT} = average control delay of right turns (sec./veh)

v_{TH1} = flow rate of major road through traffic from the left side (vph)

The t-statistics showed that the independent variable was significant at a 95-percent confidence level. The intercept value of 5 sec./veh reflects the field data, which showed that the minimum waiting delay of right-turn movements at a 15-minute interval was 4.53 seconds.

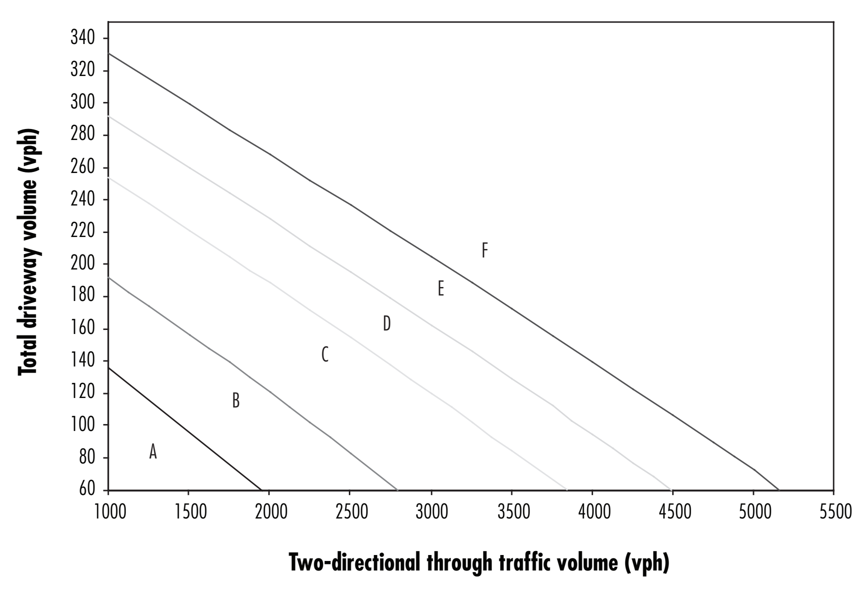
Total Delay and Level of Service

As defined above, the average control delay of a TWSC approach is equal to the weighted average control delays of right turns and left turns from the minor street. The equation for estimating

Table 3. Level of service at a sample T-intersection.

v_{TH}	v_{TH1}	SPLIT	v_{LTin}	v_{LT}	v_{RT}	d_{LT}	LOS of LT	d_{RT}	LOS of RT	d_A	LOS
3500	1750	0.5	40	30	30	24.80	C	19.29	C	22.04	C
3600	1800	0.5	50	40	40	29.18	D	19.72	C	24.45	C
3700	1850	0.5	60	50	50	34.53	D	20.17	C	27.35	D
3800	1900	0.5	70	60	60	41.07	E	20.63	C	30.85	D
3900	1950	0.5	80	70	70	49.06	E	21.11	C	35.08	E
4000	2000	0.5	90	80	80	58.81	F	21.60	C	40.21	E
4100	2050	0.5	100	90	90	70.72	F	22.11	C	46.42	E

*Note: LOS = level of service for an approach at the TWSC intersection.



* Note: left-turn-in = 50 vph; split = 0.5; $v_{LT} = v_{RT}$

Figure 3. Level of service of TWSC intersections.

approach delays for a TWSC approach can be expressed as follows:

$$d_A = (v_{LT} \times 2.4e^{0.0006 v_{TH} + 0.01 v_{LT} + 0.004 v_{LTin} - 0.9 SPLIT} + v_{RT} \times 5.0e^{0.0006 v_{TH1}}) \,/\, (v_{RT} + v_{LT}) \qquad (6)$$

The level of service of an unsignalized approach can be obtained by comparing the average delay with the level of service criteria for TWSC in Exhibit 17-2 of the 2000 edition of HCM.[10] Table 3 lists the results of estimated delays and level of service at a sample TWSC intersection by using the developed models.

Figure 3 was developed based on Equation 6 to show the level of service of the intersections for a combination of the through traffic volumes and driveway volumes (assuming left-turn-in = 50 vph; split = 0.5; $v_{LT} = v_{RT}$).

CONCLUSIONS AND RECOMMENDATIONS

Approximately 300 hours of field data were collected at eight unsignalized intersections at urban or suburban areas in west central Florida. Empirical models were developed to estimate average delays of right-turn and left-turn movements from a driveway or side street. The models can be used to perform operational analysis of an unsignalized intersection on multi-lane arterials. It should be noted that the majority of traffic on the major streets at the study locations is in platoon flow because the signal spacing at study sites is less than 3.2 kilometers (2 miles).

The vehicles can only make left or right turns out of minor streets when the gaps are available between platoons. Therefore, the models may not reliably estimate delays in rural areas where through traffic arrival is more random. At locations where the minor street through volume is significant, their delay is estimated to be similar to the left-turn delay. However, additional research should be conducted to validate this assumption. ■

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10. *Highway Capacity Manual*, note 1 above.

HUAGUO ZHOU, *Ph.D., P.E., is a senior research associate at the Center for Urban Transportation Research at the University of South Florida (USF). He holds a Ph.D. in transportation engineering from USF and a bachelor's and a Ph.D. in railway engineering from Beijing Jiaotong University. He has conducted research on many transportation projects, including traffic operations, highway safety, computer simulation, access management and incident management. He is a member of ITE.*

LARRY HAGEN, *P.E., PTOE, is the program director for ITS, Traffic Operations and Safety at the Center for Urban Transportation Research at USF. He earned a B.S.C.E. and a master of engineering from the University of Florida. He is a past president of the Florida Section and is a fellow of ITE.*

JIAN JOHN LU, *Ph.D., P.E., is a professor in the Department of Civil and Environmental Engineering at USF. He received his Ph.D. from the transportation program at University of Texas at Austin in 1990. His main research and teaching areas cover traffic operations, highway safety, intelligent transportation systems and pavement-vehicle interaction.*

ZONGZHONG TIAN, *Ph.D., P.E., is an assistant professor at the University of Nevada, Reno. He has been actively involved in research relating to unsignalized intersections. He is a member of the Highway Capacity and Quality of Service Committee and the Traffic Signal Systems Committee of TRB. He is an associate member of ITE.*