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Modifications to the Incremental Queue Accumulation Method for Complex Left Turn Phasing

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ABSTRACT

The performance of signalized intersections is mostly determined based on average control delay. Uniform delay is an integral part of average control delay. A new method for calculating uniform delay is being considered for inclusion in the 2010 version of the Highway Capacity Manual (HCM). This method is known as Incremental Queue Accumulation (IQA). Validation of the IQA method has shown that it is a major improvement over the current HCM 2000 method. For through movements, the IQA method can produce uniform delay values that are exactly the same as field measured delay, if the arrival and departure patterns are precisely known. However, it has also been found that the IQA method cannot accurately estimate uniform delay for left turn movements at signalized intersections. This paper developed models that can be used to modify the IQA method to provide more accurate estimates of uniform delay for left turns. Three different configurations were analyzed: protected plus permitted lefts from an exclusive lane, permitted lefts from an exclusive lane, and shared lanes with permitted lefts. A modification model was developed and validated for each configuration. Results showed that, when the proposed modifications were applied to the IQA method, more accurate delay estimates were produced.

KEY WORDS: Delay, Actuated, Permitted, Stochastic, Empirical, Control.

INTRODUCTION AND METHODS

The performance of an intersection can be determined by estimating measures of effectiveness such as speed, number of stops, delay, capacity, degree of saturation, and queue lengths. Control delay is the principal performance measure that influences level of service for signalized intersections. It is a direct measure of lost travel time.

According to the 2000 Highway Capacity Manual (HCM), average control delay is the sum of the average uniform delay, incremental delay and initial queue delay (TRB, 2000). In most cases, average control delay comes from the uniform delay term.

In the 2000 HCM, the procedure for calculating uniform delay is based on Webster's delay model (Webster, 1958), which assumes a uniform arrival rate and a uniform departure rate, during the entire cycle. See Figure 1. The total uniform (deterministic) delay per cycle is the area under the queue profile triangle. The average uniform delay per cycle is the total uniform delay divided by the number of vehicles that arrive during the cycle. This model is appropriate for a simple case, like a protected movement from an exclusive lane where the queue formation follows a triangular shape. It is inappropriate for many common situations where the queue accumulation defies the simple triangular shaped polygon, such as permitted left turns, protected-permitted left turns, multiple green displays, and protected-permitted right turns.

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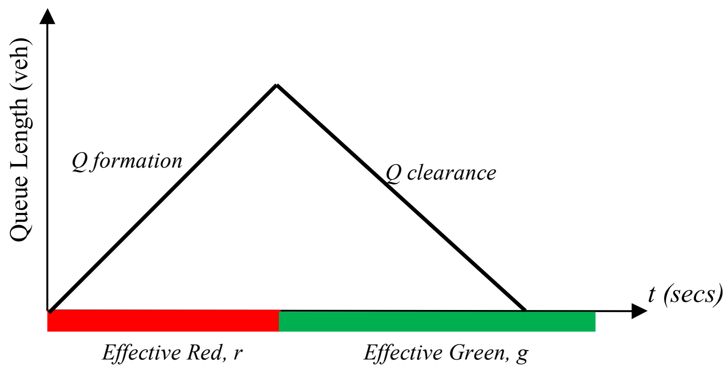

Figure 1. Queuing Diagram at a Traffic Signal

Permitted left turn vehicles have to yield to the opposing through movement traffic. The departure process is adversely affected by the presence, length and saturation of the opposing queue. The green time is effectively reduced by the opposing traffic queue clearance times. Start and end lost times also affect the amount of green time available. The arrival pattern influences the amount of delay estimated as well. Therefore, delay computation for a permitted left turn is difficult. Shared lanes with permitted left turns pose a more complicated case in delay computations. This is because, in addition to the yielding effect, the arrival and departure process is also affected by the interaction between through and left turn traffic in the subject lane. While the permitted left turn vehicles wait for acceptable gaps in the opposing queue to turn left, they also impede the through traffic in the shared lane from proceeding through the intersection. This leads to an increase in overall intersection delay.

An analytical procedure for signalized intersections was proposed by Robertson (Robertson, 1969) for control delay estimation. This procedure models vehicle arrivals and departures based on small (often two seconds or less) time steps, eradicating the need for the triangular Queue Accumulation Polygon (QAP). Robertson proposed that the characteristics of one assumed signal cycle can be used to model the operation of a signalized intersection. This model has been widely applied in the development of the TRANSYT software (Robertson and Gower 1977).

The 2000 HCM makes assumptions to compute delay for left turn movements. Six different scenarios are considered based on lane usage and signal phasing. Several adjustments are made to account for possible timing sequences and queue clearance times for the opposing flows during permitted left turn periods. However, the arrival and departure process is still assumed to be uniform and therefore, does not estimate uniform delay accurately.

Various modifications to the 2000 HCM uniform delay methodology have been developed. Qureshi (Qureshi, 2000) developed models of uniform delay that incorporate right turns on red based on queuing theory. Results showed that the proposed models predicted delays that were generally lower than delays based on the 2000 HCM method. Benekohal and El-Zohairy (Benekohal and Zohairy 2001) developed and validated uniform delay models for coordinated signalized intersections, using an Arrival-Based approach that eliminates the need for applying a progression adjustment factor. The results showed that the Arrival-Based models provided accurate results for all arrival types, when compared with field data. (Kim Kim, 2006) demonstrated the limitations of the 2000 HCM delay model in the estimation of uniform delay of permitted left turns from an exclusive lane, and proposed a new uniform delay model. Simulation results indicated that the HCM model underestimated uniform delay. Ming-Heng (Ming-Heng, 2008) developed models for estimating uniform delay for protected-permitted left turn traffic, by considering the effects of arrival type (platooning). When the control delay from the proposed and 2000 HCM models was compared to simulated field data, the results indicated that the HCM model underestimated control delay.

A new method for calculating uniform delay is being considered for inclusion in the 2010 version of the Highway Capacity Manual: the Incremental Queue Accumulation (IQA) method and is an extension of Robertson's model (Strong, *et al.,* 2006). The IQA method is based on arrival and departure patterns with small time periods. It releases the uniform delay computation procedure in the 2000 HCM from the assumption that there is only one green time with one uniform departure rate per cycle. Strong and Rouphail (Strong and Rouphail 2006) extended the IQA method to model non-uniform arrivals.

The IQA method has been validated using high resolution vehicle trajectory data for through movements (Kyte, *et al.,* 2008) and protected plus permitted left turns (Kyte, et al., 2009). For through movements, it has been shown that the IQA method can produce uniform delay values that are exactly the same as field measured delay, if the arrival and departure patterns are precisely known. However, validation results showed that the IQA method cannot accurately estimate uniform delay for left turn movements at signalized intersections. For the two scenarios validated, the IQA method produced more accurate estimates of uniform delay, compared to the current 2000 HCM methodology. Therefore, though the IQA method is an improvement to the current method, further improvement is required.

The IQA procedure considers arrival rates and departure rates as they may occur during the average cycle. The method requires the construction of a QAP which can be decomposed into an equivalent set of trapezoids or triangles, for the purpose of delay estimation. The arrival and departure rates must be effectively constant during the associated time period in order to construct a trapezoid or triangle. Figure 2 illustrates this concept using a hypothesized case for a protected plus permitted left turn movement from an exclusive lane.

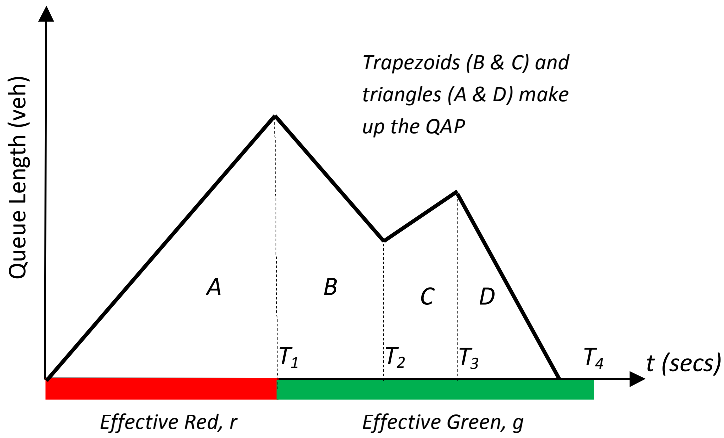

Figure 2. Decomposition of QAP into Trapezoids and Triangles

In Figure 2, during the first increment of time to T_1 (red interval), the queue is assumed to grow at a constant rate. When the light turns green, the queue is assumed to decrease at a constant rate from T_1 o T_2, during the protected left turn interval. From T_2 to T_3, the queue grows again at a constant rate during the permitted left turn interval as the opposing queue clears. During the last portion of permitted green time (T_3 to T_4), the queue clears as opposing acceptable gaps become available. The total uniform delay for this cycle is determined by summing the area of the trapezoids and triangles.

The arrival and departure process for left turns is stochastic. It is virtually impossible to represent this stochastic process in a macroscopic manner as shown in Figure 2, because it is difficult to accurately determine the exact points where the arrival and departure changes occur, in order to construct the QAP. This is the reason why the IQA method cannot accurately estimate uniform delay for left turns. As a result, the IQA method does not capture each random variation in arrivals and departures and therefore, the traffic process is not modeled correctly. This paper develops models that can be used to modify the IQA method to provide more accurate estimates of uniform delay for left turn movements. Three different configurations are evaluated: protected plus permitted lefts from an exclusive lane, permitted lefts from an exclusive lane, and shared lanes with permitted lefts.

Study Intersections and Data Generation

The analysis required high resolution field data, collected by tracking individual vehicle trajectories and recording queue lengths every second. In the absence of field vehicle trajectory data, the VISSIM (version 5.3, released August 2010) microsimulation software was utilized to generate high resolution queue length data. VISSIM models the traffic flow process by imitating its stochastic nature (PTV, 2010). Each vehicle, with predetermined destination, vehicle type and driver characteristics, is tracked through the network over time intervals of one second or less. It has been shown that VISSIM can replicate real speed and flow data, aggregated using vehicle trajectories collected through the Next Generation SIMulation (NGSIM) research program (Menneni, *et al.,* 2008). Further, Hirschmann and Fellendorf (Hirschmann and Fellendorf 2009) were able to match acceleration and deceleration rates produced by VISSIM with values collected using vehicle trajectories in the field. Therefore, with properly calibrated and validated VISSIM models, we were able to obtain accurate queue length information and used it as a ground truth.

Two real actuated signalized intersections were used to analyze protected plus permitted left turns and permitted left turns. The Bangerter Highway & South Frontage Road intersection in Salt Lake City, Utah was used to develop the modification equations presented later. Another intersection, in a different part of the Salt Lake City metropolitan area, was utilized to validate the equations; the 500 South & 200 West intersection in Bountiful. Each intersection had one street with protected plus permitted left turn phasing and the other street with permitted left turn phasing.

Each of these two study intersections are part of an actuated-coordinated network. Therefore, a segment of each network, which included the study intersections was correctly built, calibrated and validated in VISSIM. The Bangerter Highway network had five intersections and the 500 South network had four intersections. The VISSIM models were calibrated based on traffic volumes to ensure that the model volumes for each movement (left, through and right), matched counted data (100% served ± 1%). Validation of the VISSIM models was based on travel times; it was ensured that travel times from the model were close to field data (100% ± 5%). For all the VISSIM runs performed in this study, i.e., during calibration, validation and queuing data collection, 10 different random seeds were utilized and the average output was computed. For each random seed, a 15 minute seeding time was coded and another 15 minutes were allowed at the end of the simulation.

Traffic volumes were collected on a Wednesday and Thursday under fair weather and dry pavement conditions for the PM peak period (4 – 6 PM) in May 2010. The geometry for each intersection was carefully surveyed, including accurate measurement of lengths of left and right turn pockets and number of lanes. Posted speed information was also obtained from the field and coded in the VISSIM models. All the data collected was thoroughly reviewed and checked for errors. Existing signal timings for the PM peak hour (5 – 6 PM) were provided by the Utah Department of Transportation. The current cycle length at the Bangerter Highway & South Frontage Road intersection is 150 seconds, while the one at the 500 South & 200 West intersection is 110 seconds.

Shared lanes with permitted left turns were also analyzed. We evaluated the delay associated with the whole shared lane, i.e., left turns plus through movements. We utilized a theoretical intersection to evaluate this scenario, for lack of an actual intersection. The intersection assumed and modeled in VISSIM had a single shared lane on each approach. A cycle length of 120 seconds was coded, with a 47/53 phase split between the two streets. Initial volumes were determined by performing tests in VISSIM to establish the amount of traffic that reported a queue of at least two vehicles, in each approach, at least once during the entire cycle. This ensured that the blocking effect of the opposing queue and the interaction impact of the left turn and through vehicles in the subject lane were modeled. For these initial tests, it was assumed that 10 percent of the traffic on each approach would be turning left. Another theoretical intersection with similar geometry, but with different volumes was utilized to validate the modification equation for shared lanes with permitted lefts.

For each of the intersections analyzed, base condition volumes were randomly changed to create different scenarios for analysis purposes. All told, 180 scenarios (data points) were generated and evaluated. Queuing data for each scenario was collected at one second intervals for one cycle.

Developing the IQA Modification Models

This part of the analysis involved developing empirical equations that can be applied to the IQA uniform delay to obtain more accurate delay estimates for left turns. The initial step in developing the equations was to calculate uniform delay using both the IQA method and the actual queuing data obtained through microsimulation. Uniform delay was first computed using the instantaneous queue length data, i.e., at a microscopic level. Then, average arrival rates and departure rates were assumed to compute uniform delay following the IQA method, ie., at a macroscopic level. Figure 3 explains how we calculated uniform delay using the two methods. This figure illustrates the queuing process for a protected plus permitted left turn movement from an exclusive lane.

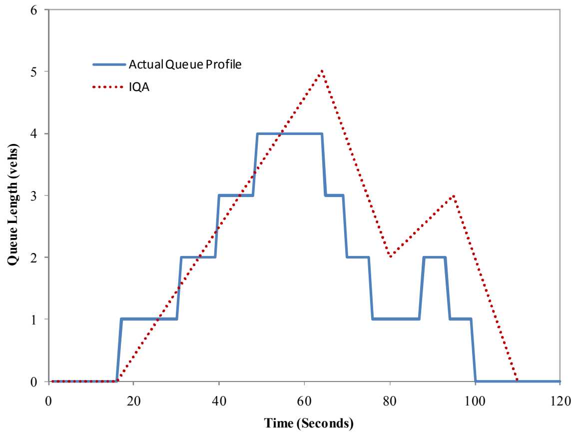

Figure 3. Example Queue Profile Diagram for One Cycle

For a Protected plus Permitted Left Turn Movement

Looking at the actual queue profile in Figure 3, we can observe that during the red interval (T_0 to T_1); four vehicles arrived in the queue. During the protected green interval (T_1 to T_2), three vehicles turned left. During the permitted green interval (T_2 to T_3), the left turn queue first grew from one to two vehicles, while the opposing queue cleared. Then, the two vehicles in the left turn queue turned left after the opposing queue had dissipated. Each time period during which the queue remains constant can be represented by a rectangle. For instance, the shaded area labeled "*3*" is the additional delay experienced by all vehicles waiting while the queue had three vehicles. If we sum the area of all such rectangles, we get the total uniform delay in vehicle-seconds for this cycle. The total uniform delay divided by the number of vehicles that arrived during the cycle gives the average uniform delay. In our analysis, using the actual queue length data, we computed uniform delay for each second; essentially, a rectangle was developed for each second.

Figure 3 also shows the QAP developed following the IQA uniform delay calculation procedure. Construction of the polygon required the identification of those points during the entire cycle when the flow rate changed. The arrival rate change points were the times when a platoon arrival condition changed. The departure rate change points were times when the saturation flow rate changed, such as at the end of a protected green period, the depletion of the subject queue, and the depletion of opposing queue. During the intervals between these points, the arrival flow rate and the saturation flow rate was assumed to be constant. The flow rates and the change points were determined using the actual queue length data. The total uniform delay was the total area of the triangles and the trapezoids that formed the QAP. The average uniform delay was determined by dividing the total uniform delay by the number of vehicles that arrived during the entire cycle. The equation below was used to compute average uniform delay.

$$d_1 = \frac{0.5}{V} \sum_{i=1}^{i=n} (T_i - T_{i-1})(Q_{i-1} + Q_i)$$

Where:

d_1 = the average uniform delay per vehicle (seconds),
V = the total number of vehicles that arrive during the cycle (vehicles),
Q_i = the queue lengths (vehicles) at particular times (T_i) (seconds) during the cycle, and
n = the number of times the queue length varies during the cycle.

For some cycles, there were some vehicles in the queue at the start or end of the cycle due to random, cycle-by-cycle fluctuations in demand that occasionally exceeded capacity. The uniform delay associated with these vehicles was also accounted for and included in the analysis, for both methods. This ensured that a more robust methodology was formulated, that addresses cycles where the degree of saturation exceeds one.

With uniform delay values obtained for the same cycles using the two methods, best fit techniques were applied to relate the two sets of data and develop analytical models for IQA uniform delay modification. Both linear and non-linear models (exponential, logarithmic, polynomial and power) were evaluated and the one that resulted in the highest Coefficient of Determination (R^2 value) was selected. The results are presented in Table 1.

Table 1. Proposed IQA Modification Models

Configuration	Proposed Modification Model	R^2 Value
Protected + Permitted Lefts from an Exclusive Lane	$y = -2E\text{-}05x^3 + 0.0065x^2 - 0.1617x + 54.517$	0.85
Permitted Lefts from an Exclusive Lane	$y = 0.0004x^3 - 0.0355x^2 + 1.7611x + 1.9344$	0.80
Shared Lane with Permitted Left Turns	$y = 25.754e^{0.0064x}$	0.35

For the proposed models in Table 1, "y" represents the uniform delay calculated using the actual queue length data, and "x" represents uniform delay calculated following the IQA method. From this table we can observe that, the proposed models for protected plus permitted left turns and permitted left turns from exclusive lanes are polynomial functions. The proposed model for shared lane with permitted left turns is an exponential function.
From Table 1, we can also notice a trend in the R^2 values, i.e., the more complex the configuration, the lower the R^2 value. The permitted left turn portion of the green time for left turn traffic is the major cause of the complexity in estimating delay, due to the yielding effect. Protected plus permitted left turns from an exclusive lane do not have to yield to opposing through traffic for the entire green interval, because part of the green indication is protected (green arrow). Permitted left turns from an exclusive lane have to yield to opposing traffic during the entire green period. Shared lanes with permitted lefts have two simultaneous processes: while the lefts yield to the opposing through traffic, they also prevent the through traffic in the shared lane from proceeding through the intersection. Therefore, the least complex (least stochastic) configuration analyzed in this study was the protected plus permitted lefts, followed by the permitted lefts, and the shared lanes with permitted lefts were the most complex. The magnitude in variations between the IQA uniform delay and the actual uniform delay followed the same order. Thus, the possibility of finding a good empirical equation (i.e., correctly relates the two data sets) is higher for protected plus permitted left turns compared to the other two scenarios. This is the reason why the R^2 value is the highest.

Validating the IQA Modification Models

The purpose of the validation was to test the reliability of the proposed models, by ensuring that they yielded results that correlated with results from a different intersection. Recall that data from the Bangerter Highway & South Frontage Road intersection was used to develop the modification models for protected plus permitted lefts, and permitted left turns. Then data from the 500 South & 200 W intersection was used validate these models. For the shared lanes with permitted lefts, two theoretical intersections were created: one was used to develop the modification model and the other was used for validation purposes.
Uniform delay was computed using both the IQA method and the actual queue length data, following the same procedure explained in the preceding section. Uniform delay computed using the IQA method was then modified using the models presented in Table 1. This was achieved by substituting "x" with the IQA uniform delay to obtain the IQA modified uniform delay "y". Correlation between the modified IQA uniform delay and the uniform delay from the actual queue length data was then tested.
Two measures of goodness of fit were evaluated in the validation process. The Coefficient of Correlation (R value) was checked to ensure that there was high correlation between the two data sets. Most importantly, the percent reduction in Room Mean Square Error (RMSE) was evaluated to determine the magnitude by which the modified delay estimates were improved. The validation results are presented in Table 2.

Table 2. Validation Results of the Proposed IQA Modification Models

Configuration	% Reduction in RMSE after Modification	R Value
Protected + Permitted Lefts from an Exclusive Lane	-14%	0.77
Permitted Lefts from an Exclusive Lane	-32%	0.96
Shared Lane with Permitted Left Turns	-63%	0.81

From Table 2, we can observe that the RMSE was reduced for all the three configurations, after the modification was applied to the IQA method. This indicates that the proposed modifications bring the IQA uniform delay estimates closer to reality. Recall from Table 1 that the model for protected plus permitted lefts had the highest R^2 value, followed by the permitted lefts and then shared lanes. From Table 2, percent reduction in RMSE values are in the reverse order. The differences between the uniform delay estimates from the IQA method, and those from the actual queue length data were very high before the modifications were applied, for the shared lanes with permitted lefts. Consequently, this configuration experienced the highest reduction in errors, compared to the other two configurations. Therefore, the higher the complexity is estimating delay, the higher the benefit achieved from applying the modification. High correlations between the IQA modified uniform delay, and uniform delay computed using the actual queue length data were also attained, as the R values in Table 2 show.

Conclusion

The IQA method is the new procedure for calculating uniform delay at signalized intersections proposed to be included in the 2010 edition of the HCM. The IQA method has been previously validated for through movements and protected plus permitted left turns. Validation results shown that the IQA method can estimate uniform delays that are exactly the same as field measured delay, for through movements. Validation for left turns showed that the IQA method cannot accurately estimate uniform delay for left turn movements at signalized intersections. However, the IQA delay estimates were more accurate than the estimates obtained using the current HCM 2000 methodology. Though the IQA method is an improvement to the current method, further improvement is required.

This paper presents models that can be used to modify the IQA delays to provide more accurate estimates of uniform delay for left turn movements. Three different configurations are evaluated: protected plus permitted lefts from an exclusive lane, permitted lefts from an exclusive lane, and shared lanes with permitted lefts. Through validation, it has been proven that, when IQA uniform delay is modified using the proposed models, more accurate delay estimates are derived. The biggest improvement was for the shared lanes with permitted left turn movements, followed by permitted lefts from exclusive lanes and protected plus permitted lefts from exclusive lanes. Delay estimation for shared lanes is the most complicated process, of the three configurations analyzed. Therefore, the higher the complexity is estimating delay, the higher the benefit achieved from applying the modification.

Future Research

This study utilized high resolution data developed through micosimulation of two real intersections. We analyzed protected plus permitted left turns and permitted left turns. Shared lanes with permitted left turns were evaluated using theoretical intersections. Though it has been shown by other researchers that VISSIM can replicate field travel patterns obtained from vehicle trajectory data, it would be necessary to utilize high resolution field data to further validate the modification models proposed in this paper.

REFERENCES

Benekohal, R. F. and Y. M. El-Zohairy, 2001. Multi-Regime Arrival Rate Uniform Delay Models for Signalized Intersections. *Transportation Research Part A 35*, Washington D.C.

Hirschmann K. and M. Fellendorf, 2009. Emission Minimizing Traffic Control – Simulation and Measurements.

Kim, J. T., 2006. Estimation of Uniform Delay of Permitted Left Turns from Exclusive Turn Lanes. *Journal of Transportation Engineering, Volume 132, Issue 9,* Reston VA, pp. 708-714.

Kyte, M., M. Dixon, V. Nayak, A. Abdel-Rahim, and D. Strong, 2008. Testing the Incremental Queue Accumulation (IQA) Method as a Replacement for the HCM Signalized Intersection Uniform Delay and Queue Method Using the Lankershim Blvd. NGSIM Data Set. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 09-9180, Transportation Research Board of the National Academies, Washington, D.C., pp. 63-70.

Kyte, M., M. Dixon, V. Nayak, A. Abdel-Rahim, and D. Strong, 2009. Validating the Incremental Queue Accumulation Method for Left Turn Delay Estimation. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 09-1101, Transportation Research Board of the National Academies, Washington, D.C., pp. 42-51.

Menneni S., C. Sun, and P. Vortisch, 2008. Microsimulation Calibration Using Speed-Flow Relationships. *Transportation Research Board, Vol 2088*. Washington D.C., pp 1–9.

Ming-Heng, W., 2008. *Development of Arrival/Departure Based Uniform Delay Model For Left-Turn Traffic at Signalized Intersections.* Ph. D. Dissertation, University of Illinois at Urbana-Champaign, Urbana, IL.

Planung Transport Verkehr (PTV) AG., 2010. *VISSIM 5.3 User's Manual.* Stumpfstraße 1, D-76131 Karlsruhe, Germany.

Hirschmann K. and M. Fellendorf, 2009. Emission Minimizing Traffic Control – Simulation and Measurements. *Proceedings of Mobil.TUM 2009*, International Scientific Conference on Mobility and Transport, TU München.

Qureshi, M. A., 2000. *A Delay Model for Exclusive Right-turn Lanes at Signalized Intersections with Uniform Arrivals and Right Turns on Red.* Ph. D. Dissertation University of Tennessee, Knoxville, TN.

Robertson D.I. and P. Gower, 1977. "User Guide to TRANSYT Version 6," Transport and Road Research Laboratory, *Supplementary Report 255*, Crowthorne.

Robertson, D.I., 1969. A Traffic Network Study Tool: TRANSYT. Road Research Laboratory. Laboratory, *Report LR 253*, Crowthorne.

Strong, D. W. and N. M. Rouphail, 2006. "Incorporating the Effects of Traffic Signal Progression into the Proposed Incremental Queue Accumulation (IQA) Method", *Paper #06-0107,* Proceedings of the 85th annual meeting of the Transportation Research Board, Washington, D.C.

Strong, D. W., N. M. Rouphail, and K. Courage, 2006. "New Calculation Method for Existing and Extended HCM Delay Estimation Procedure", *Paper #06-0106,* Proceedings of the 85th annual meeting of the Transportation Research Board, Washington, D.C.

Transportation Research Board (TRB), 2000. Highway Capacity Manual. *National Research Council,* Washington, D.C.

Webster, F., 1958. "Traffic Signal Settings. *Road Research Technical Paper No. 39.* Road Research Laboratory, Her Majesty's Stationery Office, London, U. K.