Validating the Incremental Queue Accumulation Method for Left-Turn Delay Estimation

Michael Kyte, Ahmed Abdel-Rahim, Michael Dixon,
Jan-Mou Li, and Dennis Strong

This paper examines the proposed incremental queue accumulation (IQA) method for the analysis of traffic flow at signalized intersections. The paper considers the formulation of the IQA method for protected plus permitted left turns. Validation of the model is presented by using the NGSIM high-resolution vehicle trajectory data set developed for an arterial in Atlanta, Georgia. A comparison of the existing *Highway Capacity Manual* (HCM 2000) method with the IQA method shows that the IQA approach produces delay estimates that are closer to field measurements. Several issues associated with the arrival and departure curves produced by the IQA method are examined.

A new method for estimating the performance of a signalized intersection is being considered for inclusion in the 2010 release of the *Highway Capacity Manual* (HCM). The method, known as incremental queue accumulation (IQA), was proposed by Rouphail et al. (*1*) and is an extension of Webster's method and Robertson's (*2*) approach to modeling traffic flow at signalized intersections.

The authors have previously presented a validation (*3*) of the IQA method for through vehicle movements at a signalized intersection that used high-resolution vehicle trajectory data collected as part of FHWA's NGSIM program (*4*). This validation showed that the IQA method produces average delay values that are exactly the same as field-measured delay when adjustments are made for travel time between a system entry point and a system exit point, and if the arrival pattern is precisely known. The authors also showed that the delay estimates produced by the IQA method are more realistic if the arrival pattern is represented by the actual arrival profile instead of an adjustment factor such as the progression factor.

A much more challenging problem is considered in the current paper: the modeling of left turns by using the IQA method. Modeling left-turning traffic flows has been problematic in the HCM 2000 methodology, with several unsatisfactory and limiting assumptions required (*1, 5*). A high-resolution vehicle trajectory NGSIM data set is used here to validate the IQA method.

This paper includes six sections. The next section describes how protected and permitted left turns are modeled in the current HCM method, and the third section describes the NGSIM data set. The fourth section shows an example of the data set applied to the IQA method, and the fifth section compares the results of the delay estimates from the HCM 2000 method (*6*) and the proposed IQA method with the field data. This section also considers the arrival and departure curves produced by the IQA method in some detail. The closing section presents some final thoughts on the results presented in the paper.

MODELING LEFT-TURN FLOWS BY USING HCM 2000 AND IQA METHODS

Correctly modeling left turns is the most difficult and complex part of the HCM 2000 operational analysis procedure for signalized intersections. Six different cases are considered depending on lane usage and signal phasing. The HCM model is based on uniform arrival and departure flows during the red and green intervals, while considering several possible timing sequences to account for protected and permitted left-turn movements. The model also considers the interaction between subject and opposing flows during permitted left-turn periods. The model can be represented by a triangular queue accumulation polygon (QAP) showing the growth of the queue during red and the clearing of the queue during green.

For permitted left turns, the departure pattern depends on the nature of the opposing flow. The HCM 2000 considers three basic time periods when modeling permitted left turns: the red interval, the initial portion of the green interval when the opposing queue is discharging, and the final portion of the green interval after the opposing queue has discharged. Here, the queue grows during red and the initial portion of green when the opposing queue is discharging and the departure rate is zero. After the opposing queue has discharged, left turners complete their movements as gaps in the opposing flow allow. For this period, the departure rate is modeled as a gap acceptance process.

The QAP for protected plus permitted left turns is represented in Figure 1. The queue that has formed during red may be partially or completely served during the protected left-turn interval (here shown as partially served), and then increase again during the initial portion of the permitted phase as the opposing queue discharges. The queue decreases, or dissipates completely, during the permitted interval as acceptable gaps become available.

Since the HCM 2000 d1 delay formula is based on Webster's d1 delay formula, which assumes one constant arrival rate and one constant departure rate during each cycle, it has great difficulty modeling the QAP shown in Figure 1. A complex method was adopted in 1994

M. Kyte, A. Abdel-Rahim, M. Dixon, and J.-M. Li, National Institute for Advanced Transportation Technology, University of Idaho, P.O. Box 440901, Moscow, ID 83844-0901. D. Strong, Strong Concepts, 15 Timber Lane, Northbrook, IL 60062-3715. Corresponding author: M. Kyte, mkyte@uidaho.edu.

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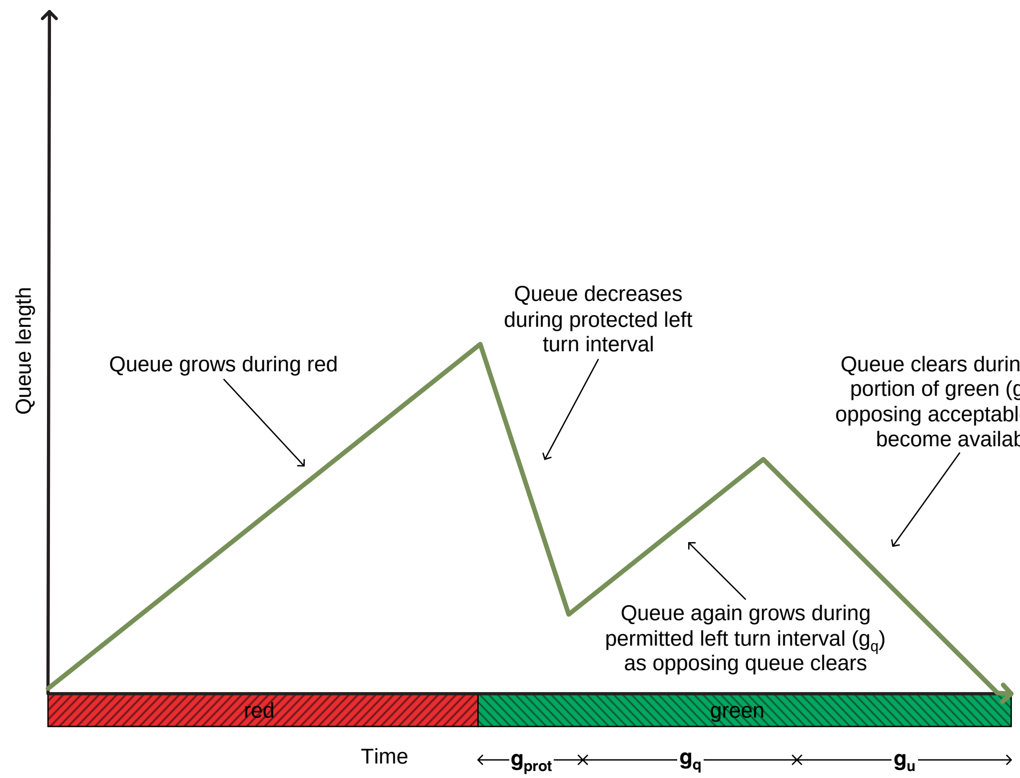

FIGURE 1 QAP for protected plus permitted left-turn operation (g_{prot} = protected left-turn interval).

to circumvent this problem to some degree, but is limited in its scope of coverage of real-world situations and thus its general accuracy.

The IQA method explicitly considers the arrival and departure patterns that exist during each of the time intervals shown in Figure 1. This QAP can be represented in a cumulative form as a set of arrival and departure functions for the same time intervals, in which arrival and departure rates remain constant during each interval. These cumulative arrival and departure functions are illustrated in Figure 2 for the time intervals shown in Figure 1.

The incremental queue is computed for the beginning and end of each of these time intervals in which both the arrival and departure rates are constant. The delay is then computed as the sum (over all the periods during which the flow rates remain constant) of the products of the average queue length and the duration of the period.

For example, the area shown in cross-hatching in Figure 2 represents the incremental delay for the protected green time interval, during which the arrival and departure rates are constant. Integrating or summing all of these areas between the arrival and departure curves yields the total delay experienced by all vehicles traveling through the intersection during this cycle.

NGSIM ATLANTA DATA SET

A high-resolution data set of vehicle trajectories was assembled for Peachtree Street in Atlanta, Georgia, as part of the NGSIM program in November 2006. The section of Peachtree Street for which data were collected is 2,100 ft in length and includes four signalized intersections and one two-way stop-controlled intersection. There are two to three through lanes in each direction of this segment. Left turns are served with either exclusive or shared lanes. The data set includes trajectories at 0.1-s resolution for 2,337 vehicles during two 15-min observation periods.

Figure 3 shows a schematic of the intersections along the study site as well as an aerial photograph of the subject intersection (Peachtree Street and 10th Street Northeast), through which 918 vehicles traveled during the 30-min period covered by this data set. A sample of 10 cycles that had queues of at least four vehicles, including 98 individual vehicles, was used for this study. This includes 25,950 individual records of vehicle positions, speeds, accelerations, and size for the 98 vehicles.

EXAMPLE CALCULATION USING THE NGSIM DATA SET

To illustrate the data that are available from the NGSIM data for left-turn traffic flows, an example is presented for the southbound approach left-turn movement at the intersection of Peachtree Street and 10th Avenue. One cycle is presented to illustrate the data discussed in this section; a more complete presentation of 15 min of data (six cycles that experience neither initial queues at the beginning of green nor cycle failures) is given later in this paper.

Figure 4 shows a time–space diagram of six southbound left-turn vehicles that arrive and depart during Cycle 7, between 650 and 750 s after the start of the study period. Four vehicles arrive during red, two of which are served during the protected left-turn interval; the other two are served during the permitted left-turn interval. The final two vehicles arrive during the permitted green interval and are served after little delay.

The stop bar is shown at a point 260 ft from the start of the study segment, the southern end of Peachtree Street, as shown in Figure 3.

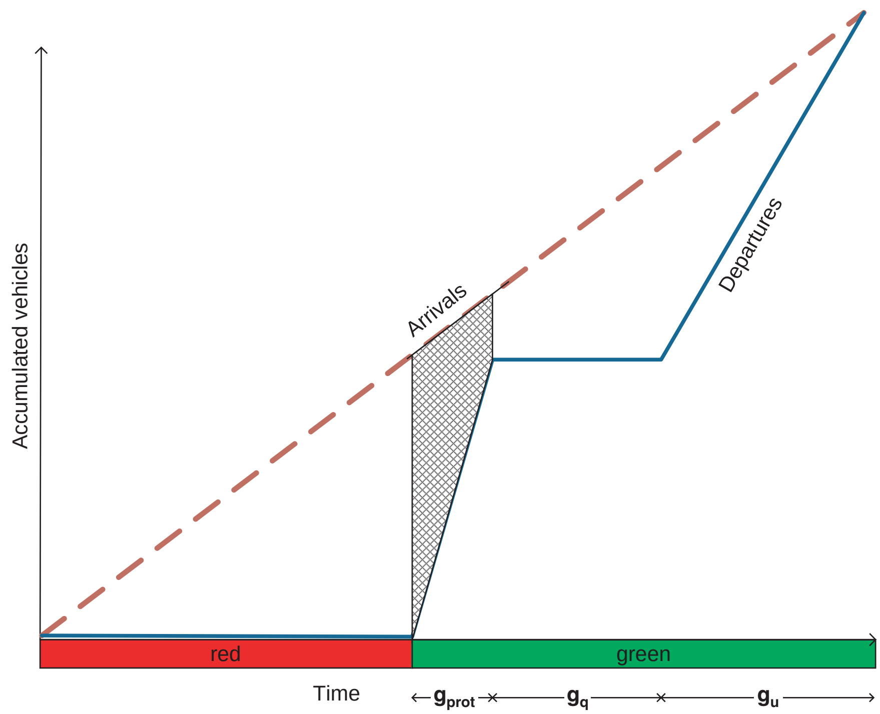

FIGURE 2 Arrival and departure patterns for protected plus permitted left-turn operation, with delay shown for protected green.

While Robertson's model (and the HCM model as well) uses the concept of the vertical queue, when using field data the horizontal queuing that results must be accounted for. To do so, a system is established with an entry point upstream of where the longest physical queue extends (in this case, Local Y = 340 ft) and an exit point downstream of the point at which the left-turn vehicle completes its turn (Local Y = 192 ft). Note that the exit point is downstream from the stop bar as many left-turn vehicles continue to wait to complete their turn even after crossing the stop bar. Delay then becomes the difference in travel time between the entry and exit points for a left-turning vehicle and a freely traveling (nondelayed) through vehicle.

The coordinate system used in Figure 4 (and subsequent figures) is based on the NGSIM reference system (*4*). The *y*-axis (Local Y) is measured in feet from the beginning of the study section. The *x*-axis (FrameID) is a 0.1-s reference system based on the time that the video data collection was initiated. Thus the *x*-axis range shown in Figure 4 ranges from 600 to 800 s, or a FrameID from 6,000 to 8,000 in 0.1 s.

Since an opposed movement (the permitted left turn) is under consideration, it is of interest to observe the interaction of the left-turn vehicles and the opposing through movements. Figure 5 illustrates the complex interactions that occur between vehicles during the three green time intervals:

- Red interval. Area 1 shows the last portion of the red interval in which four vehicles are in queue in the southbound left-turn lane.
- Protected left-turn interval. Area 2 shows the protected left-turn interval; two of the queued vehicles are served during this interval, while the other two are delayed until the permitted left-turn interval.
- Permitted left-turn interval (g_{qo}). Area 3 shows the g_{qo} portion of the permitted left-turn interval when 11 northbound through vehicles in the two opposing through lanes travel through the intersection as part of the discharging queue, blocking the southbound left-turn vehicles.
- Permitted left-turn interval (g_u). Area 4 shows the g_u portion of the permitted left-turn interval, after the opposing queue clears. The waiting left-turn vehicles are served during the initial portion of Area 4. The first one accepts a gap of 4.1 s, while the second vehicle completes its turn after the departure of the last northbound vehicle. The final two left-turn vehicles complete their turns at the end of Area 4 with little delay.

The arrival and departure curves in Figure 6 (solid lines) are plotted by using the system entry and exit points defined in Figure 4. The time difference between the arrival and departure points is also shown in the figure for each of the six vehicles. The travel times for vehicles 5 and 6 are only slightly longer than the 3.3 s that an unobstructed through vehicle takes to travel this segment. The other four vehicles, each having arrived during red, experience travel times of between 49.1 and 65.8 s. For comparison, the arrival and departure curves for the IQA method (dotted lines) are also included in the figure.

Table 1 shows the steps needed to compute the average delay on the basis of the arrival and departure times shown in Figure 6. Column 2 shows the arrival time in the system, the point noted in Figure 4 as just upstream from the end of the queue. Column 3 shows the free-flow travel time from this system entry point to the stop line. Column 4 is the calculated arrival time at the hypothetical point of the vertical queue (the stop bar), assuming that no real physical queue is present. It is the sum of columns 2 and 3. Column 5 is the actual departure time from the system (or time that the vehicle was observed passing the stop bar). Column 6 is the difference between columns 4 and 5, and represents the delay experienced by the vehicles. The average delay for all six vehicles is 36.8 s per vehicle.

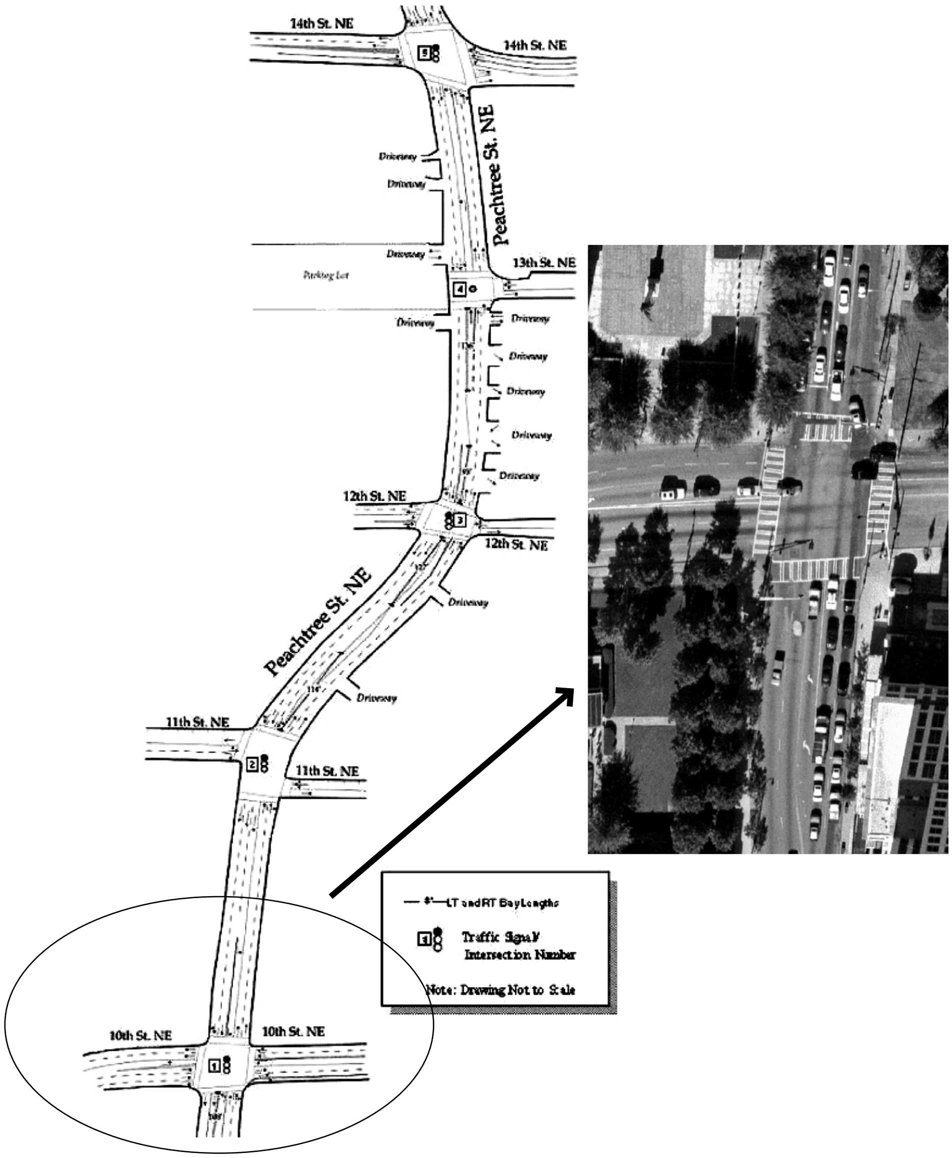

FIGURE 3 Peachtree Street study site and subject intersection (10th Street Northeast).

Figure 7 shows the QAP for Cycle 7. Each time interval during which the queue remains constant can be represented by a rectangle. For example, the shaded rectangle noted by "1" is the incremental delay experienced by all vehicles waiting while the queue includes four vehicles. The sum of all such rectangles yields the total delay in vehicle-seconds (veh-s) for this cycle.

To cast the QAP of Figure 7 in the form of an IQA analysis, each row in Table 2 represents one such rectangle. Row 4, for example, represents the shaded area "1" in Figure 7, for which the queue length is four vehicles for a duration of 31.5 s. For Cycle 7, the total delay is 220.8 veh-s, while the average delay for the six vehicles is 36.8 seconds per vehicle (s/veh).

The actual IQA calculations are not performed for individual vehicles as illustrated for the field data in Table 2, but rather for average flow rates estimated for the red and green periods (using the observed proportion of arrivals on green). These average rates are shown with dotted lines in Figure 6, and the IQA method literally calculates the area between the dotted lines as 117.9 veh-s (19.65 s/veh), then adds a d2 delay (2.5 s/veh) for an overall average delay of 22.2 s/veh. See below for further discussion of the differences between the field data and the IQA assumptions.

COMPARING DELAY ESTIMATES AND ARRIVAL AND DEPARTURE PATTERNS

Table 3 presents the field-measured delay for the southbound protected plus permitted movements (from an exclusive left-turn lane) for intersection 1 for seven consecutive cycles. There are no initial queues or cycle failures, so the HCM and IQA methods are easily compared directly to the field data.

The table also includes the delay estimates produced by the HCM 2000 method and the IQA method for these same conditions. The proportion of arrivals on green (shown in Table 3) was computed

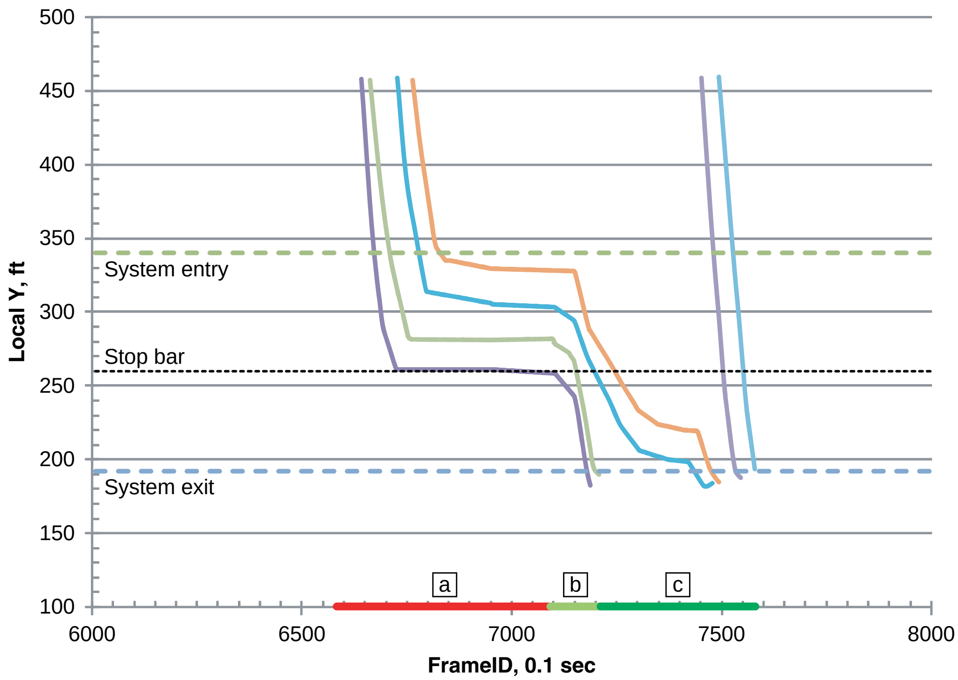

FIGURE 4 Time–space diagram for field data, Cycle 7 (a = red, b = protected left turn, and c = permitted left turn).

directly from the vehicle trajectories from the field data set and was used in both the HCM and IQA methods.

The IQA method yields delay estimates that are closer to the field measurements in all cases except one (Cycle 6, in which the differences between the field measurement and the model estimates are less than 2 s). It can be concluded that the HCM delay model result is significantly different than zero while the IQA delay method result is not, supported by the *t*-statistics and the *p*-values presented in Table 3. Note that the observations are independent, irrespective of cycle. This is reasonable as no cycle failure occurred, so the operations of a previous cycle will have little effect on the following cycle.

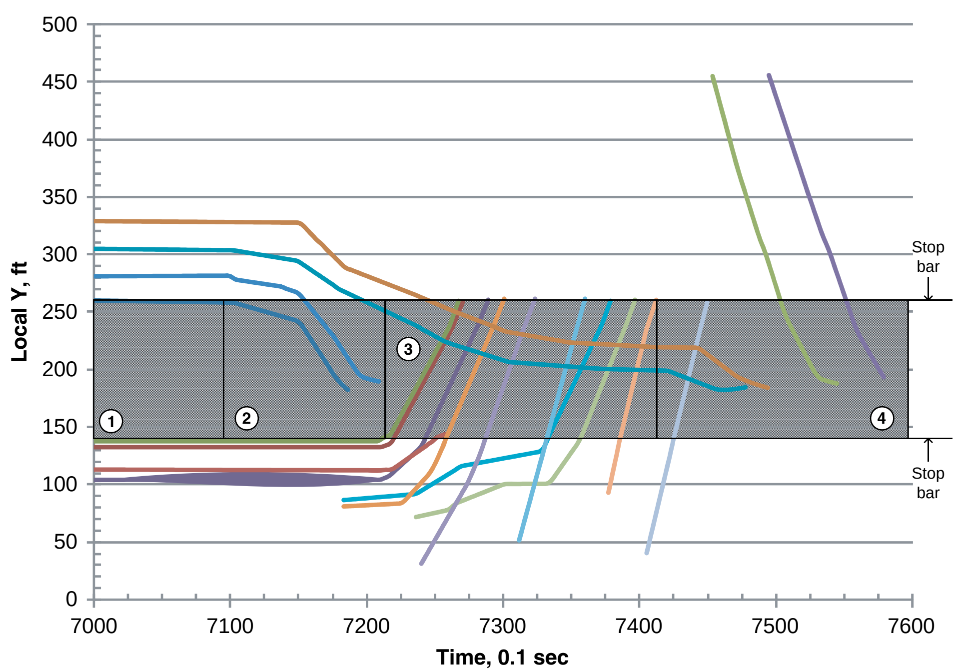

FIGURE 5 Time–space diagram for field data, Cycle 7, showing both northbound and southbound vehicle trajectories.

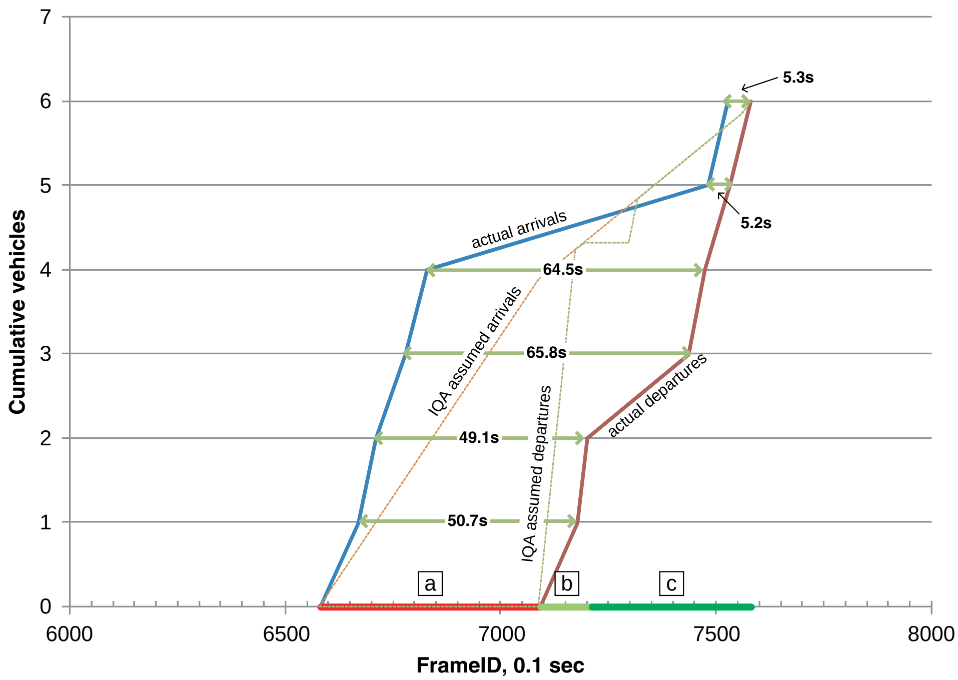

FIGURE 6 Cumulative arrivals and departures for field data, Cycle 7.

Another important result is the comparison of the arrival and departure patterns of the field data and those that are explicitly computed by the IQA method. This discussion follows.

It is worth emphasizing the importance of accurately accounting for the arrival patterns. The HCM 2000 method uses the progression adjustment factor to approximate the effect of the time during which platoons arrive during the cycle (reducing the uniform delay when a higher proportion of the flow arrives during green, and vice versa). The IQA method is a more direct approach that relates better to reality, as discussed below.

Figure 4 shows the time–space diagrams for Cycle 7, the example described in detail earlier in this paper. Here, the four vehicles that arrive on red do so early during the red interval, and the two vehicles that arrive on green arrive late in the green interval, leading to the proportion arriving on green of 0.333 shown in Table 3. Neither flow is uniformly distributed through each interval. This nonuniformity in the arrival pattern explains in part the difference between the field-measured delay (36.8 s/veh) and the model estimates (17.8 and 22.2 s/veh for the HCM 2000 and IQA methods, respectively), particularly the underestimation that results from the early arrival during red of the first four vehicles.

To further emphasize the difference that the arrival pattern makes in the delay estimates, the cumulative arrival curves for the field data (solid line) and the HCM and IQA methods (dotted line) are shown in Figure 8. The models assume uniform arrivals, one constant rate for red and one for green. While it can be argued that these differences may tend to negate each other in this example (underestimating the delay for the red and overestimating the delay during the permitted green), it does point up the weakness of the uniform arrival assumption.

The HCM 2000 method does not produce an explicit departure curve. However, departure curves for the field data (dashed line) can be compared with the IQA model (dotted line), which does produce departure rates for key parts of the green (Figure 9). Four points of interest for the IQA curve are noted in Figure 9:

- The IQA method shows an initial 2-s start-up lost time (noted by "1" in the figure). This is a more realistic representation than the

TABLE 1 Travel Time and Delay for Vehicles Served During Cycle 7

Vehicle (1)	Arrival Time in System (s) (2)	Free-Flow Travel Time (s) (3)	Arrival Time at Point of Vertical Queue (s) (4)	Departure Time from System (s) (5)	Delay (s/veh) (6)
1	667.1	3.3	670.4	717.8	47.4
2	671.0	3.3	674.3	720.1	45.8
3	677.8	3.3	681.1	743.6	62.5
4	683.0	3.3	686.3	747.5	61.2
5	748.1	3.3	751.4	753.3	1.9
6	752.7	3.3	756.0	758	2.0

NOTE: Mean delay = 36.8 s/veh.

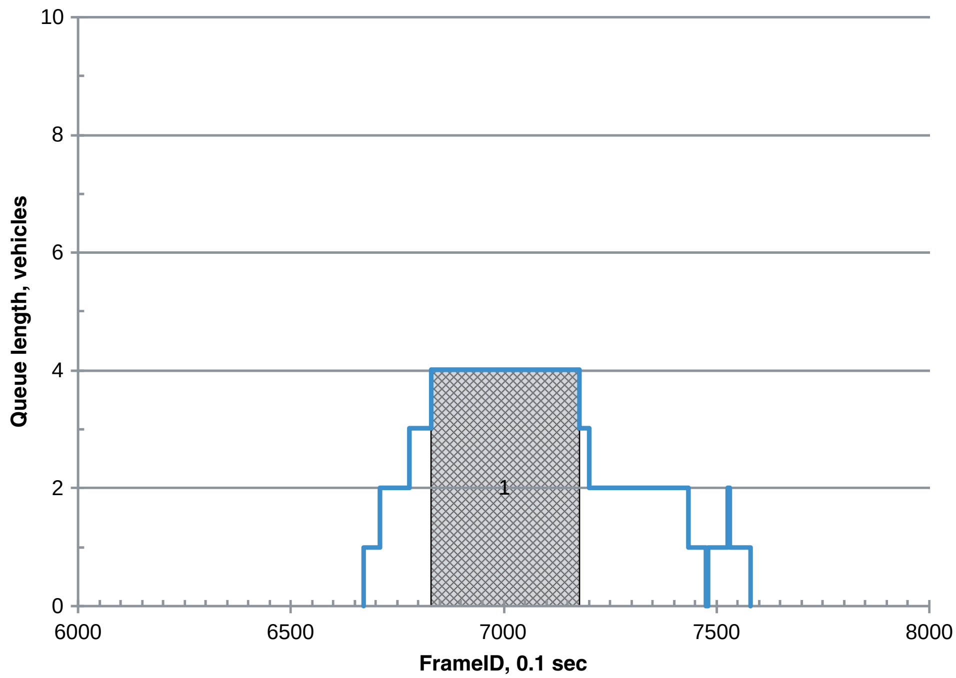

FIGURE 7 Queue accumulation for Cycle 7.

HCM 2000 method, which allocates all lost time to the beginning of the protected green.

- The departure saturation flow is indicated by "2" in the figure.
- The beginning of the permitted left-turn interval, when the opposing flow prevents any left turns from departing from the intersection, is indicated by "3."
- Vehicles departing after the opposing queue clears, as acceptable gaps become available, are indicated by "4."

Two additional points should be noted regarding the differences in these curves:

- The IQA curve at "2," noting the saturation flow rate during the protected green, extends considerably higher than the field data curve. This is reflective of an instantaneous observed saturation flow rate for this cycle that is much lower than the average saturation flow rate, which has been assumed and which was verified to match the average saturation flow rate observed in the data.
- It must also be recognized that this chart is a plot of two very different kinds of variables that are inherently difficult to compare. The IQA curve is a plot of a continuous variable whose slope represents the average departure rate of the macroscopic IQA model, while the field data curve is a plot of specific events that occurred at a micro-

TABLE 2 Field Delay Computations for Cycle 7

Clock Time (s) (1)	Event (2)	Time Δ (s) (3)	Vehicle In (4)	Vehicle Out (5)	Incremental Queue (6)	Incremental Delay (7) = (3) × (6)
670.4	Entry	3.9	1		1	3.9
674.3	Entry	6.8	1		2	13.6
681.1	Entry	5.2	1		3	15.6
686.3	Entry	31.5	1		4	126.0
717.8	Exit	2.3		1	3	6.9
720.1	Exit	23.5		1	2	47.0
743.6	Exit	3.9		1	1	3.9
747.5	Exit	3.9		1	0	0.0
751.4	Entry	1.9	1		1	1.9
753.3	Exit	2.7		1	0	0.0
756.0	Entry	2.0	1		1	2.0
758.0	Exit	0.1		1	0	0.0
758.1					0	0.0

NOTE: Total delay = 220.8 veh/s; no. of vehicles = 6; average delay = 36.8 s/veh.

TABLE 3 Comparison of Delay Measurements and Estimates

		Delay (s/veh)			Difference Between Field Data and Method	
	Proportion of Arrivals on Green	Field Data	HCM 2000 Method	IQA Method	HCM 2000 Method	IQA Method
Cycle						
3	0.600	25.9	9.9	12.9	16.0	13.0
4	0.222	27.8	21.8	29.6	6.0	–1.8
5	0.500	24.7	16.2	17.9	8.5	6.8
6	1.000	3.9	5.2	5.7	–1.3	–1.8
7	0.333	36.8	17.8	22.2	19.0	14.6
8	0.667	12.7	6.4	9.1	6.3	3.6
9	0.800	13.0	10.4	10.9	2.6	2.1
Model Results						
Mean		20.69	12.53	15.47	8.2	5.2
Standard deviation		11.24	6.19	8.31	7.2	6.6
t-statistic					3.01	2.09
p-value					.02	.08

scopic level with sloped lines connecting these events that represent the instantaneous departure rate (really, a single headway) of that individual random event. It is hopeful that similar trends can be observed in these two disparate plots, but expecting a good match for a single microscopic cycle against an average of flow rates is not realistic.

For Cycle 4, the delay estimates produced by both the models (16.2 s/veh for the HCM 2000 and 17.9 s/veh for the IQA method) are much closer to the field measurement (24.7 s/veh) than in Cycle 7. One can see why when comparing the arrival and departure curves. Figure 10 shows the arrival curves for the field data (solid line) and the HCM and IQA methods (dotted line). The arrivals during red and green compare reasonably between the field data and the model estimates.

The departure curves for the field data (dashed line) and IQA method (dotted line) are shown in Figure 11. Again, the IQA model explicitly shows the start-up lost time (1), the saturation flow during the protected green (2), the zero flow during the initial portion of the permitted green when the opposing queue is discharging (3), and the permitted flow after the opposing queue has discharged (4).

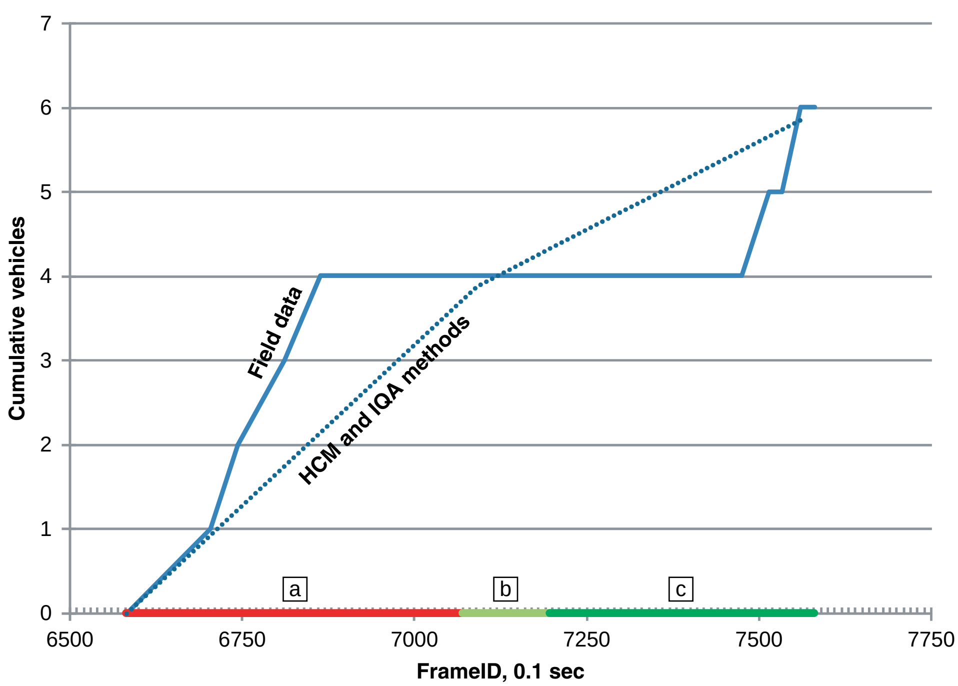

FIGURE 8 Arrival patterns for field data and IQA method, Cycle 7.

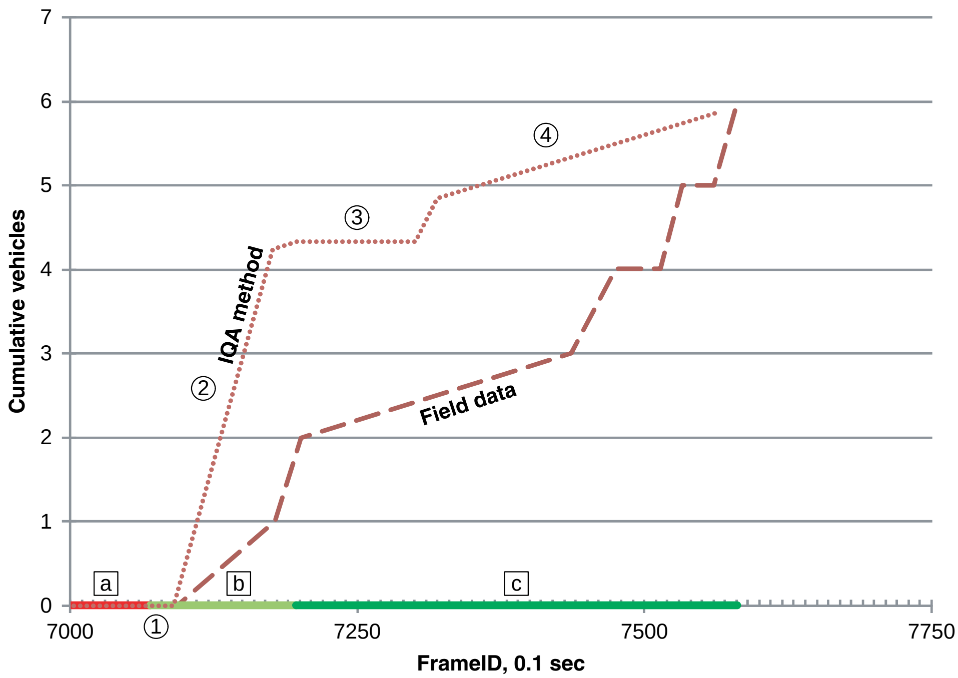

FIGURE 9 Departure patterns for field data and IQA method, Cycle 7.

FINAL THOUGHTS

The IQA method has been described (*1, 5*) and validated for through vehicle movements (*3*) at a signalized intersection. This paper describes in detail the foundation for analyzing a much more challenging process, protected plus permitted left turns at a signalized intersection. The basic traffic flow process during the red, protected left turn, and permitted left-turn intervals is described, and examples are presented of a time–space diagram for the left-turn and opposing movements, as well as cumulative arrival and departure diagrams for two cycles of a signalized intersection in Atlanta, Georgia, based on the high-resolution vehicle trajectory data collected as part of FHWA's NGSIM program. Delay comparisons are made for seven cycles.

The IQA method has been proposed as a replacement for the current HCM 2000 procedure as part of the development of the new

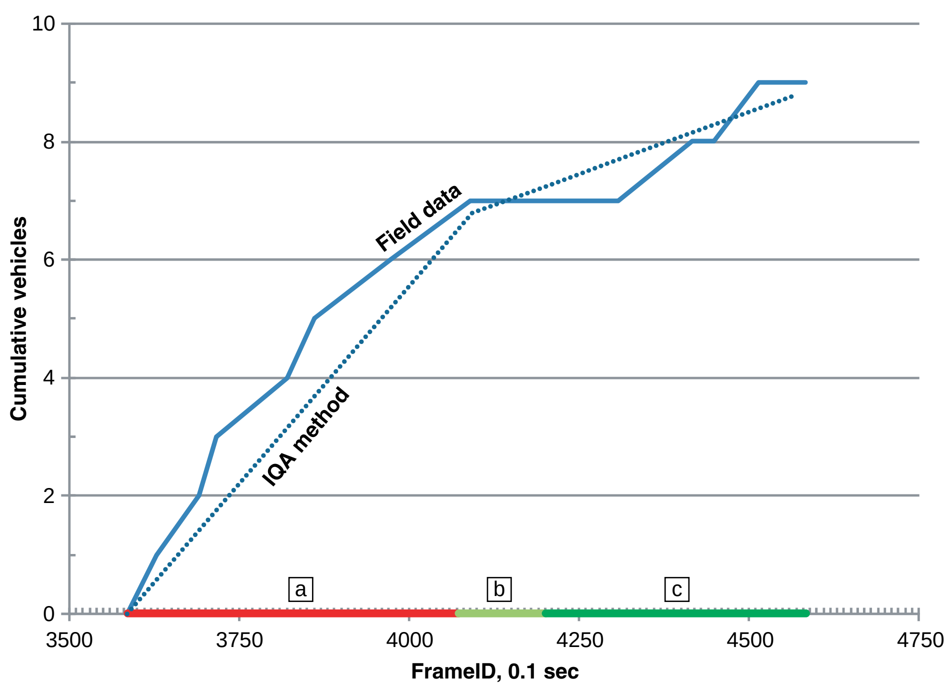

FIGURE 10 Arrival patterns for field data and HCM and IQA models, Cycle 4.

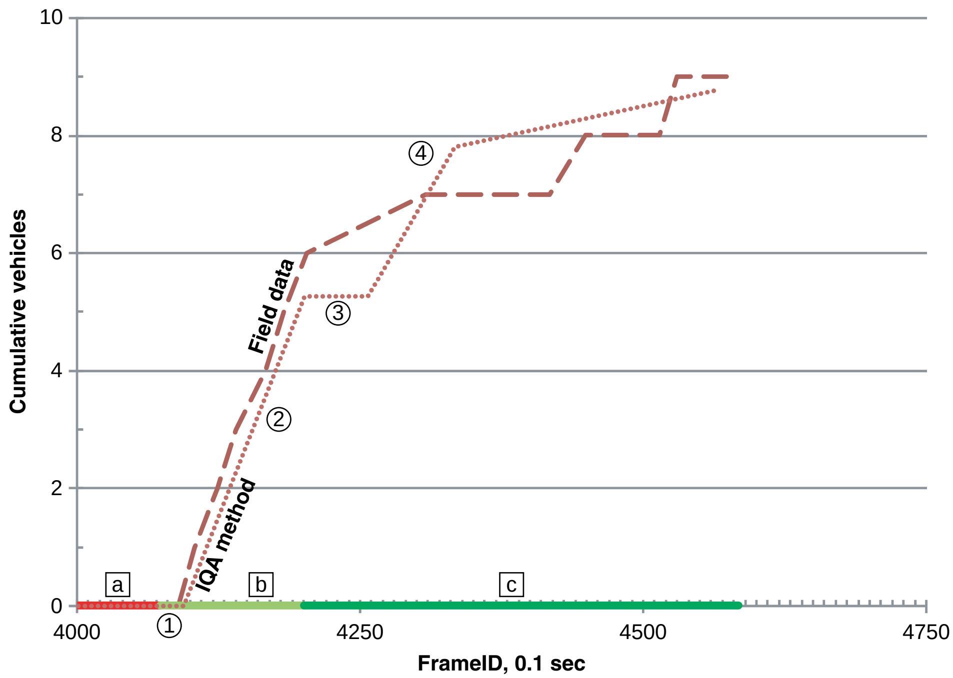

FIGURE 11 Departure curves for field data and IQA model, Cycle 4.

HCM 2010. In this paper and for through movements (*3*), the authors have shown that the delay estimates produced by the IQA method are closer to field measurements than the existing HCM 2000 method for the case of protected plus permitted left turns, for the examples presented here.

Two other advantages of the IQA method above the existing procedure have been shown. First, at a minimum, the arrival pattern is explicitly modeled by the proportion of arrivals on green rather than the approximate correction, which the HCM 2000 progression factor offers for the basic Webster d1 term. Second, the departure pattern is explicitly defined as a sequence of intervals, representing more realistic traffic flow patterns during all subintervals of the protected and permitted intervals.

It has also been shown that while the IQA method is an improvement over the existing HCM procedure, it does not completely represent the reality of left-turn movements at a signalized intersection. First, the HCM approach is macroscopic, considering an average cycle that represents both traffic flow and signal timing processes over a study period that is typically 15 min in length. It is impossible to completely represent a phenomenon that is fundamentally microscopic in a macroscopic manner. Second, unless the arrival and departure patterns are known to a relatively fine degree, their representation by the IQA method will always be approximate. However, the inherent flexibility of the IQA method allows the traffic analyst to add whatever degree of detail is known to the analysis of the performance of a signalized intersection, something not possible with the HCM 2000.

The researcher's common cry, "more work is needed," certainly fits here. But the IQA method represents a significant step in the right direction in the macroscopic modeling of traffic operations at a signalized intersection.

ACKNOWLEDGMENTS

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