ESTIMATION OF LANE-SPECIFIC QUEUE LENGTH FOR CAR-TRUCK MIXED TRAFFIC AT SIGNALIZED INTERSECTIONS

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Introduction

Queue length has been recognized as an important measure for evaluating the operational performance of signalized intersections. It can be used to predict intersection delay, travel times and level of service at intersections. At signalized intersections, queue length is a necessary input data for optimizing signal timing [1,2]. Queue length is also critical to determine the required length of turn bays to prevent queued turning vehicles from overflowing in the bay and blocking vehicle flow in the adjacent through lanes. Queue length is also used to determine the spacing between successive intersections so that a queue does not frequently spill over the upstream intersection. Queue length at signalized intersections is typically defined as the distance between the stop line of the intersection and the rear end of the last queued vehicle (horizontal queue).

A number of real-time queue length estimation methods for signalized intersections have been developed using the traffic data observed from loop detectors at various fixed locations. In this study, the queue that spills over detectors upstream of the stop line is defined as the “long queue” and the queue that does not spill over detectors is defined as the “short queue”. Sharma et al. [3] estimated the length of short queue (vertical queue) at signalized intersections using cumulative arrival counts (input) and departure counts (output) collected from loop detectors. Queue length is calculated as input minus output. This estimation method is called the “input-output technique”. The study evaluated two input-output techniques with departure counts at constant saturation flow rate and departure counts with actual departure flow collected from the detectors at the stop line. However, these techniques have inherent limitations that they cannot be used to estimate the length of the long queue.

To overcome the limitation, some researchers developed a method of estimating the length of long queue using the shock wave theory [4,5]. For instance, Skabardonis et al. [6] developed the shock-wave-based queue length estimation method using 30-sec. flow and occupancy upstream of the stop line and free-flow speed collected from loop detectors. However, the queue length can be estimated only when queue spills over the detectors called “queue spillback”. Liu et al. [7] also developed a method to estimate the maximum queue length using second-by-second occupancy time and time gaps of individual vehicles. The method was also applied to estimate the length of residual queue for the oversaturated conditions [8]. The method identifies three traffic states, calculates shock wave speeds and the maximum queue length (horizontal queue) formed in each cycle at the intersection. However, these methods cannot be used to estimate the length of the short queue since the shock wave cannot be captured at the upstream detector. Clearly, there is no comprehensive method that can estimate both long and short queue.

Regardless of the long and short queue, most queue length estimation methods did not extensively investigate the effects of three factors: 1) the variation in queue length across lanes; 2) the variation in vehicle length; and 3) the location of detectors. First, lack of consideration of lane-by-lane variation in queue length overlooks the effect of lane changes upstream of the stop line on queue length. Zheng et al. [9] estimated lane-by-lane queue length (vertical queue) using vehicle counts in each lane obtained from detectors upstream of the stop line and at the stop line. In spite of considering lane-specific queue length, the method implicitly assumes that vehicles do not change lanes as they pass the upstream detectors. If more vehicles change lanes after passing the detectors, the estimated queue length is less likely to be accurate.

Second, most studies assume that the effective vehicle length is constant regardless of vehicle type. However, when the percentage of trucks is higher, this assumption is not valid. Geroliminis [10] found that the effect of variation in vehicle length on occupancy was not significant when the queue spills over to the upstream intersection. However, the effect of variation in vehicle length on queue length has not been investigated.

Third, traffic data collected from loop detectors vary at different detector locations. For instance, if loop detectors are located closer to the stop line, vehicles are less likely to change lanes after they pass the detectors. Thus, lane-specific queue length estimation is more likely to be accurate. On the other hand, queue is more likely to spill over the detectors and it is harder to estimate the number of queued vehicles beyond the detector location. Thus, detector location significantly affects the accuracy of queue length estimation. The past empirical studies reported that detectors are typically located 30-123 m (100-405 ft) upstream of the stop line [3,7,11-13].

Although the location of detectors is important for capturing shock waves at signalized intersections [14], no studies analyzed the impact of detector location on queue length estimation. The queue length can also be estimated using travel times estimated from mobile sensors of individual vehicles to overcome the limitations of fixed-location detectors [15]. However, since not all vehicles are equipped with mobile sensors, queue length is estimated based on sample vehicle data instead of all vehicle data.

Thus, the objectives of this study are 1) to develop the comprehensive model framework of estimating the length of the long and short queue at a signalized intersection considering the variations in queue length across lanes and vehicle length and 2) to examine the effect of detector location on accuracy of queue length estimation.

Method

Shock wave method

Most conventional queue length estimation methods (e.g. input-output technique) cannot estimate the length of the long queue. Thus, Liu et al. [7] developed a queue length estimation method using the shock wave theory. For a given cycle at a typical signalized intersection, the following three traffic states exist: 1) normal traffic state: when the vehicles arrive the signalized intersection at normal speed; 2) queued traffic state: when the vehicles stop behind the stop line and form a queue during the red interval; and 3) saturation traffic state: when the queued vehicles are discharged at maximum flow rate during the subsequent green interval.

Each traffic state is characterized by flow and density as follows [7]: 1) normal traffic state: q_a (arrival flow rate) and k_a (density of arrival flow); 2) queued traffic state: zero flow (due to stoppage of vehicles) and k_j (jam density or maximum density); and 3) saturation traffic state: q_m (maximum flow rate or capacity) and k_m (density at capacity). The three shock wave speeds are calculated using the following equations:

Queuing shock wave speed: $$v_1 = \frac{0 - q_a}{k_j - k_a} \qquad (1)$$

Discharge shock wave speed: $$v_2 = \frac{q_m - 0}{k_m - k_j} \qquad (2)$$

Departure shock wave speed: $$v_3 = \frac{q_a - q_m}{k_a - k_m} \qquad (3)$$

Fig. 1 shows the movements of these three shock wave speeds in the fundamental diagram and the time-space diagram. When these shock waves pass the detector upstream of the stop line, a significant change in speed, flow and occupancy (surrogate measure of density) can be observed at the location of detectors [7]. The time when this change is observed is called “Break Point”. Three Break Points (A, B and C) were defined as follows (refer to Fig. 1(b)):

Break Point A: when the queuing shock wave passes detectors;

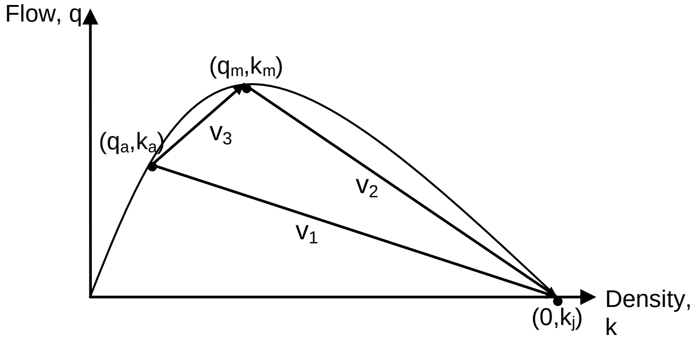
Break Point B: when the discharge shock wave passes detectors;

Break Point C: when the departure shock wave passes detectors.

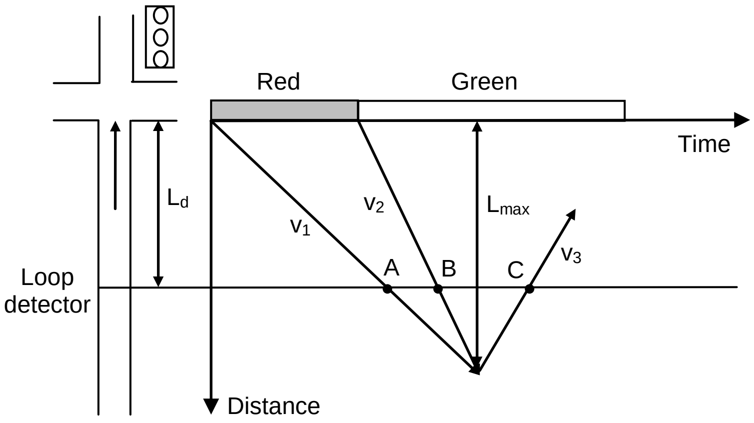
Then the maximum queue length for any given cycle (L_{max}) is calculated using the following expression:

$$L_{max} = L_d + \frac{T_C - T_B}{\left(1/v_2 + 1/v_3\right)} \qquad (4)$$

where L_d = the distance between the stop line and detectors, T_B, T_C = times of Break Points B and C, respectively, v_2 = discharge shock wave speed and v_3= departure shock wave speed.



(a) Fundamental diagram



(b) Time-space diagram

Fig. 1. Shock waves at signalized intersections.

In spite of strong theoretical background, the shock wave method cannot estimate the length of the short queue since shock waves cannot be detected at detector location. Also, it is cumbersome to determine Break Points B and C, and calculate discharge and departure shock wave speeds. The calculation time will drastically increase if the queue length in multiple lanes is estimated.

The shock wave method has a limitation when the queue length is estimated at signalized intersections when truck volume is high. Since trucks are longer and maintain longer distance headway than cars, capacity and jam density are expected to be lower when percentage of trucks is higher. Clearly, flow-density relationship, and three shock wave speeds (v_1, v_2 and v_3) are affected by percentage of trucks.

To account for the variation in capacity (q_m) and jam density (k_j) with the truck percentage, discharge shock wave speed can alternatively be calculated based on the time of Break Points B (T_B) identified from detector occupancy time and time gap profiles as follows [7]:

$$v_2 = \frac{L_d}{T_B - T_r} \tag{5}$$

where T_r = end time of red interval. However, since the variation in jam density due to change in truck percentage was not still considered, the calculation of queuing and discharge shock wave speed using Eq. (2) and (3) will be subject to errors.

Simplified method

To overcome the limitations of the shock wave method, simpler and more comprehensive model framework of queue length estimation at signalized intersections was developed. In this model framework called the “simplified method”, only the numbers of vehicles by length in a queue are needed. If we assume that there are two types of vehicles with different length – cars and trucks, the queue length can be estimated using the following equation:

$$L_{max} = L_f + N_C L_C + N_T L_T + (N-1)\bar{h} \tag{6}$$

where L_{max} = estimated maximum queue length; L_f = average distance between the stop line and the front end of the first queued vehicle; N_C = the number of queued cars; N_T = the number of queued trucks; L_C = the average length of car; L_T = the average length of truck; N = the total number of vehicles in a queue; and $\bar{h}$ = the volume weighted average distance headway. Since distance headways are different for different vehicle-following situations, $\bar{h}$ is calculated using the following equation:

$$\bar{h} = \frac{N_{CC}h_{CC} + N_{TT}h_{TT} + N_{TC}h_{TC} + N_{CT}h_{CT}}{N} \quad (7)$$

where N_{CC} is the number of car following car; N_{TT} is the number of truck following truck; N_{TC} is the number of truck following car; N_{CT} is the number of car following truck; and h_{CC}, h_{TT}, h_{TC} and h_{CT} are average headways between two consecutive vehicles in a queue. The headway is defined as the distance between the rear end of the lead vehicle to the front end of the following vehicle. Fig. 2 illustrates the flow chart of the simplified method for queue length estimation.

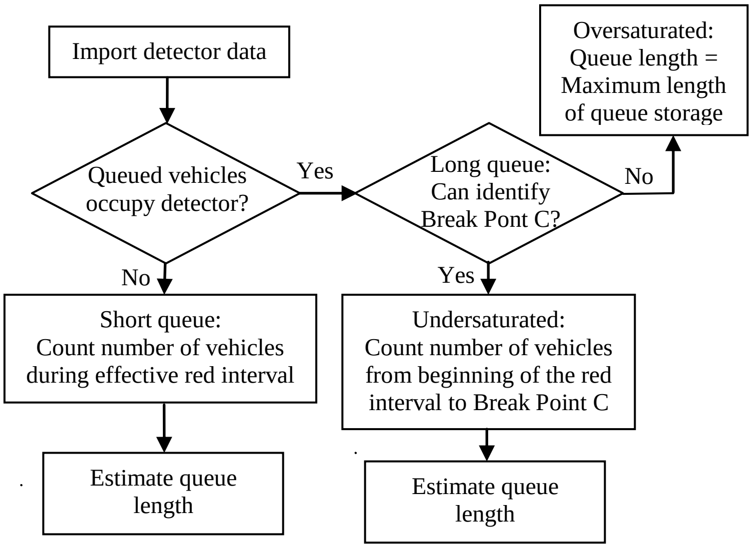


Fig. 2. Queue length estimation using Simplified method.

For the long queue, the total number of vehicles in a queue is counted for the time period from the beginning of the red interval to the Break Point C [7]. However, when the traffic is oversaturated, Break Point C cannot be identified because there is no distinctive time gap between the queue discharge flow and the new arrival flow for the subsequent cycle [8]. In this case, queue length is set to the maximum length of the link which can store the queued vehicles.

For the short queue, the total number of vehicles that pass the detectors during the effective red interval is counted. The effective red interval typically includes the displayed red interval, yellow interval excluding the portion used for clearing the vehicles and all red interval. The effective red interval was chosen since vehicles are most likely to stop during this time period.

Data

This study analyzes the signalized intersection at Huron Church Road and Tecumseh Road in Windsor, Ontario, Canada. Due to proximity of the intersection to the Ambassador Bridge, the busiest Canada-U.S. international border crossing, high volume of trucks pass through the intersection and a long queue of vehicles frequently occurs on the northbound road. The posted speed limit at this intersection is 60 km/h and the cycle length is 120 sec. The durations of the displayed green and red intervals for northbound through approach are 42 seconds and 71 seconds, respectively. Huron Church Road has three through lanes (Lanes 1, 2 and 3), an exclusive left-turn lane and an exclusive right-turn lane. There are three driveways at 30 m, 61 m, and 165 m upstream of the stop line.

To evaluate the accuracy of queue length estimated by the simplified method, second-by-second detector data (occupancy and headways) and cycle-by-cycle queue length data are needed. However, these data could not be directly obtained from the intersection due to absence of loop detectors. Instead, the data were collected using VISSIM traffic simulation [16]. VISSIM can track individual vehicle movements and accurately measure the physical length of a queue. To simulate traffic movements at the intersection, the geometric drawing, signal timing plans and hourly car and truck counts in different approaches were obtained from the City of Windsor. The queue length in the northbound through lanes was only analyzed.

Three loop detectors were placed in the three northbound through lanes at the same distance upstream of the stop line. Second-by-second speed, vehicle count by type of vehicle, and occupancy in each lane were obtained from the detectors.

The length of car and truck was assumed to be 4.55 m and 22 m, respectively, based on the field observation. However, since it was complicated to differentiate distance headways between different types of vehicles in VISSIM, default constant headway of 2 m was used. The default distance between the stop line and the front end of the first queued vehicle is 1.2 m in VISSIM. It was observed that maximum queue length was more likely to occur in the center through lane due to high number of trucks in the lane. This is similar to the actual observed conditions at the study site.

Since the accuracy of queue length estimation depends on the location of detectors, it is important to determine the suitable detector location that minimizes the estimation error. A total of 7 locations – 40 m, 60 m , 80 m, 100 m, 120 m, 140 m and 160 m upstream of the stop line – were considered in the study. Since queue length varies in each cycle, detector data were collected for 30 cycles in a one-hour simulation period using VISSIM.

Since only the maximum of actual queue length in all lanes can be obtained from VISSIM, the queue length was only estimated in the lane where the maximum queue length occurs (called "the analysis lane"). The analysis lane was identified after the queue length was estimated in each lane based on the number of vehicles in a queue, distance headway and vehicle length using the simplified method.

Results and Discussion

To evaluate the accuracy of queue length estimation in different traffic conditions, the simulations were run for the following three cases: 1) the long queue with car-truck mixed flow; 2) the long queue with car-only flow (hypothetical case); and 3) the short queue. The estimated queue length by the simplified method was compared to the actual queue length in each case.

Long queue with car-truck mixed flow

Queue length was estimated only at the detector locations where the queue spillback occurs. For instance, if the estimated queue length in the analysis lane was 90 m, queue length was estimated at 40 m, 60 m and 80 m. Then the queue length was estimated for the analysis lane using the shock wave method and the simplified method, and compared with the actual queue length.

Since the queue length varies across lanes, the times of Break Points B and C for each lane also vary. These times can be identified from the individual occupancy time and time gaps [7] in each lane separately. However, it was difficult to objectively determine Break Point C based on time gaps. Instead, these times were identified from the second-by-second vehicle count and occupancy. Break Point B occurs when occupancy suddenly drops after occupancy remains 100% during red interval (i.e. vehicles are stopped). This is the time when the queue discharge starts. Break Point C occurs immediately before zero occupancy is observed for 2 or more consecutive seconds after Break Point B and followed by increasing occupancy [7]. This is the time when the rear end of the last queued vehicles passes detectors.

These estimated queue length, $(L_{max})_{est}$, was compared with actual observed queue length, $(L_{max})_{obs}$, and the estimation error was calculated using the following equation:

$$\varepsilon = \frac{\left|(L_{max})_{est} - (L_{max})_{obs}\right|}{(L_{max})_{obs}} \times 100$$

The estimated queue length at 7 locations of detectors is shown in Fig. 3. The average estimation errors were generally lower for the simplified method than the shock wave method.

It was found that the average error per cycle was the lowest when the detectors were located 140 m and 100 m from the stop line for the shock wave method and the simplified method, respectively. Fig. 3 shows that average estimation error of the shock wave method gradually decreases as the detectors are located further away from the stop line whereas the error of the simplified method is generally constant for all detector locations. Thus, the simplified method provides more reliable results for all detector locations. Although the average estimation error is the lowest at 100 m from the stop line for the simplified method, the errors are not significantly different among 7 locations of detector at a 95% confidence interval.

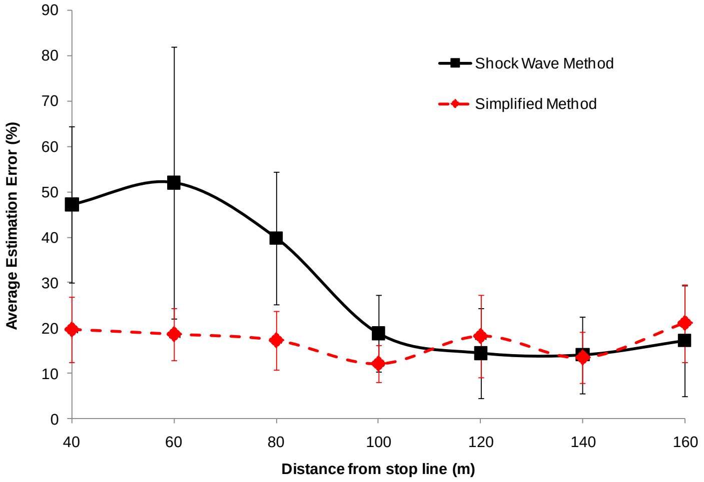


Fig. 3. Comparison of estimation errors between the shock wave and simplified methods (Long queue with car–truck mixed flow).

Long queue with car-only flow

To evaluate the effect of vehicle composition on queue length estimation, the hypothetical case with cars only at the intersection was also considered. In this case, it was assumed that the same number of vehicles as the existing case with car-truck mix arrives the intersection. Given that queue length is generally shorter due to shorter length of cars, queue length was estimated at 5 locations of detectors – 40 m, 60 m, 80 m, 100 m and 120 m.

Fig. 4 shows that the average error per cycle was the lowest when the detectors were located 80 m and 40 m from the stop line for the shock wave method and the simplified method, respectively. Similar to the long queue with car-truck mixed flow case, the estimation error and the standard error for the simplified method are almost constant for all detector locations. the simplified method also provides more reliable results regardless of detector locations. There is no significant difference in average estimation error among different detector locations at a 95% confidence interval.

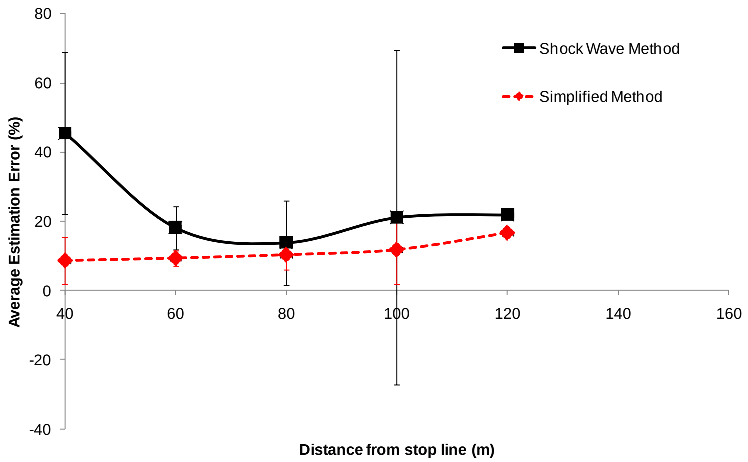


Fig. 4. Comparison of estimation errors between the shock wave and simplified methods (Long queue with car–only flow).

It is worth to note that the estimated error of the simplified method was significantly lower for car-only flow than that of car-truck mixed flow. This indicates that the variation in the estimated queue length across the lanes is higher for car-truck mixed flow than car-only flow.

Short queue

The simplified method was also applied to estimate queue length when the queue did not spill over the detectors (i.e. short queue). Fig. 5 shows that the simplified method also estimated the queue length for the short queue at a similar level of accuracy as the long queue. Again, difference in errors was not significant among different detector locations at a 95% confidence interval.

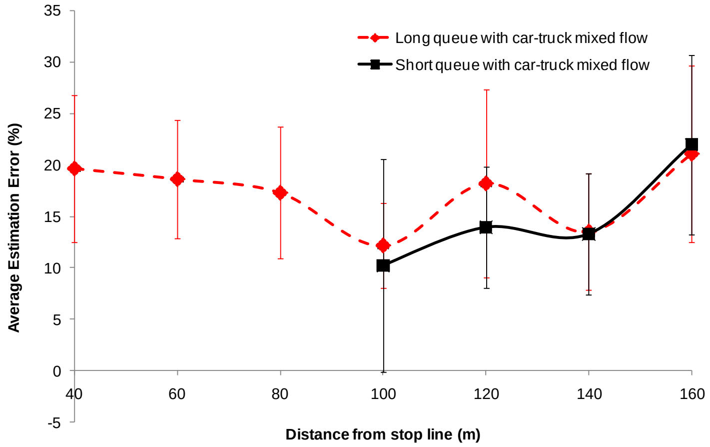


Fig. 5. Comparison of estimation errors between the long queue and short queue using the simplified method.

Conclusions and Recommendations

This study develops the model framework for estimating the queue length using the traffic data collected from detectors upstream of the stop line. In this model framework called the “simplified method”, queue length can be estimated for the cases with and without queue spill over detectors - the long queue and the short queue, respectively. For the long queue, the queue length estimation method developed by Liu et al. (2009) was adapted. For the short queue, the number of queued vehicles was counted during the effective red interval.

The estimation errors of the simplified method were generally lower than the errors of the shock wave method for the long queue at different detector locations. The accuracy of queue length estimation is lower for car-truck mixed flow than car-only flow. This is because the variation in queue length across lanes is greater for car-truck mixed flow than car-only flow due to different vehicle length and the error associated with identifying the lane with maximum queue length is likely to be higher.

The average errors and standard deviations over multiple cycles were generally constant at all detector locations. This implies that the accuracy of the simplified method can estimate queue length at similar level of accuracy regardless of detector locations.

The simplified method can also estimate queue length even when the queue does not spill over detectors (i.e. short queue) at similar level of accuracy as the long queue. Thus, the method can be applied to queue length estimation regardless of queue spillback.

Based on the findings, it is recommended that the simplified method be applied to the queue length estimation at signalized intersections since the calculation is simpler and accuracy is more consistent at any detector location and regardless of queue spillback. The model is also suitable for queue length estimation at the signalized intersection with more heterogeneous vehicle composition.

In future studies, it is recommended to develop the method of identifying the boundary condition between the queue discharge flow and the new arrival flow in the undersaturated condition. It is also recommended to estimate the queue length for exclusive left-turn and right-turn lanes to evaluate how protected or permissive turning movement phase affects queue length.

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