QUEUE LENGTH AT SIGNALIZED INTERSECTIONS FROM RED-TIME FORMULA AND HCM COMPARED TO FIELD DATA

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ABSTRACT

This study compares the HCM 2010 procedure and the “red-time” formula for estimating the back-of-queue to field data. The comparisons are made for 50th and 95th percentile queue lengths for data collected at four signalized intersections along a corridor in 4 time periods (off peak period and AM, Noon, and PM peak periods). For the 50th percentile queue length, the HCM 2010 method had significant differences from the field data in 52% of the cases (major and minor streets cases combined); of which in 93% of the cases it overestimated and in 7% underestimated the queue length. For the major street, in 28% of the cases the HCM significantly overestimated the field queue length on average by 66%, and in 4% of the cases it underestimated on average by 42%. For the minor streets, in 70% of the cases HCM significantly overestimated the queue length on average by 44%, and in 5% of the cases the field queue length was significantly underestimated on average by 20%. For practical purposes of lowering the number of cases with significant discrepancy and balancing the frequency of overestimation and underestimation, a multiplicative correction factor of 0.93 for major streets and 0.78 for minor streets could be applied on HCM estimates.

In the 95th percentile queue length comparison, in general, HCM 2010 presented better estimation than “red-time” formula. And for minor streets the “red-time” formula tends to overestimate queue length at higher-volume approaches, while underestimate at lower-volume ones. But on major streets with heavier traffic than the minor, such trend is not clear.

Keywords: Queue length estimation, HCM 2010, “Red-time” formula, queue at signalized intersections, queue field data
INTRODUCTION

Queue length is an important indicator in performance evaluation and design of signalized intersections. Queues that overflow the available storage space often deteriorate the overall performance of the intersection (1). It is common to use 95th or 99th percentile queue length, which is computed based on average queue at the end of red time, to determine the storage length for left-turn lane (2). Several models have been proposed for queue length estimation. For instance, Hao et al. (3) proposed a kinematic equation-based method to estimate queue length and vehicle locations in queue with mobile sensor data, Anusha et al. (4) developed a model-based scheme to estimate the queue length using erroneous automated data, and Lee et al. (5) developed a discriminant model to estimate the lane-based queue length with real-time detector data. Viti and Zuylen (6, 7) proposed probabilistic queuing models to analyze the queue dynamics at fixed and actuated controlled signals, which also allowed the computation of queue length. In terms of the commonly-used models, Viloria et al. (2) reviewed queue length models for SIDRA, HCM 2000, TRANSYT-7F, SOAP, NCHRP Report 279 Guidelines, SIGNAL 97, NETSIM and others. Among them HCM 2000 model was recognized as a standard methodology for queue length analysis (2).

Another method for queue length estimation is “red-time” formula (RTF), recommended by AASHTO as the conventional rule of thumb for the storage length design of left-turn lanes (8). Left-turn pocket length is often determined either based on the space needed to store the left turning vehicles in queue or based on the queue length in the adjacent through lane that could block the entrance to the left-turn lane. When queue length on the adjacent through lane is longer than the length of left-turn pocket, the left turning vehicles have to wait for the through vehicles to move forward to be able to get into the left-turn pocket. Blocking entrance to the left-turn pocket can cause starvation on left turning movement, which results in waste of left-turn green time. When the starvation occurs, queue length on the left-turn lane by itself does not give a meaningful assessment value. That is why the focus of this study is on the through lane queue that may block the entrance to the left-turn lane. Left-turn pocket length in permitted-plus-protected signal timing situation not only is controlled by the starvation issues, but also depends on the permitted phase capacity and is not addressed in this study.

The back-of-model for signalized intersections was first introduced in HCM 2000 (9). It took into account the queuing effects due to uniform arrival, random fluctuations in arrival and overflow. In HCM 2010 (10), the back-of-queue calculation was improved to include the effects of initial queue. While some previous studies have been conducted on evaluating the HCM queue length model for interchange ramp terminals and all-way stop-controlled intersections, few are found for regular signalized intersections (11, 12). Viloria et al. (2) compared the queue length model of HCM 2000 with other queue models in common software products, and found that the HCM 2000 estimated a longer queue length than most of the other models. However, these comparisons were based on two virtually generated traffic datasets, and did not compare the HCM estimates to field data. Similarly, few studies have been conducted to evaluate RTF. Qi et al. (8) argued that the accuracy of RTF depended on the arrival rates, i.e. it would overestimate (or underestimate) the left turn queue length if the arrival rates are high (or low); however, no further discussion was provided.

To assess the accuracy of these two methods, this study compared the queue length estimates from HCM 2010 model and RTF to the field data. Field data were collected at four signalized intersections along a corridor over three peak periods (AM peak, noon peak, and PM peak) and one off-peak period. The 50th and 95th percentile queue lengths from HCM were compared to field data. The RTF results were compared to 95th percentile values from field data. The relationships between the comparison results of 50th and 95th percentile queue length were
examined and the effects of traffic volume on the estimation accuracy were analyzed. Finally, the
directions for further improvements of these two methods were discussed.

STUDY AREA

The study area consists of the six intersections on Neil Street in Champaign, IL (FIGURE 1). At
the north end the Neil St corridor Stadium Drive and the south end the intersection of Windsor
Road is located. During the data collection time, these six intersections were actuated-coordinated
along directions of Neil Street, i.e. northbound and southbound. As for the traffic patterns, on Neil
Street the heavy direction is northbound during the morning and southbound in the afternoon,
which corresponds to the daily commute pattern to downtown Champaign. And on the cross streets
of the typical four-legged intersections, i.e. Stadium Drive, Kirby Avenue, St. Mary’s Road and
Windsor Road, higher volume goes eastbound towards the campus area of the University of Illinois
at Urbana-Champaign in the morning, and vice versa in the afternoon.

Since the intersection of Neil Street & Devonshire Drive is a T-intersection and the
westbound of Neil Street & Knollwood Drive is only a driveway for a commercial plaza, the
following study primarily focused on the queue length comparisons of the other four typical
intersections.

DATA

Field Data Collection
The Field data were collected at the six intersections of the study area in the fall of 2013 during
October, November, and December. For each intersection, the traffic data were recorded using
video cameras for two days in the morning (7:00 AM – 9:00 AM), noon (10:30 AM – 1:30 PM)
and afternoon (4:00 PM – 6:00 PM). Weekdays with normal weather conditions, except Mondays
and Fridays, were selected to capture typical traffic conditions. One of the two data collection days
was selected for data reduction and queue length calculation per intersection, as to exclude the
traffic affected by activities such as unusual weather conditions and road construction, as well as
to ensure the availability of data for the entire time period on that day. For the intersection of Neil
Street & St. Mary’s Road, the traffic data during PM Peak were unavailable on the selected day
(November 20, 2013), and thus were obtained on December 11, 2013. The dates and days of data
reduction are shown in TABLE 1.

TABLE 1 Dates and Day of Data Reduction

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Date</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neil Street &amp; Stadium Drive</td>
<td>November 7, 2013</td>
<td>Thursday</td>
</tr>
<tr>
<td>Neil Street &amp; Kirby Avenue</td>
<td>November 13, 2013</td>
<td>Wednesday</td>
</tr>
<tr>
<td>Neil Street &amp; St. Mary’s Road*</td>
<td>November 20, 2013</td>
<td>Wednesday</td>
</tr>
<tr>
<td>Neil Street &amp; Devonshire Drive</td>
<td>October 29, 2013</td>
<td>Tuesday</td>
</tr>
<tr>
<td>Neil Street &amp; Knollwood Drive</td>
<td>November 12, 2013</td>
<td>Tuesday</td>
</tr>
<tr>
<td>Neil Street &amp; Windsor Road</td>
<td>November 5, 2013</td>
<td>Tuesday</td>
</tr>
</tbody>
</table>
**Data Reduction**

The traffic videos were reduced to obtain traffic data used in queue length calculation and estimation. The time periods of data reduction include morning (7:10 AM-8:40 AM), noon (10:40 AM – 1:15 PM), and afternoon (4:40 PM – 6:00 PM). The items of data reduction include peak hours, hourly volume, saturation flow rate, signal timing, arrival type, truck factor, and queue length, which were described as following:

**Peak Hours**

In the study, three peak hours, i.e. AM, noon, and PM peak, and one off peak hour were supposed to be determined for data reduction and comparison analysis. Therefore, at the four typical intersections, the through movement volumes of Neil Street directions in the traffic videos were counted manually with a 2-minute interval during the three data reduction time periods. During AM and PM periods, the peak hour was determined as the hour with the highest total through volume in the heavy direction at these four intersections, i.e. northbound in the morning and southbound in the afternoon. The noon peak hour was the hour with the highest total through volume in both directions at these four intersections during the noon time period. And the off peak hour was the first hour of the noon time period. The selected peak hours include 7:30-8:30 am for AM peak, 10:40-11:40 am for off peak, 12:10-13:10 pm for noon peak, and 16:40-17:40 pm for PM peak.

**Hourly Volume**

The hourly volume was used in the queue length estimation by the HCM 2010 procedure and the “red-time” formula. For each studied time period, the left, through and right turning movement volumes of all intersections were manually counted from the traffic videos with an interval of 15 seconds. Each volume count lasted for 1.5 hours, from 18 minutes prior to the start of the peak/off-peak hour to 12 minutes after the end of it. The hourly volumes during the 3 peak hours and the off peak hour were then picked up for further studies.

For eastbound and westbound approaches at the intersections of Neil Street with Stadium Drive and St. Mary’s Road, the entrances of the shared through and right-turn lanes are wide enough to allow vehicles to skip the queue for through traffic and turn right during red. As these right turn on red (RTOR) traffic did not account for the queue generation for the shared lane group, they were counted and excluded from the right-turn volumes in the HCM 2010 back-of-queue estimation procedure.

TABLE 2 shows the hourly volume of typical intersections. The right-turn volumes listed do not include the RTOR volumes. From the table it is evident that the volume in northbound during AM peak was higher than that in southbound at these intersections, and vice versa during PM peak. For the cross streets the eastbound volume was higher in AM peak, while in PM peak that in westbound was higher. These observations support the traffic patterns mentioned in the previous section.

**Saturation Flow Rate**

Saturation flow rate was used in HCM 2010 queue length estimation procedure. HCM 2010 technique for measuring saturation flow rate was adopted to calculate the base saturation flow rate of through lanes for local conditions in the study area, and the unit of it is passenger car per hour of green per lane (pcphgpl). Adjustments were made on the base saturation flow rate to obtain the saturation flow rate for left and right turns. To obtain a stable result for an approach, 50 “valid” headways, i.e. the headway of any vehicle after the fourth one in queue, were required as a
minimum. And thus only the intersections of Neil Street with Kirby Avenue and Windsor Road were saturated enough for the measurement. In FIGURE 1, the intersections labeled with ‘X’ did not have adequate data for measuring saturation flow rate, and the measuring results for the intersections of Neil Street with Kirby Avenue and Windsor Road are shown.

Based on the field measurement and the geometries of intersections, a saturation flow rate of 1900 pcp/h/gpl was used for northbound and southbound through lanes at all typical intersections. For westbound through lanes, 1750 pcp/h/gpl was used at all typical intersections except Windsor Road, where 1900 pcp/h/gpl was used. For eastbound through lanes, at Kirby Avenue and Windsor Road 1900 pcp/h/gpl was used, while 1750 pcp/h/gpl was used for Stadium Drive and St. Mary’s Road.

### TABLE 2 Hourly Volume of Typical Intersections

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Time Period</th>
<th>NB*</th>
<th></th>
<th></th>
<th>SB*</th>
<th></th>
<th></th>
<th>EB*</th>
<th></th>
<th></th>
<th>WB*</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>LT**</td>
<td>THRU**</td>
<td>RT**</td>
<td>LT</td>
<td>THRU</td>
<td>RT</td>
<td>LT</td>
<td>THRU</td>
<td>RT</td>
<td>LT</td>
<td>THRU</td>
</tr>
<tr>
<td>Neil St &amp; Stadium Dr</td>
<td>AM Peak</td>
<td>53</td>
<td>903</td>
<td>29</td>
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<td>173</td>
<td>40</td>
<td>10</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Off Peak</td>
<td>23</td>
<td>553</td>
<td>30</td>
<td>41</td>
<td>559</td>
<td>20</td>
<td>26</td>
<td>28</td>
<td>6</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Noon Peak</td>
<td>37</td>
<td>739</td>
<td>49</td>
<td>57</td>
<td>838</td>
<td>19</td>
<td>34</td>
<td>52</td>
<td>30</td>
<td>51</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>PM Peak</td>
<td>31</td>
<td>842</td>
<td>23</td>
<td>50</td>
<td>1025</td>
<td>26</td>
<td>28</td>
<td>38</td>
<td>42</td>
<td>69</td>
<td>181</td>
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<td>88</td>
<td>824</td>
<td>118</td>
<td>153</td>
<td>516</td>
<td>47</td>
<td>150</td>
<td>678</td>
<td>131</td>
<td>91</td>
<td>215</td>
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<tr>
<td></td>
<td>Off Peak</td>
<td>101</td>
<td>532</td>
<td>64</td>
<td>71</td>
<td>514</td>
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<td>93</td>
<td>116</td>
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<td></td>
<td>Noon Peak</td>
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<td>642</td>
<td>104</td>
<td>135</td>
<td>751</td>
<td>115</td>
<td>108</td>
<td>353</td>
<td>141</td>
<td>153</td>
<td>252</td>
</tr>
<tr>
<td></td>
<td>PM Peak</td>
<td>170</td>
<td>719</td>
<td>112</td>
<td>159</td>
<td>960</td>
<td>139</td>
<td>124</td>
<td>466</td>
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<td>155</td>
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<td>Neil St &amp; St Mary’s Rd</td>
<td>AM Peak</td>
<td>33</td>
<td>888</td>
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<td>531</td>
<td>68</td>
<td>17</td>
<td>81</td>
<td>16</td>
<td>22</td>
<td>36</td>
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<tr>
<td></td>
<td>Off Peak</td>
<td>18</td>
<td>577</td>
<td>42</td>
<td>63</td>
<td>631</td>
<td>34</td>
<td>33</td>
<td>46</td>
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<td>26</td>
<td>49</td>
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<tr>
<td></td>
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<td>24</td>
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<td>241</td>
<td>625</td>
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<tr>
<td></td>
<td>Off Peak</td>
<td>60</td>
<td>430</td>
<td>127</td>
<td>82</td>
<td>445</td>
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<td>108</td>
<td>243</td>
<td>57</td>
<td>136</td>
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<tr>
<td></td>
<td>Noon Peak</td>
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<td>520</td>
<td>175</td>
<td>134</td>
<td>575</td>
<td>146</td>
<td>144</td>
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<td>167</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>PM Peak</td>
<td>67</td>
<td>387</td>
<td>140</td>
<td>237</td>
<td>877</td>
<td>235</td>
<td>120</td>
<td>370</td>
<td>85</td>
<td>298</td>
<td>659</td>
</tr>
</tbody>
</table>

NOTE: *NB, SB, EB, and WB are the abbreviations of northbound, southbound, eastbound, and westbound, respectively. Same abbreviations will be used in the following tables and figures.

** LT, THRU, and RT are the abbreviations of left turn, through, and right turn volume, respectively. Same abbreviations will be used in the following tables and figures.
**FIGURE 1** Saturation Flow Rate Measurement Results for the six study intersections on Neil Street in Champaign, Illinois.

**Signal Timing**

Signal timing, including phase sequence, phase splits, and cycle length, was used in both the HCM 2010 procedure and “red-time” formula. The phase sequence and splits varied due to the presence of actuated-coordinated signal control. Therefore, an average signal timing plan was built for each intersection, in order to represent the behavior of its actuated signal operation during the study periods. Similar to the hourly volume reduction, the signal timing data were collected with a duration of 1.5 hours for each studied time period per intersection. The total number of signal timing cycles was about 90 for Neil Street & Stadium Drive, and about 45 for the other three intersections. Therefore, the average signal timing plan for the peak/off-peak hour was obtained by analyzing the cycles between the 20th and 78th for Neil Street & Stadium Drive, and the 10th and 39th for the other three intersections from the traffic videos and the signal controller settings.

The phase sequence consisting of the most recurring phases was adopted as the average phase sequence, and the average phase splits were determined by either using the mean or the mode of the observed splits, whichever was more suitable. For instance, if a consistent green split existed in a phase over more than 50% of the cycles during the study period, the mode of the observed splits would be determined as the green split for this phase in the average signal plan. Otherwise, the mean of the observed splits, with the outliers excluded, would be determined as the green split for this phase.

According to the signal controller settings, the yellow change values were 3.2, 3.6, or 3.9 seconds, and a 2-second red clearance was decided to be used. Due to the coordinated signalized operation, during each time period the cycle length was equal for all typical intersections except Neil Street & Stadium Drive: the cycle length of this intersection was half of that of the others. And the cycle length of these three intersections was 110 seconds for AM peak, noon peak and off peak hours, and 120 seconds for PM peak hour.

**Arrival Type**

The arrival type data was used in HCM 2010 queue length estimation. For all movements on cross streets and left-turns on Neil Street at all typical intersections, random arrival, i.e. arrival type 3,
was assumed. For through movements on Neil Street, arrival types of 1, 5, and 6 were not observed in the field. The proportion of vehicle stopped was computed for each through movement on Neil Street. This was used to estimate proportion of vehicles stopped at each approach. The computed values as well as the review of the video tapes of the intersections and the information given in Exhibit 18-8 of HCM 2010 (10) were used to determine arrival types. And the arrival types were 2, 3, or 4.

**Truck Factor**

The truck factor was used in both HCM 2010 queue length estimation and the “red-time” formula. The two intersections, Neil Street with Kirby Avenue and St Mary’s Road, were selected to compute the truck factors for all the intersections per time period due to their representative traffic volumes with respect to the four typical intersections. For each of them the number of heavy trucks was counted during the middle half-an-hour per time period, and was divided by the corresponding middle half-an-hour volume to obtain the truck factor. The computation results closed to the default value of 2% in Highway Capacity Software (HCS). To simplify the estimation procedure, a truck factor of 2% was used for all intersections during all time periods.

**Queue Length**

The field queue lengths of through lane groups of the four typical intersections were determined by manually counting the number of stopped vehicles at the end of the red phase on a cycle-by-cycle basis; and adding to that the number of vehicles that joined the queue during the beginning of the green phase and came to a complete stop. This was considered as the back-of-queue reach from the field data. For each through lane group, the queue lengths of the cycles during 3 peak hours and the off peak hour were counted. For approaches with 2 through lanes, if the lanes had a similar number of vehicles in queue (half an hour of video for each approach was watched to make such determination), then the queues on the lane closer to the camera site were used because it had less blocked view. If unbalanced queues were observed, the queue lengths of both lanes were counted and the averages were used. Only those lane groups that have a maximum queue length of at least 2 vehicles were considered, of which the 50th and 95th percentiles queue lengths were calculated for the comparison analysis.

**METHODS OF QUEUE LENGTH ESTIMATION**

**HCM 2010 Back-of-Queue Procedure**

Highway Capacity Manual 2010 provides a procedure for estimating back-of-queue reach, i.e. the average maximum backward extent of queued vehicles for the analysis period (10). The back-of-queue size for a given lane group is computed with the following equation:

\[
Q = Q_1 + Q_2 + Q_3
\]

where

- \(Q\) = back-of-queue size (veh/ln);
- \(Q_1\) = queue caused by signal cycling (veh/ln);
- \(Q_2\) = queue caused by random, cycle-by-cycle fluctuations and a sustained oversaturation (veh/ln), and
- \(Q_3\) = initial queue (veh/ln).

Accordingly, a percentile back-of-queue estimate can be computed as following:
\[ Q_{50\%} = Q \]
\[ Q_{9\%} = (Q_1 + Q_2) f_{B\%} + Q_3 \]

where

\[ Q_{50\%} \] is the 50th percentile back-of-queue (veh/ln);
\[ Q_{9\%} \] is the percentile back-of-queue size (veh/ln), and
\[ f_{B\%} \] is the percentile back-of-queue factor.

More detailed equations for \( Q_1, Q_2, Q_3, \) and \( f_{B\%} \) can be found in HCM 2010. To perform this back-of-queue calculation procedure for each intersection, HCS 2010 version 6.70 was used (13). Inputs for demand, saturation flow rate, phasing, signal timing, and arrival types in HCS runs were obtained from the field data. The cycle length at the intersection of Neil Street & Stadium Drive was different from the other intersections, so individual HCS runs per intersection were made, rather than a single run for the corridor. Pre-timed signal with Field-Measured option was selected since the through lanes on the major street did not have detectors. From HCS runs the 50th and 95th percentile back-of-queue estimates were obtained.

“Red-Time” Formula

“Red-time” formula (RTF) is used to estimate the storage length requirements at signalized intersections. It is based on the assumption that doubling the number of vehicles stored (queued) during the red phase would give enough length to handle most of the traffic conditions. The storage length in RTF is computed as following:

\[ \text{Storage Length (ft)} = \frac{(1-\frac{G}{C})(DHV)(1+\%\text{trucks})(25\times2)}{(# \text{cycles per hour})(# \text{traffic lanes})} \] (4)

where

\[ G \] = green time (second);
\[ C \] = cycle length (second);
\[ DHV \] = Design Hourly Volume of the through lanes (in this study) (veh/h);
\[ \%\text{trucks} \] = the fraction of the volume that is heavy truck;
\[ 25 \] = average storage length for a passenger vehicle (ft), and
\[ 2 \] = a margin of safety.

This storage length was considered to be comparable to the 95th percentile queue length values, as in the formula the average storage length is converted to the 95th percentile storage length by a safety parameter of 2. Thus it was used to estimate the 95th percentile queue length for each through lane group. The total volume of the through lane group under consideration was used as DHV. For comparison purposes, the unit of computed storage length was changed from feet (ft) to vehicle per lane (veh/ln) by dividing it by the assumed average vehicle length of 25 ft.

ANALYSIS OF COMPARISONS

The estimated 50th and 95th percentile queue lengths by HCM method were compared to the queue length from field data. For the RTF only the 95th percentiles were compared. As only through lane groups with a maximum queue length over 2 vehicles were considered, 52 out of the total 64 cases were analyzed. Thus, the cases during off peak period and the eastbound/westbound cases during noon peak period at the intersections of Neil Street with Stadium Drive and St Mary’s Road were not analyzed.

50th Percentile Queue Length Comparison

50th percentile queue length estimations from HCM were statistically compared with the 50th
percentile queue length from the field. The differences of comparison were tested using the single-sample Wilcoxon signed-rank test with 90% confidence level.

TABLE 3 shows the summary of comparison results. Overall, 27 out of 52 cases (52%) have p-values smaller than 0.1, which indicates that significant differences (discrepancies) exist between the HCM estimates and field data. In 93% of these cases HCM significantly overestimated the field queue length on average by 52%. However, in 7% of the cases HCM significantly underestimated it by 31%. To further analyze the data, all cases were divided into two categories: major street (northbound and southbound) cases and minor street (eastbound and westbound) cases.

In 32% of the major street cases, the queue lengths from HCM were significantly different than those from the field. In 89% of these cases HCM overestimated the queue length on average by 66%; however, in 11% of the cases (this is the only one case) it underestimated it on average by 42%. Such significant discrepancies are shown in FIGURE 2(a) in forms of vehicle per lane and percentage over field data.

For minor streets, in 75% of the cases significant discrepancies exist between the HCM queue length estimates and field data. Within them, in 94% of the cases HCM overestimated the field queue length on average by 44%, and only in 6% of the cases (this is the only one case) HCM underestimated it by 20%. Similar to the major street cases, the cases with significant discrepancies are shown in FIGURE 2(b), where the discrepancies are reported in forms of vehicle per lane and percentage over field data.

Queue Length Adjustments
It was attempted to see if adjustments can be applied to the HCM queue length estimates to make them closer to the field data. Trials were conducted to find such correction factors (CFs) for major and minor street cases. Different CFs were applied and the number of cases with significant differences were obtained. According to TABLE 3, the expected underestimation rates in cases with significant discrepancy for major and minor streets were 4.6% and 1.2%, respectively. These values are too low compared to the corresponding expected overestimation rates (58.7% and 41.4%) and were not taken into account in CF definition.

To begin with, the multiplicative inverses for the 2 expected overestimation rates for the significant discrepancy cases were used as the initial CFs for major and minor street cases, which were 0.630 and 0.707, respectively. For each category, the HCM 50th percentile back-of-queue estimates were multiplied by the corresponding CF and the corrected HCM estimate results were obtained. Then the above statistical comparison procedure was conducted between the field median queue length and these corrected HCM estimates and new comparison results were analyzed. The values of CFs were increased with an increment of 0.025 until they reached 1, and for each set of CFs the same approach was repeated to find out the best correction results.

Nevertheless, such overall CFs were observed to cause shifts between the significant level of discrepancy: while they lowered the overestimation rates of the significant overestimation cases, they might also increase the underestimation discrepancies or change the initially insignificant discrepancies to significant underestimations in other cases. As a result, it was found that for the major street a CF of 0.930 yielded the lowest number of cases with significant discrepancy while the frequencies of overestimation and underestimation by HCM were balanced. Similarly, for the minor streets, the lowest number of cases with significant discrepancy was obtained when a CF of 0.757 was used; however, a balanced frequency for overestimation and underestimation by HCM was obtained when the CF was 0.782. Thus, if it is desired to have minimum amount of discrepancy and yet a balance in frequencies for overestimation and underestimation, a CF of 0.93 for major streets and a CF of 0.78 for minor streets should be applied.
# TABLE 3 50th Percentile Queue Length Comparison Summary

<table>
<thead>
<tr>
<th>Categories</th>
<th>Number of cases</th>
<th>Percentage*</th>
<th>Range of (HCM-Field)/Field %**</th>
<th>Average Discrepancy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>52</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Significant Discrepancies</td>
<td>27</td>
<td>52%</td>
<td>(-42) - 137%</td>
<td>-</td>
</tr>
<tr>
<td>Significant Overestimation</td>
<td>25</td>
<td>93%</td>
<td>14 - 137%</td>
<td>52%</td>
</tr>
<tr>
<td>Significant Underestimation</td>
<td>2</td>
<td>7%</td>
<td>(-42) - (-20)%</td>
<td>(-31)%</td>
</tr>
</tbody>
</table>

**Major Street (NB/SB)**

| Total                             | 28              | -           | -                              | -                       |
| Significant Discrepances          | 9               | 32%         | (-42) - 120%                   | -                       |
| Significant Overestimation        | 8               | 89%         | 17 - 120%                      | 66%                     |
| Significant Underestimation       | 1               | 11%         | (-42)%                         | (-42)%                  |

**Minor Street (EB/WB)**

| Total                             | 24              | -           | -                              | -                       |
| Significant Discrepances          | 18              | 75%         | (-20) - 137%                   | -                       |
| Significant Overestimation        | 17              | 94%         | 14 - 137%                      | 44%                     |
| Significant Underestimation       | 1               | 6%          | (-20)%                         | (-20)%                  |

*: Data not applicable

*In each Percentage column, the percentages correspond sequentially to $\text{Significant Discrepancies Total} \%$, $\text{Significant Overestimation} \%$, and $\text{Significant Underestimation} \%$.

**(HCM-Field)/Field % for eastbound PM and westbound AM at Neil Street & Stadium Drive are unavailable, because the field queue lengths of these two cases are 0 veh/ln
FIGURE 2 Cases with significant discrepancies between HCM estimates and field data in median queue length comparison.
95th Percentile Queue Length Comparison

The 95th percentile queue lengths estimated by the RTF and HCM 2010 methodology were compared with those calculated from the field data (see FIGURE 3). Since eastbound and westbound cases did not have data during noon peak period at the intersections of Neil Street with Stadium Drive and St Mary’s Road, the northbound and southbound noon peak cases at these two intersections were not used in FIGURE 3.

As shown in FIGURE 3, for each intersection two graphs display the discrepancies between the HCM and RTF versus the field data. The differences are shown both in units of vehicles per lane and in percentages. When comparing the two estimation methods, the results varied for different intersections. At Neil Street & Stadium Drive, both of these two methods showed estimations close to the field data, as the two percentage curves are relatively flat and the deviations rested in range of (-79) to 32%.

Nevertheless, at the intersections of Neil Street with Kirby Avenue and St. Mary’s Road, more deviations are observed between the RTF estimates and field queue lengths than in the HCM ones. For Neil Street & Kirby Avenue, in 7 out of the total 16 cases the RTF overestimated the queue length by more than 50% (the highest one was 256%). By contrast, in only 1 case the queue length was overestimated by HCM by more than 50%, which is 112%. Similar trend also existed at Neil Street & St. Mary’s Road, as the RTF made 4 estimations with discrepancies larger than 50% (both overestimation and underestimation) while the HCM method made 0. All these indicate that HCM procedure performed better estimation at these two intersections than the RTF.

Unlike these three intersections, at Neil Street & Windsor Road mixed results are shown. In the cases of northbound, eastbound and westbound, the two methods showed similar estimations, while in the southbound cases the RTF overestimated the field queue length much more than the HCM method, of which the average overestimation rates are 76% and 26%, respectively. Therefore, considering all four intersections, HCM 2010 procedure, in general, estimated the 95th percentile queue length better than the RTF.

To further explore the relationship between the comparison results of 50th and 95th percentile queue length, the cases in which the HCM estimate was significantly different from the field data in 50th percentile queue length comparison were marked in FIGURE 3. Among these 26 cases, the 2 that significantly underestimated by HCM procedure in 50th percentile queue length comparison were still underestimated in 95th percentile comparison. And for the other 24 cases, 14 of them (or 58%), were still overestimations in the 95th percentile comparison, while the rest 10 were underestimations. These 10 discrepancies may be due to the assumption HCM makes in computing the 95th percentile queue length. In HCM procedure, a normal distribution is used to determine the percentile back-of-queue factor ($f_{p%}$), while the collected field queue length data may not be normally distributed.

Effects of traffic volume on the discrepancies

Further analyses were conducted to see if the discrepancies depend on traffic volume. In FIGURE 4, the discrepancies for major and minor streets versus hourly traffic volume are shown. As TABLE 2 indicates, the through volumes on northbound and southbound approaches were similar at all intersections, but that was not the case for the eastbound and westbound traffic. The through volumes on minor streets at Neil Street with Kirby Avenue and Windsor Road were significantly larger than those at Neil Street with Stadium Drive and St. Mary’s Road. Therefore, all cases were divided into major street and minor street ones, and the trend lines of all cases and these two categories were drawn.
FIGURE 3  95th percentile queue length comparison for typical intersections.

Columns: Discrepancies between estimation and field queue length (No. of Vehicles);
Curves: Percentage of RTF (or HCM) estimation over field queue length;
- ▲: HCM significantly overestimates 50th percentile queue length;
- ▣: HCM significantly underestimates 50th percentile queue length.
FIGURE 4 The relationship between estimation discrepancy and hourly volume.
As shown in FIGURE 4(a) and (b), the data points for minor street cases were mainly concentrated in low volume range (under 300 veh/hr) and some points were scattered in the medium volume range between 300 and 700 veh/hr. However, those for the major street were scattered in the medium to moderately-high volume zone range (400 to 900 veh/hr). In FIGURE 4(a), the three trend lines showed the relationship between RTF estimation and volume. The slope and $R^2$ values for all data points and the major street cases were low. However, for the minor street cases there was an upward trend with an $R^2$ value of 0.4877. As traffic volume increased the underestimation changed to overestimation, which indicates the RTF underestimated the queue length when through volume was low (about 200 veh/hr or less) and overestimated when through volume was higher. This supports the statement of Qi et al. (8), but further studies are needed to explore the relationship between arrival rates and the accuracy of RTF estimation for major streets. In FIGURE 4(b), similar trend lines are shown to explore the relationship between HCM estimation accuracy and volume. The slopes and $R^2$ values of these trend lines are lower than the RTF.

**CONCLUSIONS AND RECOMMENDATIONS**

This study used field data to assess the estimation accuracy of HCM 2010 back-of-queue procedure and the red-time formula. Traffic data came from four signalized intersections and covered three peak periods and one off-peak period. The 50th percentile queue lengths were estimated by the HCM 2010 method and statistically compared to field queue lengths. Also, the 95th percentile queue lengths were estimated by both methods compared to each other (since suitable statitical test were not found).

When the 50th percentile queue length were compared, the HCM 2010 method had significant differences from the field data in 52% of the cases (major and minor street cases combined); of which in 93% of the cases it overestimated and in 7% underestimated the queue length.

For the major street, in 68% of the cases the HCM queue length estimates were similar to the field queue lengths. However, in 28% of the cases the HCM significantly overestimated the field queue length on average by 66%; and in 4% of the cases it underestimated on average by 42%.

For the minor streets, only in 25% of the cases the HCM queue length estimates were similar to the field queue lengths. In 70% of the cases HCM significantly overestimated the field queue length on average by 44%, and in 5% of the cases the field queue length was significantly underestimated on average by 20%.

Attempts were made to find overall CFs for major and minor streets. For major street cases, the HCM estimates could be multiplied by an overall CF of 0.93, to obtain the fewest cases with significant discrepancy as well as balanced frequencies for overestimation and underestimation. For minor street cases, an overall CF of 0.78 was able to yield minimum number of cases with significant discrepancy while maintaining a balance in the frequencies of overestimation and underestimation.

For the 95th percentile queue length, in general, HCM 2010 provided more accurate estimations than “red-time” formula. The trends in 50th and 95th percentiles supported each other in 67% of the cases. On the minor streets the “red-time” formula tends to overestimate queue
length at higher-volume approaches, while underestimate at lower-volume ones. But on major streets with heavier traffic than the minors, such trend was not observed.

Further studies are recommended to find the reasons for discrepancies in 50th percentile queue length, to explore statistical methods to compare in the 95th percentile queue length estimation, and to explore the possibility of improving the accuracy of these two methods.
REFERENCES


