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# New Calculation Method for Existing and Extended HCM Delay Estimation Procedures

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# Abstract

The Highway Capacity Manual (HCM) capacity analysis for signals was converted from a volume to capacity (v/c) to a delay-based method starting with the 1985 HCM. Several structural changes (with significant impact) have been made, resulting in the methods employed in the 1985 and subsequent updates in 1994, 1997, and 2000. However, the basic structure of the method remains unchanged. The delay computation procedure, founded on the Webster delay model which was developed in the 1960's, has stood the test of time as a fundamental method of traffic signal analysis.

The formula for delay (and queues) in the first term of the Webster delay equation is founded on the assumed shape of the queue accumulation diagram being a triangle, with the uniform delay (first term) equivalent to the area of that triangle. As such, all elements of the 1985-2000 delay methods must conform to this fundamental assumption. For many basic cases, this is not a problem. However, there exist many common cases that have been unnaturally altered in order to meet this basic triangular requirement. These problematic cases create an overly-complex, inflexible and often inaccurate approximate solution to signal analysis problems that are solved frequently using the HCM methods. These inadequate methods result in a lack of confidence in the models, and ultimately lead some HCM users to search for alternate means to evaluate such problems.

The authors have developed an alternate calculation method for the HCM first-term delay model, which produces the same results when the same, limiting assumptions are made, but a method that does not require most of these limiting assumptions. The paper proposes that the same fundamental relationship between delay and the queue accumulation diagram can be evaluated in a different manner (the Incremental Queue Accumulation method, or IQA), which releases the HCM capacity analysis from many of these limiting assumptions while still being faithful to the Webster model intent. The result is a proposed HCM delay calculation method that is easier to understand and which will deliver more accurate results over a broader range of conditions.

## Background

The 2000 Highway Capacity Manual (HCM) [1] capacity analysis method for signals is the most recent edition since the procedure was converted from a v/c-based to a delay-based method in the 1985 HCM [2], and has retained basically the same fundamental delay model since. The delay computation procedure, founded on the Webster delay model [3] developed in 1958, which has stood the test of time as a fundamental method for traffic signal analysis.

The delay model is comprised of two elements:

1. *"The First Term"* ($d_1$): Produces the average delay per vehicle in the average cycle, assuming that traffic arrivals and departures are completely uniform, both within each signal cycle and across all cycles during the analysis period.
2. *"The Second Term"* ($d_2$): Produces the incremental delay due to randomness in arrivals from cycle to cycle. The incremental delay assumes steady state conditions.

Several structural changes (with significant impact) have been made that resulted in the methods employed by the 1985 and subsequent updates of the HCM (1994, 1997, and 2000) [1-2, 4-5], but the basic structure of the method has remained unchanged. These changes included:

1. Replacement of Webster's original incremental delay term with a time-dependent form based on the coordinate transformation method by Kimber and Hollis [6]. This form accounts for both random and over-saturation delays during a finite analysis period of duration (T).
2. Treatment of the effects of the arrival characteristics of vehicles within a signal cycle due to progression, resulting mainly from the work of Fambro, Chang and Messer [7].
3. More rational treatment of the effects of protected-permitted phasing on the departure characteristics of vehicles within a signal cycle.
4. Treatment of oversaturated conditions in which the demand exceeds the capacity over an entire analysis period and the effects of initial queues, mainly from the work of Fambro and Rouphail [8].

The essential formula for delay (and queues) in the first term of the Webster delay equation is founded on the assumed shape of the queue accumulation diagram being a triangle (see Figure 1), resulting in the formula for the uniform delay (first term) being the area of that triangle. As such, all elements of the 1985-2000 delay methods must conform to this fundamental assumption. For many basic cases, this is not a problem, and the model has stood up well to the test of time. However, there exist many common cases that have been significantly twisted in order to meet this basic triangular requirement.

The HCM delay model limitations addressed in this paper lie in the "first term" ($d_1$) of the delay equation. Therefore, the balance of this paper will focus on the first or "uniform" term.

**Problem Statement**

Many aspects of the HCM signal delay method are impacted by the necessary assumption that the uniform delay portion ($d_1$) of the Webster delay formula must take the form of a triangle in the associated queue accumulation diagram. This basic assumption requires that:

1. There can be only one green and one red period during the cycle so that there is a single triangle to be evaluated for the uniform delay.
2. During the red period, there is a single straight line on the leading edge of the queue accumulation triangle that represents a uniform arrival rate during the red period.
3. During the green period, there is a single straight line on the falling edge of the queue accumulation triangle that represents the difference between the uniform arrival rate (above) and a uniform saturation flow rate of departure.

Below is a partial list of the sub-models within the signal delay method that must be unnaturally altered to accommodate the assumption above:

1. *Permitted Left Turn Model:* Must utilize a single, weighted-average saturation flow rate during the entire green period, which is unrealistic and doesn't properly model where the departures occur in the cycle (including sneakers).
2. *Protected-Permitted Left Turn Model:* Special cases have been developed to circumvent the problems caused by the need for the above assumption. These cases cover some (but not all) protected-permitted and permitted-protected situations (compound left turn phases) with complicated formulas to estimate the uniform delay (Exhibits 16-23 and E16-1 in HCM 2000).
3. *Sneakers:* The HCM method imposes a minimum saturation flow rate across entire green period, which is an unrealistic representation of when sneakers discharge.
4. *Progression Effect:* The effect of progression is accounted for after the delay is calculated assuming uniform arrivals, using an approximate method based on a crude Arrival Type determination.
5. *Multiple Green Displays:* Such displays are not uncommon in the field, but cannot be even approximated with the current method. Two examples are a) right turn overlap phases that are separated from the main green phase for the right turn by red phases before and after the overlap phase, and b) compound left turn phases which include significant separation by an all-red phase and/or an intervening red phase.
6. *Protected-Permitted Right Turn Model:* Similar problems as with compound left turns regarding two periods of different saturation flow rates during green, which must be represented by a single, constant saturation flow rate.
7. *Start and end lost times:* Lumped together and assumed to occur at the start of the green period to simplify the computations, particularly in regard to the need to reference the g* values to account for more complex left turn phasing situations (Exhibits 10-11 and C16-4 thru C16-8 in HCM 2000).
8. *All-red Model:* All-red time is assumed to behave the same as and is included in the yellow time due to the previous start/end lost time assumption for computational simplification. However, this causes problems regarding the definition of adjacent phases and multiple green periods in regard to the g* figures.

In summary, the basic model for $d_1$ is appropriate for simple cases, but fails to address many common situations that defy a simple triangular, formula-based approach, thus subverting the HCM objective to provide the most realistic delay estimation method upon which the HCM LOS is based.

**An Alternative Approach: The IQA Method**

The prescribed way to calculate the first term of the Webster model in the HCM is to calculate the area of its triangle, divided by the number of arrivals per cycle using the formula:

$$d_1=0.5C\,(1-g/C)^2/\,(1-\mathrm{Min}\,(1, X)\,g/C) \qquad \text{Eq. 1}$$

An alternative way to accomplish the same result would be the following. If one assessed the signal operation incrementally every Δ seconds and recorded how many vehicles have arrived (at the assumed arrival rate during that interval) and how many vehicles have departed (based on the signal display, the presence of un-served vehicles, and the assumed departure flow rate at that time) during that same interval", one can estimate the net increase or decrease in the queue accumulation during Δ. By accumulating the net increase/decrease every Δ, assuming uniform arrival and departure rates, and by plotting a graph of this accumulation, one would obtain the same triangle that is evaluated by Webster's first term. Further, if one counted the total number of vehicles in queue in each Δ interval in this diagram over the course of the entire cycle, and divide it by the number of arrivals, the result will be exactly the same as Eq.1. If the flow rates are such that an integer number of vehicles do not both arrive and depart during the Δ increment, then 'partial' vehicles will be in queue each Δ but (if we tolerate this more abstract view) the result will be still exactly the same. Finally, the Δ increment boundary must coincide exactly with those times where the signal and/or and vehicle flows change. However, if one is willing to reduce the size of the Δ increment to a fraction of a second, the same results as Eq.1 will be obtained. Such an equivalent method of calculating delay is called here the 'Incremental Queue Accumulation' (IQA) method, in many ways, similar to Robertson's simulation method in TRANSYT.

**Numerical Illustrations of the IQA Method**

A series of examples illustrate the points made above. Example 1 describes the case for a simple movement controlled by a single green/red cycle. Example 2 depicts a permitted left turn that uses a weighted-average saturation flow rate during the green, consistent with the HCM method. Example 3 described a compound left turn phase. These examples are intended to illustrate that exactly the same results are achieved regardless of whether Eq.1 or the IQA method are used. In these examples, conditions have been selected very carefully in order that whole vehicles arrive and depart during the Δ-increment so that the example is easy to visualize, but this is not a requirement for the IQA method. In a white paper [9] presented to the Signals Subcommittee of the TRB Capacity Committee (AHB40) in January 2005 on this subject, SIGNAL2000/TEAPAC input data files and output text files were prepared for these examples, which confirm the HCM calculation portion of the Examples. These outputs are not included here due to space constraints.

In all tables for the numerical examples, the following explanation applies. The Δ# column represents the Δ-increment number starting with the beginning of red display for the subject movement. The time column indicates the time from the start of red for which the increment applies. The #In column is the number of vehicles approaching the intersection (i.e. to be served) during the time increment, and the #Out column is the number of vehicles that depart the intersection (stop bar) during the time increment. The IQA column is the accumulated number of vehicles waiting to be served, up to and including the time increment. IQA is the sum of the #In minus the #Out since the start of red. The MBQ column is the location of the last vehicle queued during the time increment measured in number of vehicle lengths from the stop bar. The IQA×Δ column is the IQA value times the length of the time increment for the current time increment, and represents the partial delay (vehicle-seconds) incurred by vehicles during the time increment. The totals at the bottom of the table represent, respectively, the total number of vehicles arriving and departing the approach, the sum of all the incremental IQA values, the largest MBQ, and the sum of the partial delays -- the total vehicle-seconds of delay in the cycle. The total vehicle-seconds of delay is also numerically equal to the total IQA multiplied by the time increment, and, when divided by the number of vehicles entering or leaving is the average uniform delay in seconds/vehicle.

Similarly, in all the triangular queue accumulation figures for the examples, the following notation applies. Each vertical column represents a time increment. Below each column are the signal display status ('r' for effective red and 'g' for effective green), the time increment number and the IQA for that time increment. Each 'X' in the diagram represents a single vehicle in the queue, as well as its position in the queue in relation to the stop bar (the vertical distance from the bottom of the diagram to the X). The IQA value at the bottom is the number of X's in that column, and each X is assumed to incur an amount of incremental delay equal to the time increment of the diagram. The total number of X's in the diagram multiplied by the time increment is the total delay of the diagram.

**Example 1 - Simple Movement Controlled by a Single Red/Green During the Cycle**

<u>Given Conditions</u>
Δ-increment = 2 sec
V = 1800 vph, or 1800/3600 x 2 = 1 veh/increment
s = 3600 vph, or 3600/3600 x 2 = 2 veh/increment
C = 60 sec
g = 40 sec

<u>Computed Results</u>
c = sg/C = 2400 vph
X = V/c = 0.75
$d_1 = 0.5C\ (1\text{-}g/C)^2 /\ (1\text{-Min}\ (1,X) \times g/C) = 6.67$ sec/veh
MBQ = (maximum back of queue or $Q_1$) = 20.0 using Eq. G16-7 in HCM2000

The results are summarized in Table 1 and Figure 1 below. From Table 1, the first term delay is easily computed as: $d_1$ = 200/30 = 6.67 sec/veh., which is identical to the analytical value of $d_1$ above.

**Example 2 - Permitted Left-Turn with Weighted-Average Saturation Flow Rate in Green**

<u>Given Conditions</u>
Δ-increment = 12 sec
V = 300 vph, or 300/3600 x 12 = 1 veh/increment

$V_o$ (opposing flow rate) = 564 vph
s = 600 vph, or 600/3600 x 12 = 2 veh/increment
C = 120 sec
g = 60 sec

Computed Results
c = sg/C = 300 vph
X = V/c = 1.00
$d_1 = 0.5\ C\ (1\text{-}g/C)^2/(1\text{-}Xg/C) = 30.0$ sec/veh

From Table 2, the first term delay is easily computed as: $d_1$ = 300/10 = 30.0 sec/veh, which is identical to the analytical computation of $d_1$ above.

**Table 1. The IQA Method Applied to Example 1**

| Δ# | time (sec) | #In | #Out | IQA | MBQ | IQAxΔ (delay during Δ) | |
|---|---|---|---|---|---|---|---|
| 1 | 0-2 | 1 | 0 | 1 | 1 | 2 | effective red phase starts |
| 2 | 2-4 | 1 | 0 | 2 | 2 | 4 | |
| 3 | 4-6 | 1 | 0 | 3 | 3 | 6 | |
| 4 | 6-8 | 1 | 0 | 4 | 4 | 8 | |
| 5 | 8-10 | 1 | 0 | 5 | 5 | 10 | |
| 6 | 10-12 | 1 | 0 | 6 | 6 | 12 | |
| 7 | 12-14 | 1 | 0 | 7 | 7 | 14 | |
| 8 | 14-16 | 1 | 0 | 8 | 8 | 16 | |
| 9 | 16-18 | 1 | 0 | 9 | 9 | 18 | |
| 10 | 18-20 | 1 | 0 | 10 | 10 | 20 | |
| 11 | 20-22 | 1 | 2 | 9 | 11 | 18 | effective green phase starts |
| 12 | 22-24 | 1 | 2 | 8 | 12 | 16 | |
| 13 | 24-26 | 1 | 2 | 7 | 13 | 14 | |
| 14 | 26-28 | 1 | 2 | 6 | 14 | 12 | |
| 15 | 28-30 | 1 | 2 | 5 | 15 | 10 | |
| 16 | 30-32 | 1 | 2 | 4 | 16 | 8 | |
| 17 | 32-34 | 1 | 2 | 3 | 17 | 6 | |
| 18 | 34-36 | 1 | 2 | 2 | 18 | 4 | |
| 19 | 36-38 | 1 | 2 | 1 | 19 | 2 | |
| 20 | 38-40 | 1 | 2 | 0 | 20 | 0 | |
| 21 | 40-42 | 1 | 1 | 0 | - | 0 | |
| 22 | 42-44 | 1 | 1 | 0 | - | 0 | |
| 23 | 44-46 | 1 | 1 | 0 | - | 0 | |
| 24 | 46-48 | 1 | 1 | 0 | - | 0 | |
| 25 | 48-50 | 1 | 1 | 0 | - | 0 | |
| 26 | 50-52 | 1 | 1 | 0 | - | 0 | |
| 27 | 52-54 | 1 | 1 | 0 | - | 0 | |
| 28 | 54-56 | 1 | 1 | 0 | - | 0 | |
| 29 | 56-58 | 1 | 1 | 0 | - | 0 | |
| 30 | 58-60 | 1 | 1 | 0 | - | 0 | |
| | **Total** | **30** | 30 | 100 | 20 | **200 veh-sec** | |

**Figure 1. Illustration of IQA Results for Example 1**

```
Increment Δ = 2 sec                 X
                                  X
each “X” is 1 vehicle           X X |
  delayed 2 sec               X X
                            X X X   |
100 X’s = 200 veh-sec     X X X
                        X X X X     |
                      X X X X
                    X X X X X       |
                  X X X X X
                X X X X X X         |
              X X X X X X
            X X X X X X X           |
          X X X X X X X
        X X X X X X X X             |
      X X X X X X X X
    X X X X X X X X X               |
  X X X X X X X X X
X X X X X X X X X X                 |

Display:
r r r r r r r r r r g g g g g g g g g g g g g g g g g g g g

Increment:        1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 3
1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0

IQA:              1
1 2 3 4 5 6 7 8 9 0 9 8 7 6 5 4 3 2 1 0 0 0 0 0 0 0 0 0 0 0
```

**Table 2. The IQA Method Applied to Example 2**

| Δ# | time (sec) | #In | #Out | IQA | MBQ | IQAxΔ | (delay during Δ) |
|---|---|---|---|---|---|---|---|
| 1 | 0-12 | 1 | 0 | 1 | 1 | 12 | effective red phase starts |
| 2 | 12-24 | 1 | 0 | 2 | 2 | 24 | |
| 3 | 24-36 | 1 | 0 | 3 | 3 | 36 | |
| 4 | 36-48 | 1 | 0 | 4 | 4 | 48 | |
| 5 | 48-60 | 1 | 0 | 5 | 5 | 60 | |
| 6 | 60-72 | 1 | 2 | 4 | 6 | 48 | effective perm. green phase starts |
| 7 | 72-84 | 1 | 2 | 3 | 7 | 36 | |
| 8 | 84-96 | 1 | 2 | 2 | 8 | 24 | |
| 9 | 96-108 | 1 | 2 | 1 | 9 | 12 | |
| 10 | 108-120 | 1 | 2 | 0 | 10 | 0 | |
| | **Total** | **10** | 10 | 25 | 10 | **300 veh-sec** | |

**Figure 2. Illustration of IQA Results for Example 2**

```
                X
              X
            X X |
          X X
        X X X   |
      X X X
    X X X X     |
  X X X X
X X X X X       |

Display:
r r r r r g g g g g

Increment:        1
1 2 3 4 5 6 7 8 9 0

IQA:
1 2 3 4 5 4 3 2 1 0
```

```
Increment Δ = 12 sec

each "X" is 1 vehicle
  delayed 12 sec

25 X's = 300 veh-sec
```

**Example 3 – A Protected-Permitted Left-Turn Movement**

Given Conditions
$\Delta$-increment = 4 sec
V = 1800 vph (2 lanes), or 1800/3600 x 4 = 2 veh/increment
$V_o$ (opposing flow rate) = 40 vph (2 lanes)
$s_{prot}$ = 3600 vph, or 3600/3600 x 4 = 4 veh/increment
$s_{perm}$ = 2700 vph, or 2700/3600 x 4 = 3 veh/increment
C = 60 sec
$g_{prot}$ = 16 sec
$g_{perm}$ = 20 sec

Computed Results
$d_1$ from HCM procedures = 10.2 sec/veh

From Table 3, the first term delay is easily computed as $d_1$ = 304/30 = 10.1 sec/veh. This value is virtually identical to the computed value of $d_1$ for the conditions that are approximated by the inputs used for the equivalent IQA analysis.

**Table 3. The IQA Method Applied to Example 3**

| Δ# | time (sec) | #In | #Out | IQA | MBQ | IQAxΔ (delay during Δ) | |
|---|---|---|---|---|---|---|---|
| 1 | 0-4 | 2 | 0 | 2 | 2 | 8 | effective red phase starts |
| 2 | 4-8 | 2 | 0 | 4 | 4 | 16 | |
| 3 | 8-12 | 2 | 0 | 6 | 6 | 24 | |
| 4 | 12-16 | 2 | 0 | 8 | 8 | 32 | |
| 5 | 16-20 | 2 | 0 | 10 | 10 | 40 | |
| 6 | 20-24 | 2 | 0 | 12 | 12 | 48 | |
| 7 | 24-28 | 2 | 4 | 10 | 14 | 40 | effective prot. green phase starts |
| 8 | 28-32 | 2 | 4 | 8 | 16 | 32 | |
| 9 | 32-36 | 2 | 4 | 6 | 18 | 24 | |
| 10 | 36-40 | 2 | 4 | 4 | 20 | 16 | |
| 11 | 40-44 | 2 | 3 | 3 | 22 | 12 | effective perm. green phase starts |
| 12 | 44-48 | 2 | 3 | 2 | 24 | 8 | |
| 13 | 48-52 | 2 | 3 | 1 | 26 | 4 | |
| 14 | 52-56 | 2 | 3 | 0 | 28 | 0 | |
| 15 | 56-60 | 2 | 2 | 0 | - | 0 | |
| | **Total** | **30** | 30 | 76 | 28 | **304 veh-sec** | |

**Enhancements and Extensions Allowed by the IQA Method**

The proposed IQA method removes virtually all of the limitations mentioned in the opening section of this paper, without creating any new limitations to speak of. This means that the proposed IQA method extends the usability of the HCM to better reflect conditions commonly found in the field without the plethora of limiting assumptions imposed by the current 2000 HCM method.

Example 4 below illustrates the point above, by altering the compound LT problem of Example 3 to a more realistic condition, including separated start and end lost times, inclusion of an all-red interval, etc. Example 5 illustrates how the method can be applied to a case with multiple greens conditions, as frequently encountered with a RT overlap. Neither of these problems can be analyzed effectively with the current HCM methods.

**Example 4 - More Realistic Protected-Permitted LT Analysis Using IQA Method**

<u>Given Conditions</u>
Δ-increment = 2 sec
V = 600 vph, or 600/3600 x 2 = 1/3 veh/increment
$s_{prot}$ = 1800 vph, or 1800/3600 x 2 = 1 veh/increment
$s_{perm}$ = 600 vph, or 600/3600 x 2 = 1/3 veh/increment
C = 60 sec
$G+Y_{prot}$ = 24 sec, $l_1$ = 2 sec, $l_2$ = 2 sec, $g_{prot}$ = 20 sec
$G+Y_{perm}$ = 18 sec, $l_1$ = 2 sec, $l_2$ = 2 sec, $g_{perm}$ = 14 sec

The corresponding Phasing Diagram for the subject LT (shown in heavy bold) is depicted at the bottom of Figure 4 below. From Table 4, $d_1$ is computed as $d_1$ = 126/10 = 12.6 sec/veh.

**Figure 3. Illustration of IQA Results for Example 3**

```
                        X
                      X |
                      X
                    X   |
                    X
                  X X   |
                  X
                X X     |
                X X
              X X       |
              X X
            X X X       |
            X X X
          X X X         |
          X X X
        X X X X         |
        X X X X
      X X X X           |
      X X X X
    X X X X X           |
    X X X X X
  X X X X X             |
  X X X X X
X X X X X X             |
X X X X X X
```

```
Increment Δ = 4 sec

each “X” is 1 vehicle
  delayed 4 sec

76 X’s = 304 veh-sec
```

```
Display:
r r r r r r g g g g g g g g g

Increment:        1 1 1 1 1 1
1 2 3 4 5 6 7 8 9 0 1 2 3 4 5

IQA:    1 1 1
2 4 6 8 0 2 0 8 6 4 3 2 1 0 0
```

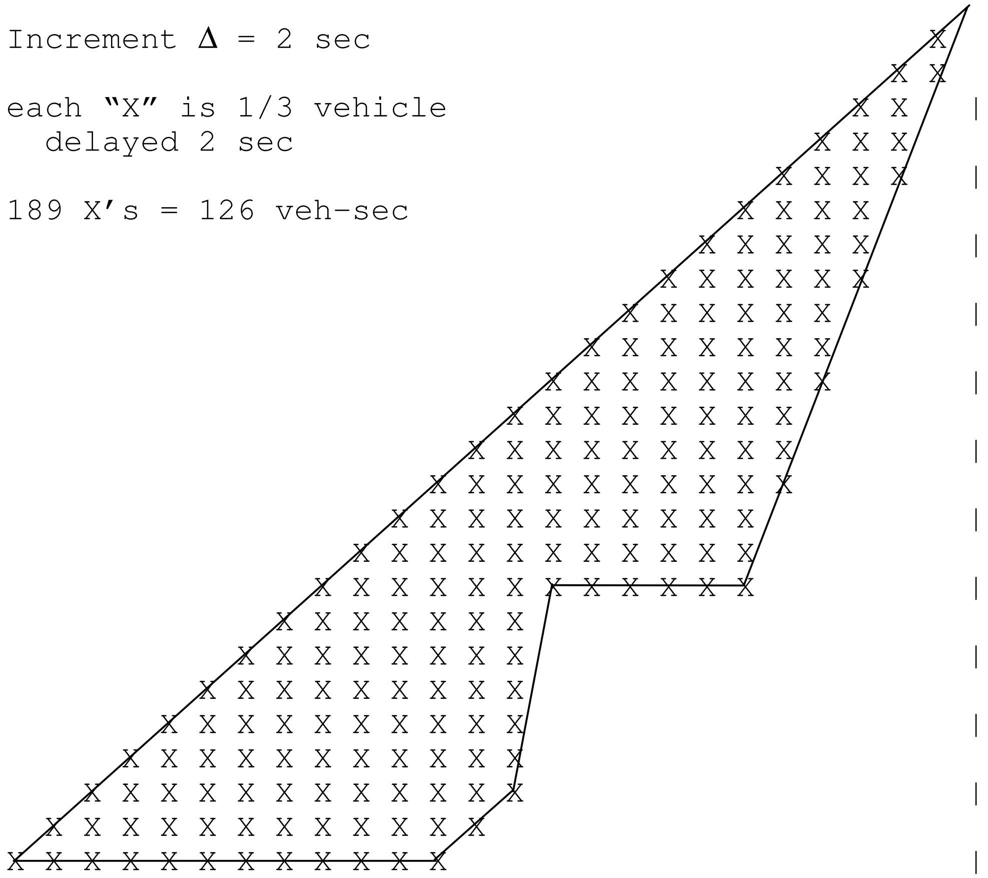
**Table 4. The IQA Method Applied to Example 4**

| Δ# | time (sec) | #In | #Out | IQA | MBQ | IQAxΔ | (delay during Δ) |
|---|---|---|---|---|---|---|---|
| 1 | 0-2 | 1/3 | 0 | 1/3 | 1/3 | 2/3 | end lost time for protected phase (4)* |
| 2 | 2-4 | 1/3 | 0 | 2/3 | 2/3 | 4/3 | 10" overlap phase for opposing LT (1) |
| 3 | 4-6 | 1/3 | 0 | 3/3 | 3/3 | 6/3 | |
| 4 | 6-8 | 1/3 | 0 | 4/3 | 4/3 | 8/3 | |
| 5 | 8-10 | 1/3 | 0 | 5/3 | 5/3 | 10/3 | |
| 6 | 10-12 | 1/3 | 0 | 6/3 | 6/3 | 12/3 | |
| 7 | 12-14 | 1/3 | 0 | 7/3 | 7/3 | 14/3 | start lost time for permitted phase (2) |
| 8 | 14-16 | 1/3 | 0 | 8/3 | 8/3 | 16/3 | 10" $g_q$ for opposing queue to clear |
| 9 | 16-18 | 1/3 | 0 | 9/3 | 9/3 | 18/3 | |
| 10 | 18-20 | 1/3 | 0 | 10/3 | 10/3 | 20/3 | |
| 11 | 20-22 | 1/3 | 0 | 11/3 | 11/3 | 22/3 | |
| 12 | 22-24 | 1/3 | 0 | 12/3 | 12/3 | 24/3 | |
| 13 | 24-26 | 1/3 | 1/3 | 12/3 | 13/3 | 24/3 | 4" $g_u$ at opposed saturation flow |
| 14 | 26-28 | 1/3 | 1/3 | 12/3 | 14/3 | 24/3 | |
| 15 | 28-30 | 1/3 | 2 | 7/3 | 15/3 | 14/3 | 2 sneakers during ending lost time (2) |
| 16 | 30-32 | 1/3 | 0 | 8/3 | 16/3 | 16/3 | effective red starts, g for cross street (3) |
| 17 | 32-34 | 1/3 | 0 | 9/3 | 17/3 | 18/3 | |
| 18 | 34-36 | 1/3 | 0 | 10/3 | 18/3 | 20/3 | |
| 19 | 36-38 | 1/3 | 0 | 11/3 | 19/3 | 22/3 | |
| 20 | 38-40 | 1/3 | 0 | 12/3 | 20/3 | 24/3 | start lost time for protected phase (4) |
| 21 | 40-42 | 1/3 | 1 | 10/3 | 21/3 | 20/3 | 20" $g_{prot}$ protected phase (4) |
| 22 | 42-44 | 1/3 | 1 | 8/3 | 22/3 | 16/3 | |
| 23 | 44-46 | 1/3 | 1 | 6/3 | 23/3 | 12/3 | |
| 24 | 46-48 | 1/3 | 1 | 4/3 | 24/3 | 8/3 | |
| 25 | 48-50 | 1/3 | 1 | 2/3 | 25/3 | 4/3 | |
| 26 | 50-52 | 1/3 | 1 | 0 | 26/3 | 0 | |
| 27 | 52-54 | 1/3 | 1/3 | 0 | - | 0 | |
| 28 | 54-56 | 1/3 | 1/3 | 0 | - | 0 | |
| 29 | 56-58 | 1/3 | 1/3 | 0 | - | 0 | |
| 30 | 58-60 | 1/3 | 1/3 | 0 | - | 0 | |
| | **Total** | **10** | 10 | 63 | 26/3 | **126 veh-sec** | |

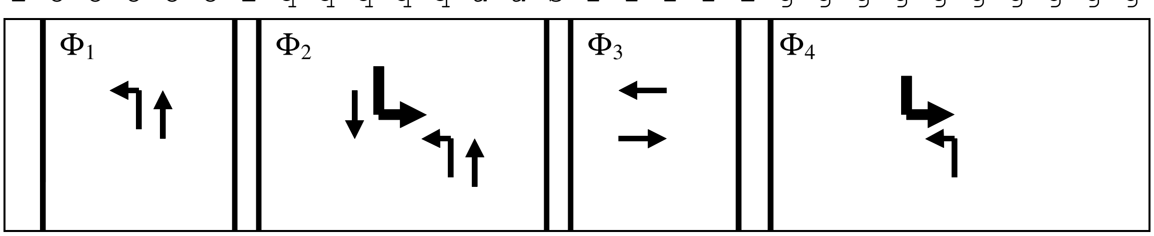
*See Figure 4 for the notation of phase numbers ( )

**Figure 4. Illustration of IQA Results for Example 4**

```
Increment Δ = 2 sec

each "X" is 1/3 vehicle
  delayed 2 sec

189 X's = 126 veh-sec
```



```
Increment:         1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 3
1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0

IQA (in 1/3 veh): 1 1 1 1 1       1 1 1 1
1 2 3 4 5 6 7 8 9 0 1 2 2 2 7 8 9 0 1 2 0 8 6 4 2 0 0 0 0 0

Display:
l o o o o o l q q q q q u u s r r r r l g g g g g g g g g g
```




l = start or end lost time
o = overlap for opposing LT (red for subject LT, could be all-red)
q + u constitute the effective green for the subject LT permitted phase, where
q = portion of permitted green blocked by opposing queue
u = portion of permitted green unblocked by opposing queue
s = sneakers departing during ending lost time
r = red time during green phase for cross street
g = protected effective green time

**Example 5 – Multiple Green and Red Times for Right Turn Movement in Single Cycle**

<u>Given Conditions</u>
Δ-increment = 2 sec
V = 600 vph, or 600/3600 x 2 = 1/3 veh/increment
s = 1800 vph, or 1800/3600 x 2 = 1 veh/increment
C = 60 sec

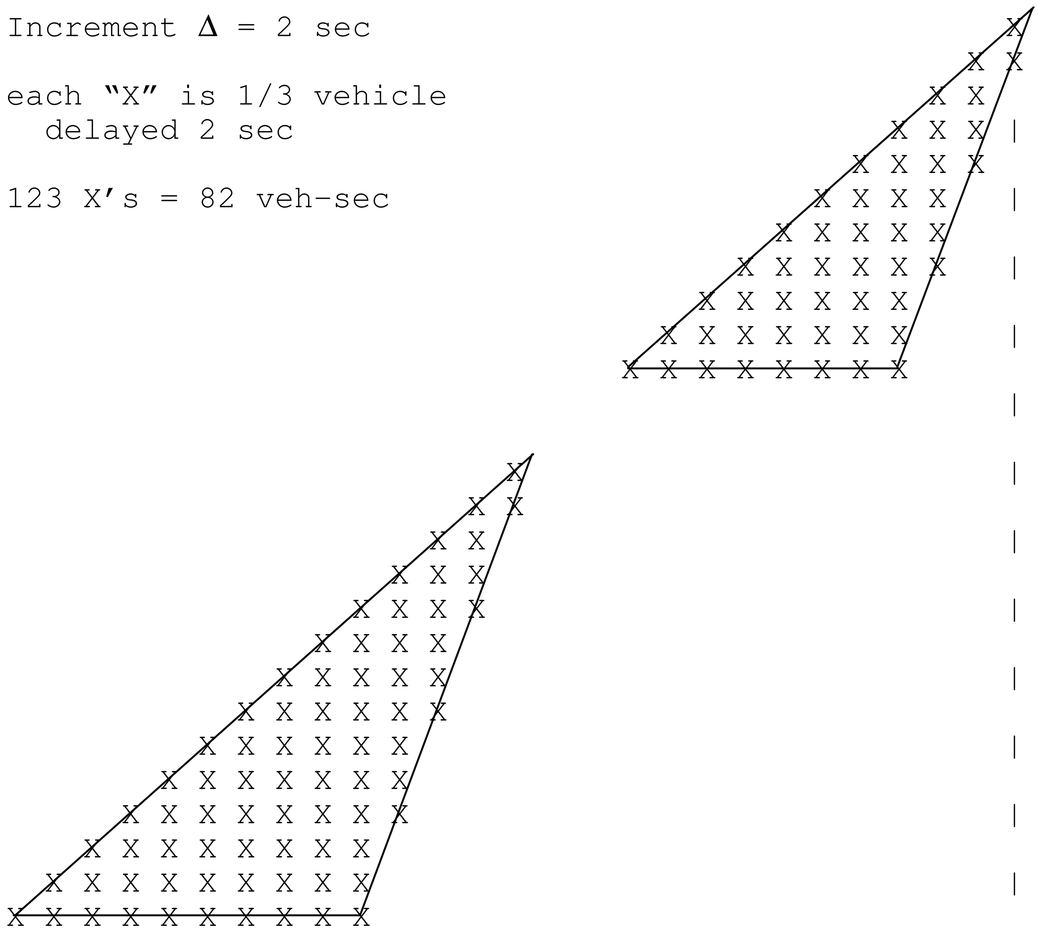
From Table 5, $d_1$ = 82/10 = 8.2 sec/veh.

**Table 5. The IQA Method Applied to Example 5**

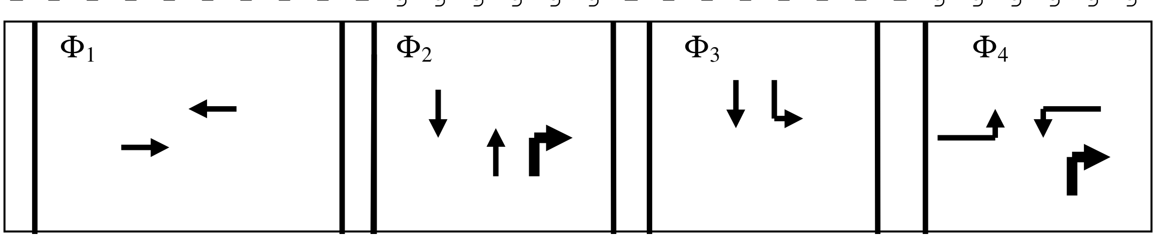
| Δ# | time (sec) | #In | #Out | IQA | MBQ | IQAxΔ | (delay during Δ) |
|---|---|---|---|---|---|---|---|
| 1 | 0-2 | 1/3 | 0 | 1/3 | 1/3 | 2/3 | end lost time of 2nd green phase (4)* |
| 2 | 2-4 | 1/3 | 0 | 2/3 | 2/3 | 4/3 | 1st red, green cross street phase (1) |
| 3 | 4-6 | 1/3 | 0 | 3/3 | 3/3 | 6/3 | |
| 4 | 6-8 | 1/3 | 0 | 4/3 | 4/3 | 8/3 | |
| 5 | 8-10 | 1/3 | 0 | 5/3 | 5/3 | 10/3 | |
| 6 | 10-12 | 1/3 | 0 | 6/3 | 6/3 | 12/3 | |
| 7 | 12-14 | 1/3 | 0 | 7/3 | 7/3 | 14/3 | |
| 8 | 14-16 | 1/3 | 0 | 8/3 | 8/3 | 16/3 | |
| 9 | 16-18 | 1/3 | 0 | 9/3 | 9/3 | 18/3 | |
| 10 | 18-20 | 1/3 | 0 | 10/3 | 10/3 | 20/3 | start lost time of 1st green phase (2) |
| 11 | 20-22 | 1/3 | 1 | 8/3 | 11/3 | 16/3 | 12", 1st green phase (2) |
| 12 | 22-24 | 1/3 | 1 | 6/3 | 12/3 | 12/3 | |
| 13 | 24-26 | 1/3 | 1 | 4/3 | 13/3 | 8/3 | |
| 14 | 26-28 | 1/3 | 1 | 2/3 | 14/3 | 4/3 | |
| 15 | 28-30 | 1/3 | 1 | 0 | 15/3 | 0 | |
| 16 | 30-32 | 1/3 | 1/3 | 0 | 16/3 | 0 | |
| 17 | 32-34 | 1/3 | 0 | 1/3 | 1/3 | 2/3 | end lost time of 1st green phase (2) |
| 18 | 34-36 | 1/3 | 0 | 2/3 | 2/3 | 4/3 | 2nd red, opposing approach phase (3) |
| 19 | 36-38 | 1/3 | 0 | 3/3 | 3/3 | 6/3 | |
| 20 | 38-40 | 1/3 | 0 | 4/3 | 4/3 | 8/3 | |
| 21 | 40-42 | 1/3 | 0 | 5/3 | 5/3 | 10/3 | |
| 22 | 42-44 | 1/3 | 0 | 6/3 | 6/3 | 12/3 | |
| 23 | 44-46 | 1/3 | 0 | 7/3 | 7/3 | 14/3 | |
| 24 | 46-48 | 1/3 | 0 | 8/3 | 8/3 | 16/3 | start lost time, 2nd green phase (4) |
| 25 | 48-50 | 1/3 | 1 | 6/3 | 9/3 | 12/3 | 12", 2nd green phase (4) |
| 26 | 50-52 | 1/3 | 1 | 4/3 | 10/3 | 8/3 | |
| 27 | 52-54 | 1/3 | 1 | 2/3 | 11/3 | 4/3 | |
| 28 | 54-56 | 1/3 | 1 | 0 | 12/3 | 0 | |
| 29 | 56-58 | 1/3 | 1/3 | 0 | - | 0 | |
| 30 | 58-60 | 1/3 | 1/3 | 0 | - | 0 | |
| | **Total** | **10** | 10 | 41 | 16/3 | **82 veh-sec** | |

*See Figure 5 for the notation of phase numbers ( )

**Figure 5.  Illustration of IQA Results for Example 5**




```
Increment:          1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 3
1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0

IQA (in 1/3 veh): 1
1 2 3 4 5 6 7 8 9 0 8 6 4 2 0 0 1 2 3 4 5 6 7 8 6 4 2 0 0 0

Display:
l r r r r r r r r l g g g g g g l r r r r r r l g g g g g g
```




l = start or end lost time
r = effective red time
g = effective green time

Space limitations prevent detailing another good example: a permitted left turn with 80 vph during a 65" green (90" cycle) and an opposing volume at capacity such that all the left turns are made as sneakers at the end of the green. The HCM distributes the left turn departures uniformly over the green with a delay of 12 sec/veh, while the IQA method recognizes the queue buildup over the whole cycle resulting in a delay of 45 sec/veh, an error of over 300 percent.

**Application of a Variable Increment Length in IQA**

The IQA method as described thus far uses a uniform Δ-increment for simplicity and clarity. A logical extension of the method would be to recognize that this increment need not be constant throughout the cycle, but rather a single (and different) time increment can be used for each period of the cycle during which both the inflow and outflow do not change. To accomplish this, one needs only to identify the points in the cycle where in or out flow values change (signal display, queue dissipation, etc.). During each of these periods, we merely need to compute the total IQA and this can be done with simple formulas using the area of the trapezoids formed by the starting and ending queue of the period and the inflow and outflow rates of the period. In effect, this clarifies that the proposed IQA method is the same as the original Webster method, by simply replacing the single triangle of Webster (forced upon us by Webster's underlying assumptions) with multiple trapezoids for each period of the cycle where flows (in and out) are constant. The Webster formula is simply a degenerate case of the more generalized IQA method.

An example application of this trapezoidal approach to the IQA method is illustrated for Example 4, reworked below as Example 4(R) (for Revised) using just 5 time intervals (or 5 trapezoids) during which constant inflow and outflow rates prevail. The trapezoids are overlaid onto the IQA diagram used previously in Figure 6. The starting and ending queues for each time interval (trapezoid) are determined using the same IQA method previously described. Table 6 illustrates the simple calculations needed to produce the same result as in the constant-increment method illustrated earlier. In this example, $q_1$ and $q_2$ represent the queue lengths at the start and end of a (variable) interval (Δ), such that:

$$q_2 = q_1 + (V-S) \times \Delta \qquad \text{Eq. 2}$$

where V and S are the arrival and departure flow rates in Δ *(in veh/sec),* respectively, and the partial delay accrued in each interval of size Δ is calculated as:

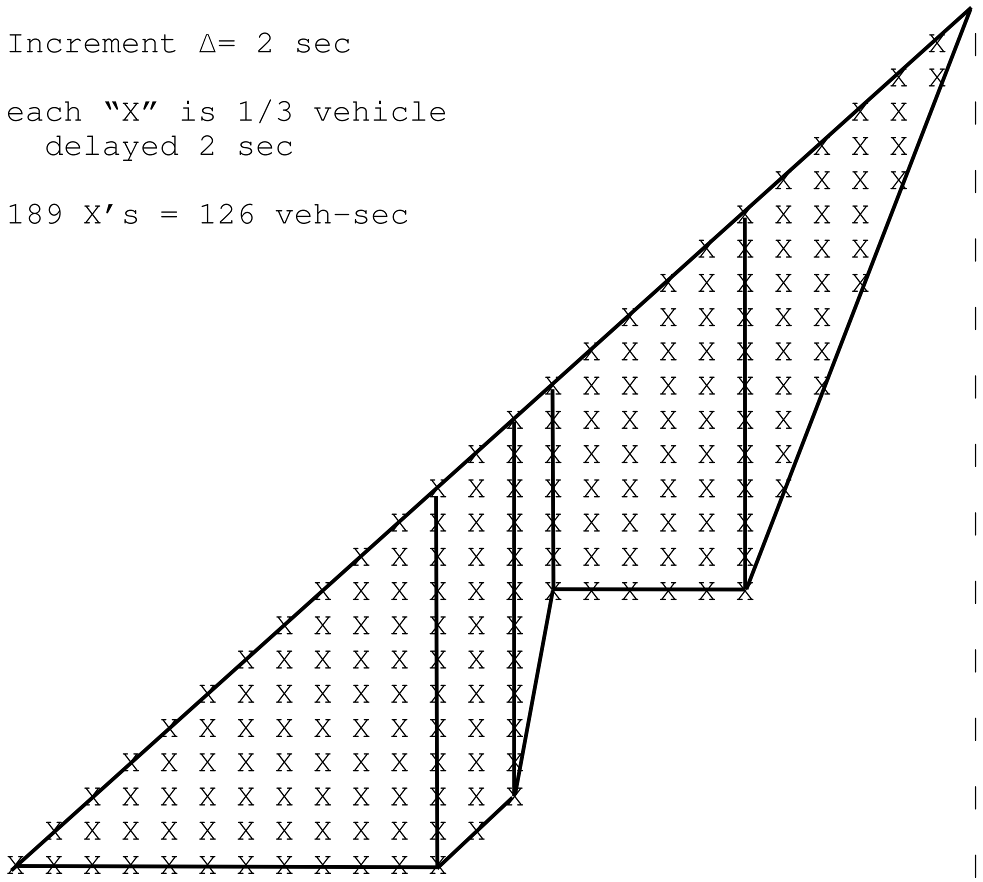
$$d_i = \Delta \times (q_1+q_2)/ 2 \qquad \text{Eq. 3}$$

**Table 6. Trapezoidal Calculations Using IQA Method Applied to Example 4(R)**

| Interval # | Δ(sec) | V* | S* | $q_1$ | $q_2$ | $d_i$ | Cycle condition covered |
|---|---|---|---|---|---|---|---|
| 1 | 24 | 1/6 | 0 | 0 | 4 | 48 | red & opp. queue clear. in perm. phase |
| 2 | 4 | 1/6 | 1/6 | 4 | 4 | 16 | perm. LT phase after opp. queue clear. |
| 3 | 2 | 1/6 | 1 | 4 | 7/3 | 19/3 | sneakers at end of perm. LT phase |
| 4 | 10 | 1/6 | 0 | 7/3 | 4 | 95/3 | red for other street phase |
| 5 | 12 | 1/6 | 1/2 | 4 | 0 | 24 | prot. phase - queue clearing |
| 6 | 8 | 1/6 | 1/6 | 0 | 0 | 0 | prot. phase - queue cleared |
| **Total** | **60** | **1/6*60=10** | | | | | **126 veh-sec** ($d_1$=126/10 = 12.6 sec/veh) |

*See Example 4 for time-dependent inflow and outflow rates.

**Figure 6. Trapezoidal Calculations for Example 4 (R)**




```
Increment:        1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 3
1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0

IQA (in 1/3 veh): 1 1 1 1 1       1 1 1 1
1 2 3 4 5 6 7 8 9 0 1 2 2 2 7 8 9 0 1 2 0 8 6 4 2 0 0 0 0 0

Display:
l o o o o o l q q q q q u u s r r r r l g g g g g g g g g g
```

## Discussion and Extensions of the IQA Method

The most important observation regarding the examples above is that given the same limiting assumptions that currently exist in the 2000 HCM, the IQA method will produce *exactly* the same results (Examples 1, 2 and 3). This point is meant to illustrate that the proposed change is not to the underlying method of the HCM, but rather in the way we evaluate the HCM equation using a method that is not so limiting. While the proposed IQA method is completely consistent with the traditional models (Webster, HCM) when applied with the same assumptions, it is not limited to conditions that match these assumptions (Examples 4 and 5).

Since the 2000 HCM queue model was also developed as a "two-term" model for consistency with the delay model, it is presumed that the IQA method could also be used in exactly the same fashion as an alternate method to calculate the first term of the 2000 HCM queue model. In addition, Eq. 1 captures only the under-saturated portion of the delay (the X<=1.0 condition). Random and over-saturated delays are automatically captured in the second delay term. Thus, the proposed IQA method will be applicable to over-saturated conditions in the same way the current method is. This will be accomplished by first calculating the capacity of all of the effective green displays. If the arrival volume exceeds the total capacity, the volume must be reduced by the inverse of the X value for purposes of estimating delay in the IQA process (similar to Eq.1).

In conjunction with the development of detailed implementation procedures for the IQA method, the authors feel the Capacity Committee should seize the opportunity to also provide the computational mechanism within the HCM procedures to handle lane-by-lane analyses since both changes will require substantial structural changes to the HCM. If lane volume data are unavailable, the method could provide default lane data consistent with the utilization factors of the current lane-group-based method. A superior solution would be to implement the technique proposed in recent research by Nevers and Rouphail [10] for lane volume assignments based on estimated queue lengths, which appear to match field data quite well.

Another desirable extension of this method would be to generate standardized Arrival Type-specific patterns for so that the use of a progression factor can be eliminated and the effect of progression can be evaluated in a more robust way using a variable arrival rate instead of an 'after-the-fact' adjustment to the triangle calculation. Some excellent work has already been accomplished in this area by Benekohal [11]. In order for such an adjustment to be effective, an assumed arrival pattern must be provided for all arrival types. At a minimum, the method should produce an arrival pattern when a user selects an arrival type. This topic is considered separately in a companion paper submitted to TRB by the authors [12].

Finally, it is important to validate the proposed model under conditions which both match the assumptions of the 2000 HCM, as well as those which go beyond those of the 2000 HCM, against field conditions. Such work has really not been carried out at the national level since the 1985 HCM. The assumption here is that where field conditions are reasonably consistent with the 2000 HCM assumptions, all methods will yield comparable results. However, under conditions which exceed the 2000 HCM assumed conditions, as in Examples 4 and 5 above, it is assumed that the proposed IQA method will better replicate field conditions than the 2000 HCM.

**Conclusions and Recommendations for Future Research**

In summary, the authors offer the following conclusions:

1. Under the same set of simplifying assumptions, the proposed IQA method delivers exactly the same delay results as the HCM2000 method.

2. The limiting assumptions of the HCM2000 method are not binding in the IQA method, thus making it more flexible and more consistent with observable field phenomena.

3. Oversaturated conditions can be handled the same way as the HCM2000 since the IQA method only considers the first-term component of delay, which inherently calculates delay up to and at capacity. Random and over-saturation delays are captured in the incremental delay term.

4. On the surface, the IQA method may appear more complex than the HCM method, but in reality it is actually less so and far easier to comprehend, just more tedious if being performed without the use of computer-aided tools. The IQA method can be completely described using the worksheet approach of the HCM.

5. The IQA method is more consistent with the more complex models which are often needed to supplement the HCM methods, thus making the HCM methods more generally applicable.

In terms of future research, the highest priorities would be (a) to conduct validation studies against field conditions, (b) to verify that a solution with varying arrival flow rates during red and green is comparable to, or better than, the progression factor approach used in the HCM2000, and (c) to illustrate how the IQA method can be accomplished using a lane-by-lane approach in the signals chapter of HCM2000. The IQA method should also be validated against the HCM2000 queue estimation method as a viable replacement for the $Q_1$ term calculations. Following this, a concerted effort to update the method and worksheets described in the HCM2000 to accommodate the IQA method (on a lane-by-lane basis, if the Capacity Committee wishes) should be undertaken with the ultimate objective of producing a revised signalized intersection chapter for the HCM.

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