ESTIMATING CONFIDENCE INTERVAL FOR HIGHWAY CAPACITY
MANUAL DELAY EQUATION AT SIGNALIZED INTERSECTIONS

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Abstract

This paper presents an analytical methodology that estimates HCM delay confidence interval. The current HCM procedure utilizes a single value of vehicle arrival demand such that it does not account for day-to-day traffic demand variations. With the field implementation of advanced signal system control such as MIST in Northern Virginia, day-to-day traffic demand fluctuation data are readily available and can be used in the estimation of demand distribution. A Monte-Carlo simulation could develop a distribution of HCM delay and consequently estimate its confidence interval. One drawback of such approach is inconsistency in the results. This is because the results vary depending on the series of random number seeds used.

An expectation function method is utilized to estimate the variance of the HCM delay. Since the expectation function method is applicable only to power functions, the HCM delay equation is approximated using Taylor Series expansion. The expectation function method estimates mean and variance of HCM delay for given traffic demand conditions. The inputs required for this methodology are the volume distribution, its mean and variance. Applicable input distributions include normal, triangle, uniform, lognormal, and gamma distributions. The output will be mean, variance and higher moments of HCM delay, which are used to estimate the HCM delay confidence interval.

It is expected that the proposed methodology can provide more valuable information than current HCM procedure and could be combined with a signal optimization program that accounts for stochastic variability.

Key words: HCM, Delay, Confidence Interval, Expectation Function Method, Monte Carlo Simulation
INTRODUCTION AND BACKGROUND

The level of service (LOS) at signalized intersections is determined by average control delay per vehicle, which is estimated from Highway capacity manual (HCM) delay equation. The HCM equation is a function of multiple input parameters arising from geometry, traffic and signal conditions. Among those input parameters, vehicle demand and capacity are the most critical ones. The HCM procedure in the signalized intersection methodology calculates demand flow rate and saturation flow rate in order to estimate volume to capacity ratio and corresponding performance measure, delay. Then, LOS is determined from a predefined range of average control delay values. In practice, most efforts are given to the estimation of capacity, while traffic volumes are collected just for a day or two with the exception of the existence of surveillance systems. At times, it was discussed that LOS is not a good performance measure when the delay value lies borderline of two LOS categories. For example, an average delay of 34.9 seconds is considered as LOS C, while 35.0 is LOS D. In addition, the average control delay at signalized intersection from real world might vary depending on traffic conditions including different arrival distribution, percentage of trucks, and drivers’ characteristics.

Many researchers extensively studied estimating delays at signalized intersection. They include Allsop (1) and Hurdle (2). A few researchers investigated issues of variability in delays and proposed methods for estimating delay variance for cycle-by-cycle. Kimber and Hollis (3) developed a numerical method that calculates average delay and time dependent distribution of cyclic delay. Olszewski (4) studied the probability distribution of delay and investigated the effect of various parameters on the distribution of delay. Akcelik and Rouphail (5) proposed a delay equation that accounts for random and platooned arrivals. They also attempted to estimate average delay for variable demand conditions using peak hour factor (6). Recently, Fu and Hellinga (7) developed an analytical model for the estimation of overall delay variance for cyclic variations in the demand. Their model was developed on the basis of simulation model output and does not consider day-to-day demand variations.

With the use of advanced vehicle detection and communication technology, traffic count data from signalized intersections are extensively archived in places such as the Smart Travel Laboratory (STL) at the University of Virginia. The data is provided from Northern Virginia Management Information System for Transportation (MIST). The MIST at Northern Virginia controls over 1,000 signalized intersections and system detectors report vehicle counts, speed, and occupancy every 15 minutes. Thus, day-to-day vehicle demand variations can be easily captured and analyzed.

This paper investigates theoretical approach to estimate HCM delay variance that accounts for day-to-day demand fluctuation. The process of estimating the variance of delay could be termed as uncertainty analysis. A number of methods that involves sampling process have been developed for uncertainty analysis and extensively used in transportation engineering. Sampling techniques involve the running of the model for a selected set of inputs based on their probability distributions to generate the probability distribution of the output. One of widely used sampling methods for uncertainty analysis
is Monte Carlo Simulation. Monte Carlo Simulation is found to be suitable for complex systems in transportation modeling (8). This method could be applied to estimate HCM delay variance but it has its limitations. Monte Carlo simulation is computationally intensive and provides slightly different results for each multiple simulation runs. A large number of multiple simulations are required to achieve the convergence of the output value. Also a different distribution of the input variable requires new simulation runs and would turn out to be a time consuming process. It should be noted that the objective of this research is to develop an analytical methodology that can be easily used for estimating variability of HCM delay equation without applying extensive simulation tools.

The paper is organized as follow. The methodology section presents models and approaches used in this study and it is followed by traffic data. In the implementation of the proposed methodology section we provide an example of expectation function method and then a comparison with the Monte Carlo method is followed. Finally conclusions and recommendations are provided.

METHODOLOGY

The methodology proposed in this paper uses expectation functions to quantify the HCM delay variability. The expectation functions for various input distributions can be found in Tyagi and Haan (9). In order to apply the expectation function method, the HCM delay equation is transformed to a polynomial equation using a Taylor Series Expansion. Then, the average and variance of HCM delay is calculated from the expectation function method.

Assumptions

The following assumptions are made in developing the methodology.

- HCM delay equation is valid.
- Intersection is being operated undersaturated conditions.
- Saturation flow rate and effective green times are constant such that only day-to-day traffic volume is varied.

Oversaturated conditions are not considered in this study due to the discontinuity of HCM delay equation where the volume-to-capacity ratio is equal to one. The variability of effective green times and saturation flow rates are not considered, either. It is believed that both factors have relatively little impact on the HCM delay compared to volume variation. In addition, data collection of saturation flow rate and effective green times are not readily available from existing ITS control system. However, it is noted that a study is being undertaken to overcome such discontinuity in HCM delay as well as to account for the variability of effective green time and saturation flow rate.
**Highway Capacity Manual (HCM) Delay Equation**

The highway capacity manual (HCM) delay equation has a number of inputs that are subject to variability.

\[
D = \frac{0.5 \times C \times (1 - g/C)^2}{1 - \min(1, X) \frac{g}{C}} + 900 \times T \times \left[ (X - 1) + \sqrt{(X - 1)^2 + \frac{8kIX}{cT}} \right]
\]  

(1)

Where,

- **C** = Cycle Length,
- **g** = Effective green time,
- **X** = Degree of saturation (v/c),
- **T** = Duration of analysis period,
- **k** = Incremental delay factor, 0.5 for pre-timed signals,
- **I** = Upstream filtering/metering adjustment factor, 1 for isolated intersection,
- **c** = Capacity

Three main variables that are of interest in this research are effective green time, traffic volume, and saturation flow rate. Effective green time and saturation flow rate vary due to different drivers’ characteristics and vehicle mix. It is noted that the ranges of these variables are relatively small and for this exploratory research, only traffic volume variability is considered. Thus, the HCM delay equation becomes a function of traffic volume or degree of saturation (X) with a fixed capacity.

**Expectation Function Method**

The expectation function method is an analytic procedure that overcomes shortcomings of the sampling procedures. In this methodology, each uncertain variable is considered as a random variable with known distribution, mean and variance. Since the output is depending on the input variables, the output is also a random variable whose higher order moments are to be calculated based on the variation of the input variables. The expectation function method can be used to calculate the first and higher order moments of an output variable that is a function of several independent random variables in multiplicative, additive and combined forms (9).

Tyagi and Haan (9) developed the expectation function equations that are function of the mean and coefficient of variance (COV) of an input random variable. The input random variable can be uniform, triangular, lognormal, gamma, exponential, or normal distributions. With a prior knowledge of the mean, variance and the distribution of the input random variable the expectation values of the higher powers of the variables can be computed. For example, consider an input variable (X) that follows a distribution with a mean value of \( \mu_X \) and a coefficient of variance of \( CV_X \).

The expectation values under various powers of X will be obtained as follows depending on its distribution (9).
For Normal distribution,
\[ E[X'] = \mu_X \sum_{n=0}^{r/2} \binom{r}{2n} CV_X^{2n} E[z^{2n}] \quad \text{When } r \text{ is even} \]
\[ E[X'] = \mu_X \sum_{n=0}^{(r-1)/2} \binom{r}{2n} CV_X^{2n} E[z^{2n}] \quad \text{When } r \text{ is odd} \]
where \( z = \frac{X - \mu_X}{\sigma_X} \)

For Uniform Distribution,
\[ E(X') = \frac{\mu_X^r}{2\sqrt{3}(r+1)CV_X} \left[ \left(1 + CV_X \sqrt{3}\right)^{r+1} - \left(1 - CV_X \sqrt{3}\right)^{r+1} \right] \]

For Lognormal distribution,
\[ E(X') = \mu_X ' (1 + CV_X^2)^{r(r-1)/2} \]

For Gamma distribution,
\[ E(X') = \mu_X ' CV_X^{2r} \exp\left[\ln[\Gamma(CV_X^{-2})] - \ln[\Gamma\left(CV_X^{-2} + r\right)]\right] \]

Using these expectation values onto the output function, the higher moments for the output function about the mean are calculated. As noted earlier, the expectation values have been developed for power functions or additive and multiplicative terms of these power functions such that this method cannot be directly applied to the HCM delay equation. The HCM delay equation has to be transformed to an equation involving only additive and multiplicative terms of the powers of X. This can be realized by approximating the delay equation to a polynomial as a function of X. We have used Taylor series expansion on the delay equation for the transformation.

**Taylor Series Expansion**

The generalized Taylor Series expansion of any function \( F(x) \) is
\[ F(X) = F(X_0) + \sum_{n=1}^{j} \frac{1}{n!} \frac{d^nF(X_0)}{dX^n} (X - X_0)^n \]

The \( X_0 \) in the above equation is the point where the function is expanded. The approximated function \( F(X) \) yields values that are very close to the true values around the point \( X_0 \) and is exact at the point \( X_0 \). Since traffic demand volume is a random variable with a particular mean and variance, day-to-day traffic demand volumes vary close to the mean value of traffic demand volume depending on the distribution. When Taylor Series expansion equation is used to approximate the HCM delay equation values, it is logical to expand it about the mean of its distribution. This will result in the best approximations. It is noted that different mean values yield different approximation equations.
Taylor Series expansion based delay estimation for the following condition is conducted and the result is compared to that of HCM delay equation. Assume the mean degree of saturation (X) and standard deviation of X of 0.5 and 0.125, respectively. The 95% confidence intervals for X will turn out to be $0.5 \pm 1.96 \times 0.125$ or $(0.255, 0.745)$. We have compared actual HCM delay values with the Taylor Series expansion based delay values within this confidence interval range. As shown in Figure 1, delays from HCM and Taylor Series expansion (with $n = 3$) match almost perfectly for the 95th percentile confidence interval range. This justifies the use of Taylor Series expansion equation in this study.

![Figure 1. Comparison of HCM equation delay and Taylor Series expansion-based delay](image)

**Calculation of HCM Delay Confidence Interval**

The expectation values for $X'$ are computed depending upon the probabilistic distribution, mean and variance of the arrival flow as elicited earlier. The expectation values for the delay ($D$) and for $D^2$ are calculated from the expectation values of $X'$ as shown below. The generalized approximate equation for delay as after using the Taylor series expansion will be a polynomial of the $n^{th}$ order as shown below.

$$D = \sum_{j=1}^{n} \alpha_j X'^j$$

Where,

- $D$ is the delay
- $\alpha_j$ are the coefficients of the power terms
\( X \) is the degree of saturation.

Using equation (7) and the expectation values generated from the equations (2)–(5) the expectation of delay is calculated as in equation (8).

\[
E(D) = \sum_{j=1}^{n} C_j E(X^j) \quad (8)
\]

Similarly, the delay equation is squared, the expectation of \( D^2 \) is computed, and from these values, the variance of delay is calculated as

\[
\sigma_D^2 = [E(D)]^2 - E(D^2) \quad (9)
\]

Using the standard deviation of delay (\( \sigma \)) from equation (9) and mean value of delay (\( \mu \)) from (8), the confidence interval is computed as follows.

\[
\text{C.I.} = \mu \pm \sigma \times (\text{percentile value}) \quad (10)
\]

The percentile points are calculated from statistical tables depending upon the distribution and the percentile value. For example, in case of normal distribution, the percentile value of 95th percentile is 1.96, while 99.99 percentile uses the value of 3.

**Monte Carlo simulation**

Monte Carlo simulation is conducted to validate the output from the proposed expectation function method. The expectation method can take in any distribution of the input variable as long as its expectation and variance are known. So, depending on the distribution of the input variable, 500 data points are generated which follow the known variable distribution. The HCM delay values are calculated for all these 500 points and their mean and variance are calculated. This procedure is repeated for different set of input values following the same distribution with different random number seeds.

**TRAFFIC DATA: DAY-TO-DAY VARIATION**

The management information system for transportation (MIST) in Northern Virginia maintains over 1000 signalized intersections in Fairfax, Prince Williams, and Loudon counties, VA. The Smart Travel Laboratory (STL) at the University of Virginia archives the traffic volume, speed, and occupancy data every 15 minutes. The data from STL is taken to estimate the actual coefficient of variance observed in the field and to find out the distribution of the day-to-day volume variations. It is noted that erroneous traffic data are eliminated from analysis using data screening procedure available at the STL.

Traffic counts data from three signalized intersections are used to calculate day-to-day variation. The signalized intersections in Northern Virginia are Chantilly, Lees Corner and Springfield located on Route 50, fairly congested commuting route. Traffic counts
for every 15min period were obtained from the MIST for over a period of 6 months (September 2001 to December 2001) at all the three intersections.

Figure 2 shows the variations in the traffic volumes for morning peak, noon and evening peak for one approach at the Lees corner intersection. The coefficient of variance (COV) for morning peak, noon, and evening peak are found to be 0.036, 0.054, and 0.048, respectively. The variability of 24-hour traffic volumes was also investigated. The calculated COV ranged from 0.04 to 0.28 throughout the day. It is noted that the observed COV values are low for peak periods and are high for non-peak periods. This is intuitive because during peak periods the volume is consistently close to capacity such that the variability of traffic counts is low and COV becomes low. Thus, for high degree of saturation the variability relatively low COV is observed, while high COV is observed for low degree of saturation.

(a) Morning Peak (7 – 8 am)

(b) Noon (12 – 2 pm)
IMPLEMENTATION OF EXPECTATION FUNCTION METHOD

The proposed expectation function method can be best explained by going through an example. Consider the following conditions.

The following data are given for an approach at a pretimed signalized intersection.

Average volume = 300 vph
COV volume = 0.25
Cycle length = 100 sec
Effective Green time = 30 sec
Saturation flow rate = 1800 vphpl

The traffic volume and v/c ratio are assumed to follow normal distribution.
The analysis period was 15 minutes, i.e., T = 0.25
For a signalized intersection K = 0.5
Also for an isolated intersection, I = 1

Calculations

The Taylor Series expansion equation is approximated about the value of X corresponding to the average demand. Therefore, the X₀ in equation (6) can be found from volume to capacity ratio, 300 / 540 = 0.55. The capacity can be found as follow.

$$\text{Capacity (c)} = s \times \frac{g}{C} = 1800 \times \frac{30}{100} = 540 \text{ vphpl}$$

An average delay of 33.48 seconds per vehicle is obtained from HCM delay equation. Using the equation (6) and substituting all the above values one can obtain the approximated equation (i.e., Taylor Series equation) as follow.
Average delay = 18.4467 + 48.6496 × X – 76.8930 × X² + 68.4761 × X³ \quad (11)

The equation is expanded only to three terms (n = 3) as it can replicate the HCM delay equation almost exactly within the 95th percentile confidence interval. The above equation provides a delay value of 33.48 at X=0.58. Given that X follows a normal distribution, using equation (2) one can obtain the followings.

\[
E(X) = \mu = 300 / 540 = 0.556 \\
E(X^2) = \mu^2 (1 + CV^2) = 0.328 \\
E(X^3) = \mu^3 (1 + 3 * CV^2) = 0.204 \\
E(X^4) = \mu^4 (1 + 6 * CV^2 + CV^4) = 0.131 \\
E(X^5) = \mu^5 (1 + 10 * CV^2 + 5 * CV^4) = 0.087 \\
E(X^6) = \mu^6 (1 + 15 * CV^2 + 15 * CV^4 + CV^6) = 0.059
\]

E(D) can be computed using equation (11) as follow.

\[
E(D) = 18.4467 + 48.6496 \times E(X) – 76.8930 \times E(X^2) + 68.4761 \times E(X^3) = 34.20
\]

Similarly squaring the delay equation and applying the expectation values, one can obtain the following.

\[
E(D^2) = 340.28 + 1794.85 \times E(X) – 470.06 \times E(X^2) – 4955.31 \times E(X^3) + 12575.20 \times E(X^4) – 10530.67 \times E(X^5) + 4688.98 \times E(X^6) = 1171.7
\]

Using equation (9), a delay variance of 15.06 is produced. The 95th percentile confidence interval on delay, 34.20 ± 1.96 × 3.88 or (26.59, 41.80), is obtained from equation (10).

**EVALUATION OF EXPECTATION FUNCTION METHOD**

**Comparison With Monte Carlo Simulation**

In order to verify the proposed expectation function method, Monte Carlo simulation is utilized. For the above example, 500 data points that follow a normal distribution with mean of 300 and coefficient of variance of 0.25. These data points can be considered as realizations of hourly traffic volumes over 500 days. Then, delays for 500 days are calculated using HCM delay equation. The mean delay and its variance are calculated from these 500 delay values. This process is repeated twenty five times and the distributions of these data sets are compared to the distribution generated from expectation function method.

As in the example in the previous section, the expectation methodology produced a mean value of 34.20 and variance of 15.06. For presentation purpose, it is assumed that the delay distribution follows normal. Note that any distribution can be used in the estimation of confidence interval and plot.
As indicated earlier, Monte Carlo simulation generates inconsistent results. The Monte Carlo simulation could produce the mean and variance that are very close to the expectation function method if extremely large number of random samplings were utilized. As shown in Figure 3, the expectation function method based distribution is well represented by distributions generated from Monte Carlo simulation.

Figure 3. Expectation Function Method versus Monte Carlo Simulation

**Evaluation of HCM Delay with respect to Varying Traffic Fluctuations**

The following conditions (same as in the previous example) are assumed for an approach at a signalized pretimed intersection.

- Green time = 30 sec,
- Cycle length = 100 sec,
- Saturation flow rate = 1800 vehicle per hour per lane,
- Lane group capacity = 540,
- Average flow through the lane group = 300,
- Analysis period = 0.25 hrs
- Initial queue = 0

From the above conditions, HCM delay of 33.48 and LOS C are obtained. Assuming that the day-to-day traffic volume fluctuation estimated through the coefficient of variance of is 0.1, using the procedure shown previously, the mean delay of 33.60 and delay variance of 1.49 can be obtained.
Further assuming the delay follows a normal distribution, the delay confidence interval at 95th percent significant level would be (30.68, 36.52) in which leads to the LOS between C and D. The following Table 1 illustrates how the LOS could vary if the variability in the traffic volumes (i.e., COV) increases.

<table>
<thead>
<tr>
<th>COV</th>
<th>Average Delay (Seconds)</th>
<th>SD</th>
<th>Upper C.I.</th>
<th>Lower C.I.</th>
<th>LOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>33.60</td>
<td>1.49</td>
<td>36.52</td>
<td>30.68</td>
<td>C-D</td>
</tr>
<tr>
<td>0.2</td>
<td>33.94</td>
<td>3.05</td>
<td>39.92</td>
<td>27.96</td>
<td>C-D</td>
</tr>
<tr>
<td>0.3</td>
<td>34.52</td>
<td>4.75</td>
<td>43.83</td>
<td>25.20</td>
<td>C-D</td>
</tr>
<tr>
<td>0.4</td>
<td>35.32</td>
<td>6.67</td>
<td>48.39</td>
<td>22.26</td>
<td>C-D</td>
</tr>
<tr>
<td>0.5</td>
<td>36.36</td>
<td>8.86</td>
<td>53.72</td>
<td>18.99</td>
<td>B-C-D</td>
</tr>
<tr>
<td>0.6</td>
<td>37.62</td>
<td>11.41</td>
<td>59.98</td>
<td>15.26</td>
<td>B-C-D-E</td>
</tr>
</tbody>
</table>

Figure 4 shows HCM delay, average HCM delay and 95th percentile confidence interval under varying demand conditions for the range of degree of saturations. The HCM delay is obtained from equation (2) using an average volume at given degree of saturation, while the average HCM delay is obtained from either equation (2) or equations (7)–(10) using varying traffic volumes. It is assumed that the coefficient of variance of traffic volume is 0.25 and the distribution of traffic volume follows normal distribution. All other conditions are same as in the previous example.

![Figure 4. The 95th percentile confidence interval with varying degree of saturation](image)

As shown in Figure 4, the HCM delay and the average delay show discrepancies when the degree of saturation is higher than 0.6 or so. It should be noted that the discrepancies
is due to the nature of HCM equation – the delay increases exponentially when degree of saturation is higher than 0.6 or so. The HCM delay line is obtained using average traffic volume per each degree of saturation, while the average delay line is obtained from the average value of HCM delays calculated from varying demands per each degree of saturation. Thus, when degree of saturation value is higher than 0.6 or so, the impact of volume that is bigger than average would result in exponentially higher delay values. Therefore, the average delay from varying demand would be higher than the delay at average volume level. However, when degree of saturation is less than 0.6 or so the HCM delay and average delay yield very similar values since the HCM delay equation is close to linear. It is noted that Figure 4 only shows the degree of saturation up to 0.8 since the confidence interval of the degree of saturation 0.8 or higher is almost meaningless due to very wide interval range.

Evaluation of HCM Delay with respect to Different Traffic Volume Distributions

The expectation function method can be used for any distribution of the input volumes as long as distribution parameters are known. These distributions include normal, gamma, uniform and lognormal distributions. In this section, we utilized normal, uniform, gamma, and lognormal distributions in order to explore HCM delay and its variability.

An example is utilized. Four different traffic volume distributions are applied under the same conditions of traffic demand and capacity. It is noted that the traffic demand conditions are consistent in all the examples. The degree of saturation is varied from 0.0 to 1.0. As shown in Figure 5, regardless of distributions average delay appears to be fairly consistent. However, variability varies significantly as volume to capacity ratio closes to 1.0 (see Figure 6). As one would expect, lognormal distribution produced the highest delay variance.

The lognormal distribution is a well spread-out distribution with a big tail on both sides causing high variability, while the gamma distribution is mostly skewed positively with a very long tail on one side resulting in a lower variance than that of lognormal. The uniform distribution is uniform throughout the entire range and hence yields a lower variability than those of the above two distributions. The normal distribution has neither any skewness nor big tail and hence has the lowest variability.
CONCLUSIONS AND RECOMMENDATIONS

In this paper, an analytical method that estimates confidence interval of HCM delay equation under varying day-to-day traffic conditions is proposed. The proposed expectation function-based method can theoretically estimate the HCM delay confidence interval as long as the distribution of underlying traffic variation and its parameters are known. An example calculation of the proposed method is presented using real world traffic volume variation. Monte Carlo simulation was conducted to evaluate the
performance of the proposed method. Average delay and its variability under various day-to-day traffic volume distributions such as Uniform, Normal, Gamma, and Lognormal were also investigated. From the evaluation of the proposed method, the following conclusions can be drawn.

- The proposed method properly estimates HCM delay mean and its variance as illustrated from Monte Carlo simulation using field input data.
- Depending on the variability in day-to-day traffic volumes the LOS of HCM delay could vary from A to D. This observation supports the use of delay variability as a part of LOS determination.
- The magnitude of HCM delay variability grows exponentially as degree of saturation closes to 1.0 and different day-to-day traffic volume distribution shows significant variations.

The following recommendations are made.

- When LOS of a signalized intersection is determined, HCM delay variance should also be considered. This is because current HCM delay and its LOS might misrepresent traffic conditions where two intersections with similar average day-to-day traffic volume but different variability or distributions exist.
- A further research on signal timing optimization should consider not only average system delay but also variance of delay.
- A further study that can consider variability of effective green times and saturation flow rates as well as cycle-by-cycle variation should be conducted.
- A further study should be conducted to estimate HCM delay confidence interval under oversaturated conditions.
REFERENCES


