■ 論 文 ■

# Development of an Average Green Time Estimation Model for Proper Evaluation of Traffic Actuated Operation

## 감응식 신호운영의 평가를 위한 평균녹색시간 추정모형 개발

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Key Words : Traffic Actuated Operation, Average Green Time Estimation, Queue Service Time, Green Extension Time, HCM

요 약

미국 도로용량편람(HCM)은 감응식 신호운영의 평가를 위하여 감응식 현시의 평균녹색시간 추정을 요구하고 있고 그 부록에서 제시한 평균녹색시간 추정모형을 적용할 것을 권장하고 있다. 이 모형은 감응식 신호운영의 기능적 특징을 반영하는 유일한 분석모형이지만 그 모형식에는 (1)대기행렬처리시간의 추정, (2)적신호우회전 교통량(Right turn on red)의 영향, (3)공유차로 비보호 좌회전의 영향에 있어 개선요소를 포함하고 있다. 본 연구는 이러한 HCM모형의 개선요소를 분석하고 수정하여 새로운 평균녹색시간추정모형을 제시한다.

다양한 교통상황, 기하구조상황, 현시조합상황을 가상설정하여 총 234개의 감응식 신호운영 시나리오를 구축하고 이로 파생되는 1,196개의 감응현시를 실험자료로 사용하였다. 각각의 시나리오를 Corridor Simulation (CORSIM)모형으로 모의실험한 결과를 기준으로 삼아 HCM 분석모형과 본 연구에서 제시하는 분석모형의 추정력을 비교하였다. 제시된 모형의 전산적용은 Average Green time Estimation(AGE) 프로그램을 개발하여 적용하였고, HCM모형은 미국 University of Florida에서 개발된 ACT348 프로그램을 사용하여 적용하였다. 예측된 결과는 비보호좌회전이 허용되지 않는 신호현시 집단(1,118개)과 허용되는 신호현시집단(78개)으로 나누어서 비교하였다. HCM모형의 경우 각각의 집단에 대한 설명력이 0.56, 0.57로 결과된 반면 본 연구를 통해 새롭게 제시된 모형의 설명력은 각각 0.90, 0.86으로 결과되었다.

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## Ⅰ. Introduction

During recent decades, advanced traffic control systems have been introduced to promote the efficient traffic flow at signalized intersections. Those systems provide operators with options to select the one of the following signal control modes: pretimed, traffic-actuated, and traffic-responsive operations. Proper performance evaluation of the system with each of those operations is one of the keys of the success in traffic management.

In the case of pretimed and traffic responsive operations, evaluation of the system performance can be made since the green-time and cycle-length data are available either through local controllers or at the traffic management center. In the case of traffic-actuated operation, however, the proper evaluation of the system performance cannot be made since the actual green-time and cycle-length data are changed based on vehicle actuations. An auxiliary procedure that estimates the average green time is required to obtain the average cycle length, to evaluate the system and to manage the system.

The Highway Capacity Manual(HCM) published in the United States in 1997 and 2000 provides with an average green-time estimation model for the evaluation of traffic-actuated operations(TRB, 1997 and 2000). The model utilizes the final product of the National Cooperative Highway Research Program (NCHRP) 3-48 Project(Courage et al., 1996), and it is the first and a unique existing model that explicitly estimates the average green time of an actuated phase. However, the model fails to follow a sound analytical approach in some aspects.

This document describes problems found in the HCM model and proposes a new model that overcomes the shortage of the HCM model. The proposed model must therefore be viewed as the current standard for average actuated green time estimation.

## Ⅱ. Background

The HCM suggests estimating the average length of an actuated phase by dividing a green time into two different portions: queue service time and green extension time(Courage et al., 1996). The former is the period that vehicle actuations occur sequentially due to the queued vehicles. During the time, vehicle gaps are rarely longer than unit-extension time. The latter is the period that vehicle actuations occur irregularly due to the random arrivals of vehicle. It is the green time portion observed after the queue clearance. The HCM method successively estimates the average lengths of those two portions and then the total length of a whole phase by summing those up.

The HCM queue service time is computed with the following equation, which was developed based on queue-accumulated polygon(QAP).

$$g_s = f_q \frac{q_r r}{(s - q_g)} \qquad (1)$$

where,
$g_s$ : queue service time(s)
$f_q$ : queue calibration factor
$q_r$ : red arrival rate(v/s)
$r$ : effective red time(s)
$q_g$ : green arrival rate(v/s)
$s$ : saturation flow rate(v/s)

The queue calibration factor, $f_q$, was originally introduced by Akcelik to account for randomness in arrivals in determining the average queue service time(Akcelik et al., 1995). The HCM suggests computing the queue calibration factor with the following equation:

$$f_q = 1.08 - 0.1(g/g_{\max}) \qquad (2)$$

where,
$g$ : actual effective green time
$g_{\max}$ : maximum green time

The HCM green extension time is computed with the following equation, which was developed based on the bunched exponential distribution function.

$$g_e = \frac{e^{\lambda}(e_0 + t_0 - \Delta)}{\varphi q} - \frac{1}{\lambda} \quad (3)$$

where,
$g_e$ : green extension time(s)
$\lambda$ : a parameter
$e_0$ : unit extension time setting(s)
$t_0$ : time during which detector is occupied by a passing vehicle(s)
$\Delta$ : minimum arrival headway(s)
$\varphi$ : proportion of free vehicles
$q$ : vehicle arrival rate during a cycle(v/s)

The values of $t_0$, $\varphi$, $\lambda$ are obtained by the following equations:

$$t_0 = \frac{3.6(L_d + L_v)}{S_A} \quad (4)$$

$$\lambda = \frac{\varphi q}{1 - \Delta q} \quad (5)$$

$$\varphi = e^{-b\Delta q} \quad (6)$$

where,
$L_d$ : vehicle arrival rate during a cycle(v/s)
$L_V$ : green extension time(s)
$S_A$ : unit extension time setting(s)
$b$ : a bunching factor

The HCM queue-service time estimation model fails to cover the proper definition of queue-service time. The HCM model implies that the queue service time, gs, be equivalent to the time required to clear the queue. In reality, the queue service time is longer than that the HCM suggests. It is because, when right after the queue is cleared, the gaps of the vehicles running in between the point of the maximum back of queue and the detector location(set-back position) would follow the identical distribution which can be observed during the queue service time. Thus, it is expected that the HCM model underestimate the queue service time and therefore the average green time of an actuated phase.

In addition, the model provides with much room for improvements. For example, the HCM model excludes the effects of the right-turn-on-red vehicles. It also fails to count the proper number of actuations of shared permitted left turns by suggesting using the adjusted left-turn saturation flow rate.

## Ⅲ. Model Development

A new average green time estimation model and its assistant computational procedures were developed based on the new definitions of queue-service time and green extension times. The new definitions are presented below:

(1) Queue-service time is the green time portion that starts when green time starts and ends when the last vehicle at the maximum back of queue leaves the detector zone.
(2) Green-extension time is the green time portion that starts with the end of queue-service time and ends with the termination of green time due to either gap out or maximum extension to the maximum green time.

The following subsections describe (1) the new model developed based on those new definitions and (2) sets of procedures developed to promote proper estimation of the average green time.

### 1. A New Green-Time Estimation Model

A new model defines the queue-service time, $g'_s$, as the sum of the HCM queue service time, $g_s$, and the additional queue service time, $g_a$. The new model is:

$$g = g'_s + g_e = g_s + g_a + g_e \quad (7)$$

The additional queue service time is the cruising time taken by the last queued vehicle to leave the detector zone from the point of the maximum back of queue. The $g_a$ can be computed with the following equation:

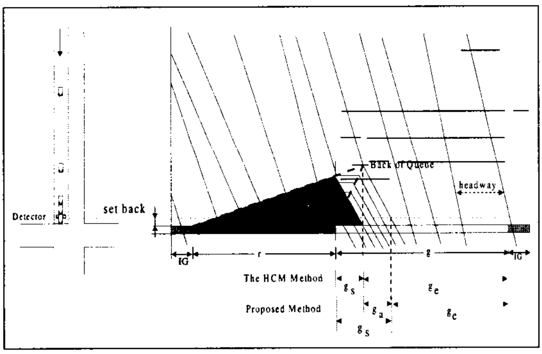
$$g_a = (d_L Q_B - d_s)/(3.6s) \quad (8)$$

where,

$d_L$ : head-to-head vehicle gap distance in queue
$Q_B$ : the maximum back of queue(m)
$d_s$ : detector set back distance(m)
$s$ : average cruising speed(km/h)

The input values needed to compute $g_a$ are field specific. The average values representing the overall characteristics of traffic stream should be used. Comparison between the concepts of the HCM and the proposed models is illustrated with the time-space diagram in ⟨Figure 1⟩.

⟨Figure 1⟩ demonstrates that the HCM method yields the underestimation of the average green time by excluding the existence of $g_a$.




⟨Figure 1⟩ Comparison between the HCM model and the proposed model

## 2. Right-Turn Treatments

For the shared right-turn-lane case, the HCM method suggests using the aggregated lane group volume, sum of right-turn and through movement volumes(TRB, 2000). With the method, it is assumed that all right-turn vehicles flow on green with the through movement and that 100% right-turn vehicles affect the vehicle actuation during green. This fails to count the right-turn vehicles turning on red(Kim, 2001). The HCM indicates that the estimation of the right-turn-on-red(RTOR) volume is a function of various complicated factors and that all right-turn volume should be considered without reduction for the performance estimation (TRB, 2000). However, the procedure introduces the overestimation of the average phase length. The RTOR volume should be excluded in the estimation procedure especially for the average green time, which is determined based on the vehicles flowing only in green.

In the development of a new method, right-turn volume that actually turns on red( $v_R$) is estimated and subtracted from the total lane group volume. The proposed method employs the following equation for the estimation of the adjusted lane group volume.

$$v'_{TH} = v_{TH} + v_{RT} - v_R \quad (9)$$

where,

$v'_{TH}$ : adjusted lane group volume
$v_{TH}$ : the number of through vehicles
$v_{RT}$ : the number of right-turn vehicles
$v_R$ : the number of RTOR/right turns overlapped with left turns

For the estimation of $v_R$, the geometric distribution function was utilized. The geometric distribution function is the one representing the probability of the number of failures, the number of right-turn vehicles flowing on red, expected to be experienced before the occurrence of the first success, the first arrival of a through vehicle blocking a shared lane. Thus, the following equations are developed for the estimation of $v_R$ :

$$v_R = P_R/(1-P_R) \quad (10)$$

$$P_R = v_{RT}/\{P_{RL}(v_{TH}+v_{RT})\} \quad (11)$$

where,

$P_R$ : % RT traffic on the right-most lane

$P_{RL}$ : % traffic using right-most lane

Estimation of $v_R$ requires the estimation of $P_R$, which is a function of through vehicles using a right most lane, and the estimation of $P_R$ requires the estimation of $P_{RL}$. For the estimation of $P_{RL}$, the following equation is developed and implemented in the proposed procedure.

$$P_{RL} = \begin{cases} P_{HL} & \text{, when \# of lanes} = 1 \\ 1-P_{HL} & \text{, when \# of lanes} = 2 \\ 0.75-1.25P_{HL} & \text{, when \# of lanes} = 3 \end{cases} \quad (12)$$

where,

$P_{HL}$ : % traffic using most heavily traveled lane

The HCM lane-utilization factors were employed in the $P_{HL}$ estimation. 〈Table 1〉 presents the $P_{HL}$ values(from the HCM) and the $P_{RL}$ values estimated by Equation(12).

While the value of $P_{RL}$ can directly be estimated based on $P_{HL}$ for the single- and two-lane cases, an assumption was used for the three-lane case. It was assumed that the percent traffic using the second heavily traveled lane be in the middle of its upper and the lower limits. In other words, the percent traffic using the second heavily traveled lane could not be higher than the percent of the most heavily traveled lane and lower than the upper limit of the lowest traveled lane. The upper limit of the percent traffic using the lowest traveled lane would be 50 percent of the sum of the percent traffic using the second most highly and the lowest traveled lanes. The middle value between its upper and lower limits was used for the estimation of $P_{RL}$.

〈Table 1〉 Lane distributions

| No of lanes | 1 | 2 | 3 |
|---|---|---|---|
| $P_{HL}$ | 1.000 | 0.525 | 0.367 |
| $P_{RL}$ | 1.000 | 0.475 | 0.291 |

## 3. Shared Permitted Left-turn Movements

The average green time estimation procedure should consider the effect of the shared permitted left turns. The HCM considers a lane group volume as the aggregation of though and left-turn movement volumes and suggests adjusting the saturation flow rate of the shared permitted left-turn movement with the vehicle-equivalent factor, $EL_1$. Such saturation flow rate adjustment should be not be made to prevent the overestimation of the average phase length. This is because the HCM saturation flow rate is the overall average saturation flow rate reflecting both vehicles' waiting time(for acceptable gaps) and flowing time. The proposed average green-time estimation model uses the 'headway based saturation flow rate' of a permitted left-turn movement for green extension time only by excluding the HCM adjustment procedure.

In addition, the HCM method uniformly treats two compound left-turn cases: (1) permitted plus protected and (2) protected plus permitted. Since the queue length on a shared lane is the function of phase sequence and lengths, those compound left turns should separately be considered. The proposed average green-time estimation model handles those two cases as two independent phasing operations.

# Ⅳ. Test Procedure

The average phase lengths estimated by the HCM and the proposed models were compared to the ones simulated by the corridor simulation(CORSIM) program(ITT, 1999). The CORSIM simulation data were used in the test due to the limitations of field data. The test data should reflect many possible combinations of traffic, geometric, and control conditions. It has been shown that the CORSIM simulation data are not statistically different from the field data and are widely accepted as the surrogating of field data(Chundury et al., 2000).

For the implementation of the proposed average green-time estimation method, a computer program was coded with the Visual Basic computer programming language. For the HCM based estimation of the average green time, the ACT348 program was employed in the test. ACT3-48 is the program developed at the University of Florida in 1996 for the automation of the HCM average green time estimation procedure.

A set of test data was developed by considering various geometric, traffic and control conditions. Those conditions and the simulation control strategy used in the CORSIM simulations are summarized below.

## 1. Geometric Conditions of the Test Data

Four different hypothetical intersections were designed to consider the different geometric conditions as specified by the permitted left-turn worksheets of the HCM. While a single lane is constantly given to the north-southbound approaches to minimize the size of the test-data set, the numbers of lanes on the east-westbound approaches are varied see ⟨Figure 2⟩.

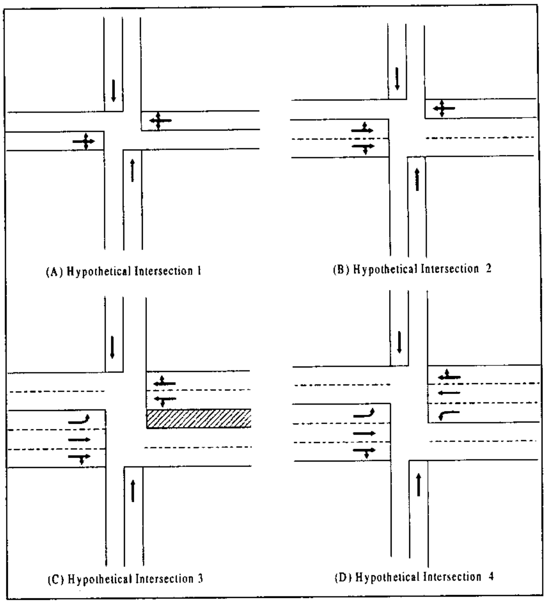
Intersection 1 covers the shared permitted left turns opposed by a single lane approach. Intersection 2 covers the shared permitted left turns opposed by multiple lanes including a permitted left-turn lane. Intersection 3 covers the case of shared permitted left turns opposed by multiple lanes with a protected left-turn lane. Intersection 4 covers the case where a protected left-turn lane is provided on both opposing approaches.

## 2. Control Conditions of the Test Data

Sets of applicable phase sequences at the hypothetical intersections were designed for the test reflecting various control conditions. A simple two-phase operation was considered for the operation at Intersections 1 and 2. Five combinations of permitted and protected left-turn treatments and leading and lagging sequences were considered for Intersection 3. The eleven sets of permitted and protected left-turn treatments and leading and lagging sequences were considered for Intersection 4. It should be noted that the left-turn phase sequences with all lagging protected left turns were excluded from the sets since they are out of bounds of the HCM method.

For the minimization of the test-data size, it was controlled to force the eastbound to be the major direction so that the eastbound phase is always longer than or equal to the westbound phase when the overlap phase operation is involved.

With the phase sequences designed for the test, 46 seconds(sec) of maximum green time, 10 sec of minimum green time, 3 sec of unit extension time, 6 meters of detector length and zero setback length are used.




⟨Figure 2⟩ Hypothetical intersections designed for the test

## 3. Traffic Conditions of the Test Data

A basic traffic condition for each hypothetical intersection was designed, and three specific variables were changed one by one based on the condition to introduce variations in traffic. The basic traffic condition was determined by the following procedure. First, a link volume was initially determined, based on 500 vehicle per hour per lane(vphpl) for a through lane, 200 vphpl for an exclusive turning lane and 100 vphpl for a shared turning lane. Then, the approach volume was controlled to follow 60:40 and 50:50 directional balances for east-westbound and north-southbound streets, respectively. The fifteen percent of the approach volume was set for each turning movement, and the rest was given to the through movement.

Based on this basic condition, three specific conditions were varied: total volume, approach balance and left-turn balance. The variations applied to the basic condition are summarized in 〈Table 2〉.

The combination of geometric-, control- and traffic-condition variations generates 234 different scenarios of intersection operations. They introduced 1,196 different operational conditions of a traffic-actuated phase. They are simulated with CORSIM and estimated by the proposed and the HCM method.

〈Table 2〉 Variation applied to the standard condition to change the traffic condition

| Items | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Total traffic volume(times) | 0.50 | 0.75 | 1.25 | 1.50 |
| Approach balance | 50:45 | 55:45 | 65:35 | 70:30 |
| Left-turn balance (% of total volume) | 0.05 | 0.10 | 0.20 | 0.25 |

## 4. Simulation Data Control

CORSIM does not provide the average phase length as an output in its text output file. The CORSIM average phase lengths were read through the TSD file, a binary file generated by CORSIM with the TSD file-name extension for the animation of the simulation. A program called TSDREADER was developed with the Visual Basic programming language to assist the TSD data reading procedure by utilizing CORTOOL. CORTOOL is an ActiveX object that provides with the access to the TSD data(Leonard, 1998). TSDREADER computes the average phase lengths over different cycles based on TSD signal timing data.

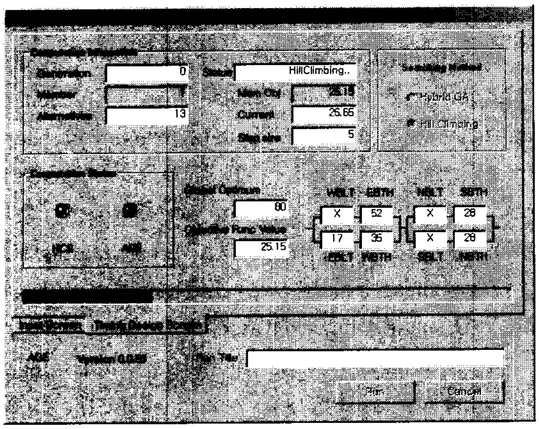
The CORSIM simulation parameters were controlled to follow the assumptions embedded in the HCM models as close as possible. Critical gap of permitted left turns was controlled to be 4.5 sec with the record type(RT) 145. No left-turn jumper was controlled with the RT 140. The left-turn sneaker was controlled to be two per cycle with the RT 141.

Multiple CORSIM runs were made with more than or equal to ten different random seed numbers for each case of operation scenarios. First, ten simulation runs were made with different seed numbers. If the standard deviation of the average phase lengths from those runs is less than or equal to the 10 percent of the overall average phase length, the simulation terminates. If not, ten more simulations were made by adding 10 more random seed numbers to increase the sample size and decrease the standard deviation.

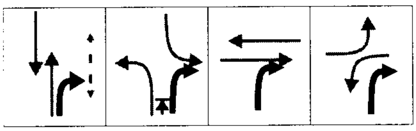
## 5. Automation of the Proposed Model

The Average Green-time Estimation(AGE) program was developed with the Visual Basic programming language for the implementation of the proposed average green-time estimation model(see 〈Figure 3〉).

Three different cases of shared permitted right-turn treatments were categorized to assist the adjustment of the lane group volume. They include RTOR, No RTOR and overlap left turn. 〈Figure 4〉 presents those groups and their concurrent movements. The word 'Go' indicates the permission to proceed, 'No Go' indicates prohibition, and 'No Conflict' indicates 'Go' without any conflict.

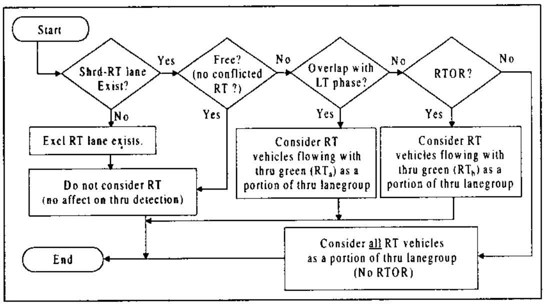



〈Figure 3〉 The AGE program developed for the study



| Treatment | Code | | | | |
|---|---|---|---|---|---|
| RTOR | 1 | Go | Go | Go | Go |
| No RTOR | 2 | Go | No Go | No Go | No Go |
| Overlap LT | 3 | Go | No Go | No Go | Go |

〈Figure 4〉 Right-turn treatments




〈Figure 5〉 A flow chart determining right-turn treatments

For computer-based determination of the right-turn treatment type, a flow chart presented in 〈Figure 5〉 was used.

AGE utilizes the dual-ring phase scheme, which is widely used in the traffic-actuated signal operation

## V. Results

The average green times estimated by the proposed method and the HCM method are compared based on the CORSIM simulation average green times surrogating field data. The estimated average green times are classified into two groups, based on the movements served during green. They are (1) the green time allowing exclusive movements only and (2) the green time allowing shared permitted left turns to flow. The average green time estimation in the former group would be different from the other since shared permitted left turns affect the vehicle actuations.

### 1. Exclusive Protected Movements

The total 1,118 out of 1,196 cases are categorized as the exclusive-movement-only group. The average green times estimated by the HCM method and the proposed method are graphically compared with the CORSIM average green time(see 〈Figure 6〉). The average green times longer than the maximum green time, 46 sec, are the ones that their phases are extended for the simultaneous termination with their concurrent phases.

The HCM results show that the HCM method underestimates the average green time when the average green time is less than the maximum green time, 46 sec. In addition, the HCM method yields the average green time to reach to its maximum green time so rapidly that plotting points appears like a barrier at 46 sec on horizontal axle in 〈Figure 6〉. Underestimation of the average green time with the HCM method would due to the definition of queue service time implied in the HCM model.

The results show that the average green times estimated by the proposed method yields much nicer one-to-one linear relationship to the CORSIM results than the ones from the HCM method. The $R^2$ values between the results from the HCM model and the proposed model and the CORSIM result are 0.56 and 0.90, respectively.

### 2. Shared Permitted Movements

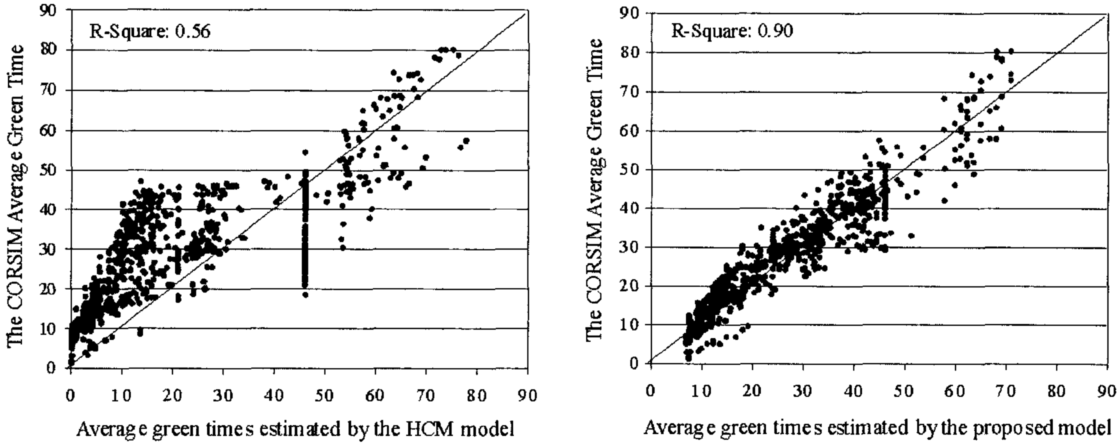
The total 78 out of 1,196 phases are categorized as the ones allowing shared permitted left turns to flow on green. The average green times estimated by the HCM method and the proposed method are graphically compared based on the CORSIM average green time(see 〈Figure 7〉).

The results show that when traffic volume is low, the HCM method underestimates the average green time. This is because of the HCM definition of queue service time. When traffic volume becomes high, the HCM method becomes to overestimate the average green time since the queue service time is increased by effects of permitted left turns. Such overestimation tendency is not the problem of the HCM average green time estimation model but the problem of the shared left-turn parameter estimation models suggested in the HCM.

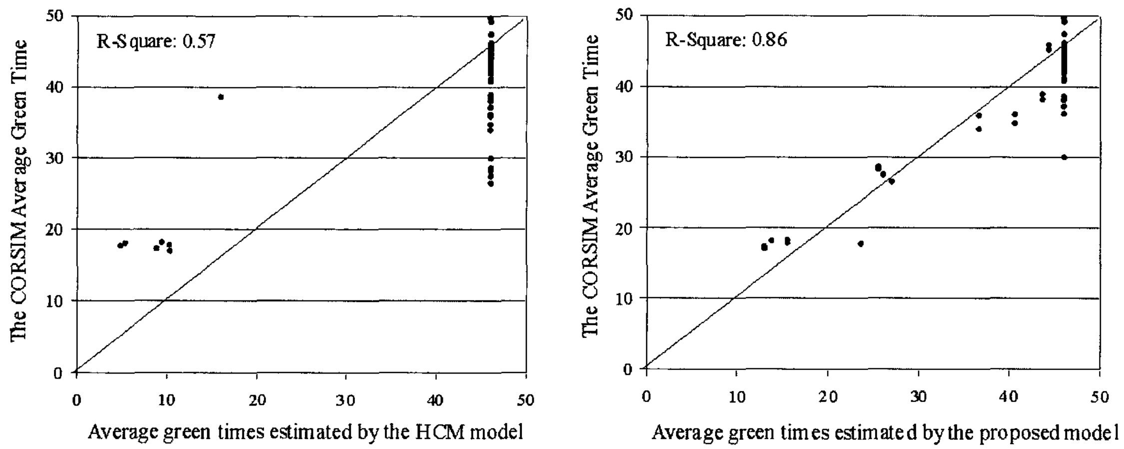
The results show that the proposed method yields much nicer one-to-one linear relationship to the CORSIM results than the ones from the HCM method. The $R^2$ values between the average green times from the HCM and the proposed models and the ones from CORSIM are 0.57 and 0.86, respectively.

## Ⅵ. Conclusions and Recommendations

A new analytical model that estimates the average green times of the traffic-actuated phases was proposed. The proposed model is featured by (1)




〈Figure 6〉 Comparison of the average green time for the phases allowing exclusive protected movements only




〈Figure 7〉 Comparison of the average green time for the phases allowing shared permitted loft-turn movements a new queue service time estimation model utilizing a new definition of the queue service time, (2) the volume adjustment for shared right turns turning on red and (3) proper use of the saturation flow rates of shared permitted left-turn movements.

Through the study, it is concluded that the estimation of the average green times of traffic-actuated phases can be improved by the proposed method. This statement can be supported by the following considerations:

(1) In comparison with the average green times estimated by the HCM and the proposed models, it was shown that the proposed model is based on a more sound analytical approach than the one used in the HCM model. For example, the HCM model defines the queue service time as the bottom length of the QAP, which indicates the time required to clear the queue, and considers all RTOR vehicles as a through lane group. The proposed model defines the queue service time as the green time affected by queued vehicles and excludes the RTOR vehicles from the lane group volume.
(2) In comparison with simulation results, the proposed model provides with better estimation of the average phase lengths than the HCM model does.

The recommendations are listed below:
(1) It is recommended to improve shared permitted left-turn parameter estimation models to reduce the overestimation tendency of the average green time when shared permitted left turns are involved.
(2) Signal control parameters were fixed in the test while other conditions were varied. It would be interesting to test the changing trend of average green time by changing such control parameter as maximum green time.
(3) It is desirable to test the performance of the proposed model based on the field data. Although collecting traffic volume and average green time data at the same time is not an easy task, it would be meaningful to test the performance of the proposed model with the real-world data.

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