USDOT Region V Regional University Transportation Center Final Report

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Estimation of Time-Dependent Intersection Turning Proportions for Adaptive Traffic Signal Control under Limited Link Traffic Counts from Heterogeneous Sensors

By

Han-Tsung Liou
Postdoc Researcher
Institute of Statistical Science
Academia Sinica, Taipei, Taiwan
iroya.liou@gmail.com

and

Shou-Ren Hu
Professor
Department of Transportation and Communication Management Science
National Cheng Kung University, Tainan, Taiwan
shouren@mail.ncku.edu.tw

and

Srinivas Peeta
Professor
School of Civil Engineering, Purdue University
peeta@purdue.edu

DISCLAIMER

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TECHNICAL SUMMARY

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Title:

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Introduction (Problem Statement and Approach)

To improve traffic safety and efficiency of urban intersections, a traffic signal control system is one of the essential components of urban traffic management systems. Theoretically, an adaptive traffic signal control (ATSC) logic is superior to a pre-time or an actuated traffic signal control logic, because it can instantly respond to traffic dynamics to provide the respective signal control strategies by on-line algorithmic computations of desirable timing plans in order to reduce travel delays and/or queue lengths. In practical applications, implementation of an ATSC system requires three components: 1) a comprehensive detective infrastructure for traffic data collection, 2) traffic flow models for on-line estimating/predicting traffic flow dynamics and/or propagations, and 3) signal control logics and/or models to determine the optimal signal timing plans. Past studies have developed various ATSC systems for field applications. These ATSC systems can be classified into two categories (Stevanovic, 2010). The first category of the systems develops traffic flow prediction models for the on-line determination of optimal cycles, splits, and offsets, and its control logic is based on a cyclical signal timing principle. These systems include: Split, Cycle, and Offset Optimisation Technique (SCOOT), Sydney Coordinated Adaptive Traffic System (SCATS), Adaptive Control Software Lite (ACS-Lite), Balancing Adaptive Network Control method (BALANCE), Method For The Optimisation Of Traffic Signals In Online Controlled Networks (MOTION). The second category of the systems compares the performance of various competitive signal timing plans based on real-time vehicular information to determine green times or unit extensions, and its control logic has no fixed cycles and splits. These systems include: Optimized Policies for Adaptive Control (OPAC), Real-Time Hierarchical Optimized Distributed Effective System (RHODES), InSync, COMDYCS-3E. Most existing ATSC systems require observed traffic link flows from densely installed sensors to capture dynamic vehicular evolutions, and some of them assume fixed intersection turning proportions, which is not realistic from a practical application's perspective. To resolve these problems, this study solves the intersection turning proportions estimation problem by a Nonlinear Least Squares (NLS) model by taking advantage of heterogeneous sensor information in terms of partial link flow counts via vehicle detectors (VDs) and turning flow observations by license plate recognition (LPR) sensors. In addition, this study also seeks to address the optimal heterogeneous sensor deployment problem that maximizes traffic observability at urban intersections for a robust ATSC system. Finally, this study proposes an integrated ATSC system by incorporating traffic flow estimation and prediction using limited traffic information provided by different types of traffic sensors. The proposed ATSC logic is developed based on the COMDYCS-3E framework (Wu and Ho, 2009) which enhances its traffic flow estimation module and incorporates the sensor location model into the data input module. The enhanced COMDYCS-3E ATSC model is capable of providing desirable signal timing plans by on-line responding to traffic flow dynamics and/or vehicular traffic demands.

The remainder of this report is organized as follows. Section II describes the methodologies for the modern ATSC problem, including heterogeneous sensors deployment model, intersection turning proportions estimation and flow propagation models, and the integrated ATSC model. Section III provides the findings of the numerical analysis. Finally, summary and recommendations are respectively given in Section IV and Section V.

Methodology

This study proposes an integrated ATSC system by incorporating traffic flow estimation and prediction using limited traffic information provided by different types of traffic sensors. The model formulation in the integrated ATSC system includes three components. The first component is the sensor location model aiming to determine the optimal number and locations of the deployed heterogeneous traffic sensors. The second component is the traffic flow estimation and prediction model for both time-varying intersection turning proportions and traffic flow evolutions along an urban arterial. Flow propagations between upstream and downstream links (network) are modeled using the Mass Balance Equation (MBE) (Davis and Lan, 1995), and flow propagation along an urban arterial (a single link) is captured using the Cell Transmission Model (CTM) (Daganzo, 1995). The third component is the ATSC logic for the determination of an optimal signal control policy. The proposed ATSC logic is developed based on the COMDYCS-3E framework (Wu and Ho, 2009) which enhances its traffic flow estimation module and incorporates the sensor location model into the data input module. The following subsections briefly describe the respective modeling components.

A. Heterogeneous Sensors Deployment Model

This study adopts the heterogeneous sensors deployment model proposed by Hu et al. (2016) for the determination of the heterogeneous sensor deployment strategy. The model is formulated as an integer program to determine the numbers of LPRs and VDs and their installation locations to maximize the available traffic information subject to constraints on the available budget, network topology, and set covering rules. The developed heterogeneous sensors deployment model takes advantage of link flow information (provided by both types of sensors) as well as path trajectory/coverage information (provided by LPRs). Detailed contents of this model can be found in Hu et al. (2016).

B. Turning Proportions and Traffic Flow Estimation Models

For an intersection proportions estimation model, it requires that vehicular propagations information between each link. For an intersection, this study utilizes the MBE (Davis and Lan, 1995) to represent flow propagations between upstream and downstream links.

For the flow propagation estimation and/or prediction along an urban arterial (link), this study applies the CTM model to describe vehicular movements, and link flows can be the aggregation of flows at each cell in a link. When a link is divided into a specific number of cells according to the CTM model, and the CTM is applied to describe flow propagations between upstream and downstream cells of a link, the MBE can be expressed in Eq. (1).

$$x_k(t+1) = \{1 - p_k[x(t)]\} \cdot x_k(t) + \sum_j x_j(t) \cdot p_j[x(t)] \cdot b_{jk}(t) + \sum_i o_{ik} \cdot f_i(t) \tag{1}$$

where,

$\boldsymbol{f_i(t)}$: flow in the *i*-th boundary at time interval *t*;

$\boldsymbol{x_k(t)}$: flow in the *k*-th link at time interval *t*;

$\boldsymbol{b_{jk}(t)}$: turning proportion from the *j*-th link to the *k*-th link at time interval *t*;

$\boldsymbol{p_k[x(t)]}$: physically exiting flow probability of the *k*-th link at time interval *t*;

$\boldsymbol{o_{ik}}$: 1, the *k*-th link is at the *o*-th boundary and 0 otherwise.

Eq. (1) indicates that the flow in the *k*th link at the time interval (*t*+1) is equal to the output flow that has not left the *k*-th link during time *t* plus the flows in the available upstream links during the time interval *t*. In addition, if the *k*-th link connects to the *i*-th boundary, it needs to incorporate auxiliary boundary flows. In Eq. (1), the observations are $f_i(t)$ and $x_k(t)$, and $b_{jk}(t)$ is estimated by the observations. $p_k[x(t)]$ is the percentage of the *k*-th link flow leaving link *k* at time interval *t*. This study uses the CTM to estimate $p_k[x(t)]$ at each time interval.

Under the MBE formulation, the flow on a specific downstream link at each time interval can be estimated by the links equipped with traffic sensors:

$$\hat{s}_k(t) = \sum_j x_j(t) \cdot \hat{b}_{jk}(t) \tag{2}$$

where,

$\hat{s}_k(t)$: the estimated flow in the *k*-th link;

$\hat{b}_{jk}(t)$: the estimated turning proportion from the *j*-th link to the *k*-th link at time interval *t*.

Eq. (2) indicates that flows in the *k*-th link are equal to the summation of the flows in the upstream links multiplying the corresponding turning proportions. This research will develop the turning proportions estimation model to compare the estimated link flow obtained in Eq. (2) to the observed link flows to solve the intersection turning proportions under an error minimization criterion.

For the turning proportions estimation model, a nonlinear least squares (NLS) formulation is proposed by incorporating link flow information and turning flow information into an integrated model framework. The NLS-based model for turning proportions is formulated based on the information minimization (IM) method, and its aim is to minimize the difference between traffic flow observations and their estimates. In the turning proportions estimation model, link flow and turning proportions information are the input data. Link traffic flow data are collected from VDs and turning proportions information is partially obtained from LPR sensors. The intersection turning proportions estimation model is formulated as an NLS-based mathematical optimization program as follows.

$$\text{Min} \sum_k [\hat{s}_k(t) - s_k(t)]^2 + \sum_{j,k} [\hat{b}_{jk}(t) - b_{jk}(t)]^2 \tag{3}$$

s.t.

$$0 \le \hat{b}_{jk}(t) \le 1 \tag{4}$$

$$\sum_k \hat{b}_{jk}(t) = 1 \tag{5}$$

$$\hat{s}_k(t) \ge 0 \tag{6}$$

where,

$s_k(t)$: the observed link flow in the *k*-th link at time interval *t*;

$b_{jk}(t)$: the observed turning proportion of the *j*-th link passing through the *k*-th link at time *t* given by an LPR sensor.

Eq. (3) is the objective function of the NLS formulation, which aims to minimize two error terms. The first one is to minimize the difference between the observed and estimated link flows, and the second term is to minimize the difference between the observed and estimated turning proportions. In this study, observed turning proportion information is incorporated into the objective function, instead of in the constraint. Because the observed turning information is captured by video-based sensors, it might contain an error in the recognition. If this information is incorporated into the constraint, it could perturb the performance of the model. Eq. (4) is the upper bound and lower bound of a turning proportion. Eq. (5) means that for a specific direction, the summation of the corresponding turn probability is equal to one. Eq. (6) is the nonnegative constraint for estimated link flow.

C. Enhanced COMDYCS-3E Model

This study proposes a robust adaptive traffic signal control (ATSC) model by incorporating intersection turning proportion estimates and traffic flow predictions using partially collected heterogeneous sensor information. The proposed ATSC model is capable of dynamically determining desirable signal timing plans in terms of cycle time, green split, and offset, etc. Using the estimate a set of time-varying intersection turning proportions and traffic flow propagations along an urban arterial, this study develops an integrated ATSC logic for the determination of an optimal signal timing plan.

The proposed ATSC logic is to revise the ATSC system of the COMDYCS-3E (Wu and Ho, 2009) by incorporating the sensor deployment model, the CTM for traffic propagations, the MBE, and turning proportions estimation model. The COMDYCS-3E is an ATSC system developed in Taiwan for an arterial network. The main components of the COMDYCS-3E include initial setup and the traffic signal control logic, described below.

The initial setup for the COMDYCS-3E is as following.

(1) The time interval (Δt) for a decision-making is 2 seconds.
(2) The clearance time is 5 seconds, 2 seconds for the all-red interval, and 3 seconds for the yellow interval. It also assumes that vehicles can be discharged during the yellow interval.
(3) The time for each green interval is estimated by Eqs. (7) and (8).

$$\text{Max } G=(G_{\min}, \sum_{i=1}^{L_{\max}} d_i) \quad (7)$$

$$L_{\max} = \text{Max}(L_a, L_b) \quad (8)$$

where,

$\boldsymbol{d_i}$: discharged headway of the *i*-th vehicle;

$\sum_{i=1}^{L_{\max}} \boldsymbol{d_i}$: time required to discharge the maximal queue length at the current green interval;

G: the green time;

G_{min}: the minimal green time;
L_a: the queue length in the *a*-th direction during the current green interval;
L_b: the queue length in the *b*-th direction during the current green interval;
L_{max}: the maximal queue length during the current green interval.

(4) The delay time is determined by the travel delay time estimation approach, and it can be formulated as Eq. (9).

$$TD(Time\ Delay) = Act.\ Dep(t) - Exp.\ Avl(t) \quad (9)$$

where,

Act. Dep(t): the time instant that a vehicle(s) really depart from a stop line;
Exp. Avl(t): the time instant that a vehicle(s) arrives at a stop line under a free-flow speed condition.

The ATSC logic in the COMDYCS-3E is based on the six-hierarchy decision process for the determination of a set of optimal traffic signal control strategies, and the main objective is to reduce system delay times and queue lengths. The six hierarchies for the optimal signal control strategy in the COMDYCS-3E are illustrated as follows.

(1) The first hierarchy: minimal green time criterion.

If the green time of the current phase is not greater than the default minimal green time, the current green time is extended by Δt seconds.

(2) The second hierarchy: maximal green time criterion.

If the green time reaches the default maximal green time, the green time will be terminated in the next Δt seconds.

(3) The third hierarchy: zero queue length criterion.

It the queue length is zero at the current phase, the green time will be terminated in the next Δt seconds.

(4) The fourth hierarchy: queue length criterion for the extended green time.

Suppose the total vehicular queue length without extending the current green time is the performance measure of the "basic" ATSC strategy. The *k*-th ATSC strategy is defined by extending the green time of the current phase by an additional ($k \times \Delta t$) seconds. Compare all the ATSC strategies (i.e., the first, second, third, …, the *k*-th, the (*k*+1)-th, …, the *K*-th, where the *K*-th extended green reaches the maximal green time) to the “basic” ATSC strategy in terms of the queue length performance measure. If the *k*-th ATSC strategy is the best among the compared alternatives, then add ($k \times \Delta t$) seconds to the green time, and terminate the current phase in the next Δt seconds. The purpose of this hierarchy is to minimize the total queue lengths for a time horizon of flow predictions into the near future (usually for ten Δt s, i.e. 20 seconds).

(5) The fifth hierarchy: discharged flow criterion for the extended green time.

If the following conditions hold: 1) all the compared ATSC strategies are not better than the “basic” strategy in the fourth hierarchy, 2) the queue length performance measure of the *k*-th strategy is the same as that of the “basic” strategy, and 3) the performance of discharge flow by implementing the *k*-th ATSC strategy is better than the “basic” strategy, then add ($k \times \Delta t$) seconds to the green time, and terminate the current phase in the next Δt seconds. The purpose of this hierarchy is to provide the opportunity for vehicle progress in the arterial segment.

(6) The sixth hierarchy: less than three vehicles criterion.

If the queue length of the current phase is less than three vehicles, then add Δt seconds in the current green time; otherwise, terminate the green time. The aim of this hierarchy is to make sure that all the arrival vehicles of the current phase are served at the same phase.

The flowchart for the six-hierarchy ATSC decision process of the COMDYCS-3E is shown in Fig. 1.

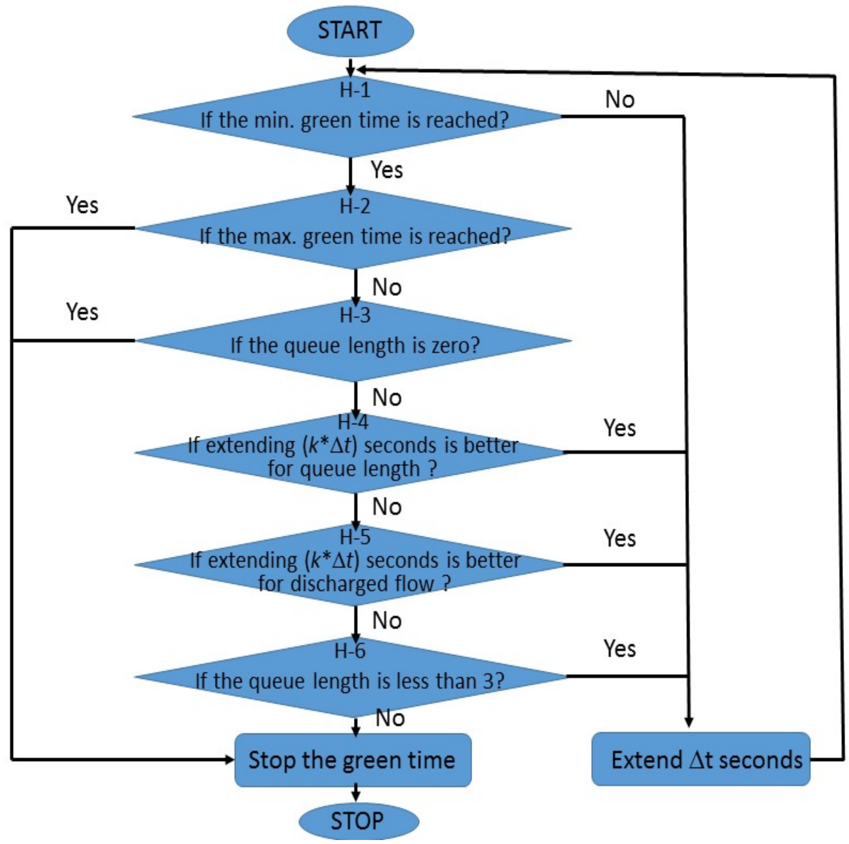


Fig. 1 Flowchart of the Six-Hierarchy ATSC Decision Process of the COMDYCS-3E System

Findings

In the numerical analysis, this study uses the signal control API built in the traffic simulation software, VISSIM (PTV GROUP), to implement the COMDYCS-3E signal control logic, the turning proportions estimation, and the CTM model. Based on the outputs of the VISSIM simulator, the performance of the proposed ATSC model is evaluated. The detailed empirical study is illustrated as following.

A. Experimental Design and Assumptions

One of the requirements of an effective ATSC system is to predict and process traffic flow evolutions in a short time duration. The assumptions and constraints of the proposed ATSC model include four parts: the simulated networks of VISSIM, the ATSC model, the CTM model, and the turning proportions estimation model. Details of the model settings and assumptions are given below.

For the experimental setup of the simulation experiments under the VISSIM platform, we have the following assumptions:

(1) All of the lanes in the simulated network are for the vehicle only. The vehicular movements are influenced by front vehicles and lane changing, and no perturbation caused by buses, motorcycles, bicycles, or pedestrians.

(2) There is no internal traffic demand in a simulated network. All vehicles are produced from boundaries and leave at the boundaries.

(3) The traffic composition is all passage cars, the average length is 5 meters, and the minimal lag is 0.75 meters.

(4) Average traffic speed is 50 km/hr.

(5) The car following behavior is simulated by the default setting in the VISSIM.

(6) Based on the design logic of the COMDYCS-3E, it assumes that a traffic sensor is located at 130 meters upstream of a stop line at an intersection.

(7) Traffic sensor can provide accurate traffic data, no missing data issue.

(8) The simulation time duration is one hour.

For the proposed ATSC model, we have the following assumptions:

(1) Δt is set to be 2 seconds.

(2) To conform to the requirement of Δt , all signal-timing parameters are a multiple of 2 seconds. The yellow interval is 2 seconds and the all-red interval is 2 seconds

(3) The minimal green time is 10 seconds, and the maximal green time is 120 seconds.

(4) To improve the efficiency in operating traffic signal controls, the phase for the left turn bay is not limited by minimal green times.

(5) The time duration for the performance prediction is 120 seconds.

For the CTM model, it includes the following assumptions:

(1) The length of a cell in each lane is 26 meters, and the maximal number of vehicles that flow into a cell is two vehicle/second.

(2) Each lane contains five cells.

(3) In each lane, the maximal number of vehicles that can be presented in a cell is four vehicles.

(4) In each lane, no more three vehicles are generated at every Δt by the VISSIM.

(5) The maximal queue length is 130 meters for each lane.

Finally, for the turning proportions estimation model, we have the following assumptions:

(1) The time interval, ΔT , for the turning proportions estimation model is 5 minutes

(2) The turning proportions are default values in the first 5 minutes. After the first 5 minutes, the turning proportions are estimated and updated at each time interval.

(3) To avoid the multiple solutions problem for the estimated turning proportions, it assumes that the turning proportions at a brunch road are greater than 50%, and the turning proportions at an arterial road are greater than 60%.

A local arterial system is selected to evaluate the proposed enhanced ATSC model. Based on field data collection in Wu and Ho (2009), this study adopts Section 3, Zhoughua Eastern Road, which located in the east district of Tainan city, Taiwan, as the experimental arterial system. The experimental arterial network contains three intersections, eight boundary nodes, 10 bi-directional links. In the arterial system, the main arterial link is the Section, 3 Zhoughua Eastern Road (Node 1-Node 2, Node 2-Node 3, Node 3-Node 4, Node 4-Node 5), the brunch links are Chongshad Road (Node 10-Node 4, Node 4-Node 10), Chongde Road (Node 8-Node 3, Node 3-Node 9), and Chongming Road (Node 6-Node, Node 2-Node 3). The network characteristics for each of the arterial links are that the length is 1200 meters, each link has two lanes, and a left turn bay is located in the upstream 50 meters of an intersection. The network characteristics for each branch link are that the length is 400 meters, each link has one lane, and a left turn bay is also located in the upstream 50 meters of an intersection. The arterial network configuration is shown in Fig. 2.

Fig. 2 Test Arterial Network (Zhoughua Eastern Road, Tainan City, Taiwan)

In this arterial network, this study assumes that the default (real) turning proportions will be changed at every 10 minutes in the VISSUM, and the default turning proportion information is illustrated in the Table. 1.

Table 1. Default Turning Proportions

Simulation time (sec)	1-600	601-1200	1201-1800	1801-2400	2401-3000	3001-3600
Straight	70%	60%	75%	80%	70%	75%
Right Turn	20%	15%	15%	10%	20%	10%
Left Turn	10%	25%	10%	10%	10%	15%

This research uses root mean squares error (RMSE) as the evaluation criterion to evaluate the performance of the estimated turning proportions.

B. Performance of the Turning Proportions Estimation Model

For the intersection turning proportions estimation problem, this study designs three scenarios based on different constraints to explore the performance of the MBE (Davis and Lan, 1995). The results of the turning proportions estimation for the ATSC system are shown in Table 2.

Scenario 1: original constraints

The estimated turning proportions are calculated by Eqs. (3) through (6). In this scenario, it may cause that left and right turning proportions at the arterial directions are overestimated, and straight proportions at the branch directions are underestimated. Estimated straight proportions at the branch directions are lower than 30%, and it is significantly different from the true vehicular movements, resulting in the high errors of the estimated turning proportions. Based on the original constraints in the turning proportions estimation model, the RMSE is 0.38.

Scenario 2: the straight proportion at branch direction is greater 50%

When the straight proportion at the branch direction is constrained to be greater than 50%, the RMSE is reduced from 0.38 to 0.14. In this scenario, straight proportions at the arterial directions are still underestimated.

Scenario 3: the straight proportion at arterial direction is greater 60%

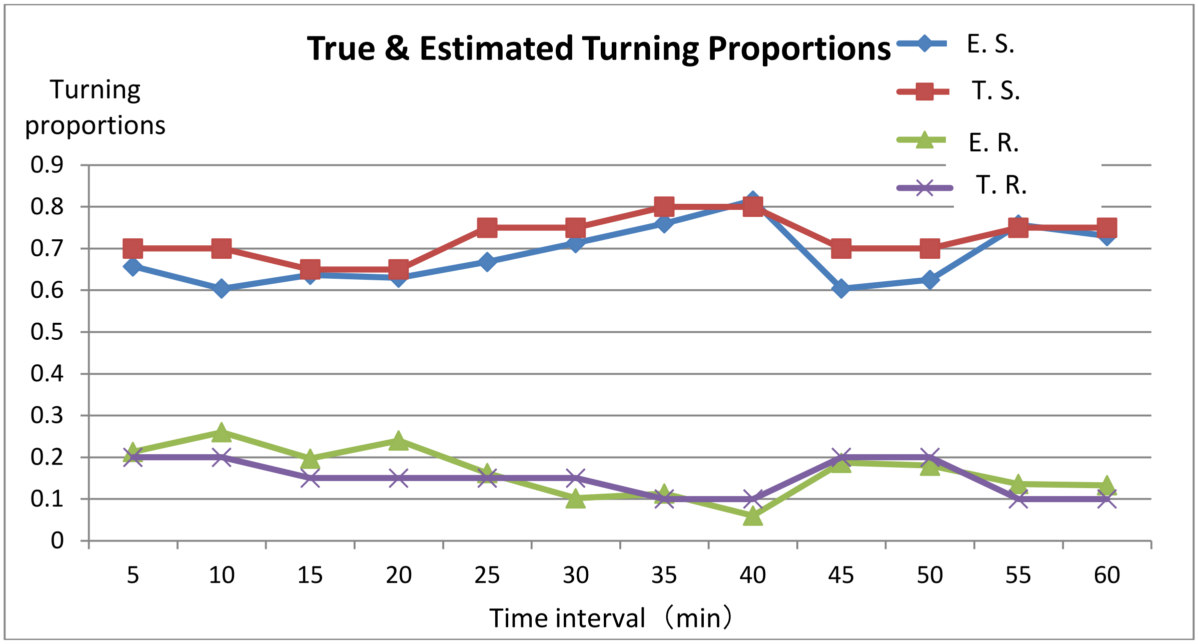
When the straight proportion at arterial direction is greater 60%, it can obviously improve the estimated turning proportions. The RMSE is reduced to 0.07

The time-dependent intersection turning proportions estimation results are shown in Fig. 3.

Table 2. Performance of the Turning Proportions Estimation Model

Scenario # (constraint)	Scenario 1	Scenario 2	Scenario 3
1. (The summation of total turning proportions is 1)	O*	O	O
2. (The lower bound for straight proportion at brunch direction is greater than 50%)	N/A**	50%	50%
3. (The lower bound for straight proportion at arterial direction is greater than 60%)	N/A	N/A	60%
RMSE	0.38	0.14	0.07

Note: *: the condition is satisfied；**: the condition does not exist



Note: E. S.: estimated proportions for straight direction;
T. S.: true proportions for straight direction;
E. R.: estimated proportions for right turning;
T. R.: true proportions for right turning.

Fig. 3 Performance of the Turning Proportions Estimation Model

C. Performance of the Integrated ATSC model

Based on the surveyed link flow and turning proportions data from Wu and Ho (2009), this subsection evaluates the performance of the integrated ATSC model. The evaluation is conducted by comparing the average vehicle delays of the enhanced COMDYCS-3E logic and those given by the fixed-time and full-actuated signal controls generated from the SYNCHRO. In the numerical analysis, three demand levels are hypothetically given, and three scenarios for the turning proportions are assumed, which are the same as the setup in the previous subsection. The results for the high demand level are shown in Table 3. In the high traffic demand case, the integrated ATSC model improves 5.4% of the average vehicle delay compared with the fixed-time signal control, and there is no significant difference between the proposed ATSC model and actuated control in terms of the average vehicle delays. For the medium level of traffic demand case, the comparison for the different traffic signal controls is shown in Table 4. As shown in Table 4, the integrated ATSC model is superior to the fixed-time control in terms of 8% to 19.2% reduction in the average vehicle delay. The enhanced COMDYCS-3E signal control logic also outperforms the actuated control logic by reducing an average of 3% of the vehicle delays.

Table 3. Comparison of Different Control Logics at the High Demand Level

Scenario	Flow rate (vehicle/per hour) Southern	Northern	Eastern	Western	Average vehicle delay (second/vehicle) Fixed-time control	Actuated control	Adaptive control	Improvement*
1	1421	1134	523	751				
2	1286	937	664	712	131.28	199.44	124.16	5.4%
3	1242	1164	456	601				

Note: *: improvement by the proposed ATSC model is calculated by comparing to the performance of a fixed-time control logic.

Table 4. Comparison of Different Control Logics at the Medium Demand Level

Scenario	Flow rate (vehicle/per hour) Southern	Northern	Eastern	Western	Average vehicle delay (second/vehicle) Fixed-time control	Actuated control	Adaptive control	Improvement*
1	1000	1000	300	300	48.20	44.73	44.36	8.0%
2	600	600	400	400	45.27	37.85	36.58	19.2%
3	500	500	100	100	32.79	28.48	28.02	15.5%

Note: *: improvement by the proposed ATSC model is calculated by comparing to the performance of a fixed-time control logic.

Under the high traffic demand condition, the ATSC model only decreased about 5% delay time due to the limitation of the CTM model. The CTM model is not able to effectively describe vehicle decelerations when they are approaching to an intersection. Later studies can improve this problem by incorporating more suitable traffic flow models for traffic evolutions along a signalized arterial for adaptive signal control purposes.

Summary

The proposed Enhanced COMDYCS-3E model for ATSC was evaluated using simulation experiments. The numerical analysis was implemented using the signal control API built in the VISSIM traffic simulator (PTV GROUP). The following summarizes the key findings of this study.

- The applied MBE provides accurate intersection turning proportion estimates with the RMSEs of 0.07~0.38 under three different test scenarios.

- In a medium demand level, the proposed ATSC model performs better than the fixed-time control in terms of 8% to 19.2 % reduction in the average vehicle delay, and it decreases 3% vehicle delay compared to that of the actuated control.
- In a high traffic demand level, the integrated ATSC model improves 5.4% of vehicle delay compared to that of the fixed-time signal control, but performs similarly to the actuated traffic signal control. This is due to the limitation of the CTM model, which is not able to effectively capture vehicle deceleration behaviors when they are approaching to a signalized intersection.

Recommendations

Based on the results found in the numerical analysis and summary of this study, two potential future research directions are described as follows.

- In view of the mixed traffic conditions in the urban areas of Asian countries, the proposed model framework can be evaluated in cities/countries with mixed traffic flow characteristics.
- As revealed in the numerical analysis, the applied CTM model cannot effectively capture vehicle deceleration behaviors when approaching a signalized intersection. Future studies may seek appropriate traffic flow models for a desirable ATSC logic and/or system.

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Contacts

For more information:

Dr. Srinivas Peeta
Purdue University - Discovery Park
3000 Kent Ave.
West Lafayette, IN 47906
(765) 496-9724
Fax Number
peeta@purdue.edu
www.purdue.edu/dp/nextrans

Dr. Shou-Ren Hu
National Cheng Kung University
1, University Road, Tainan City, 70101, Taiwan
+886-6-2757575 ext. 53203
+886-6-2753882
shouren@mail.ncku.edu.tw
www.tcm.ncku.edu.tw

NEXTRANS Center
Purdue University - Discovery Park
3000 Kent Ave.
West Lafayette, IN 47906

nextrans@purdue.edu
(765) 496-9724
www.purdue.edu/dp/nextrans