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On-line Traffic Signal Control Scheme with Real-time Delay Estimation Technology

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Abstract: This paper presents an on-line signal control scheme integrated with the real-time intersection delay estimation technology. The primary goal of this study is to design a complementary optimization module to the existing controller to minimize the total delay experienced by traffic and improve the system performance at the signalized intersections. This paper proposes a feedback control algorithm that optimizes the signal timing plan based on delay estimated via vehicle re-identification technology. Main thrust of the algorithm is on-line control capability utilizing direct delay measures. A description of overall signal control system architecture and optimization algorithm is given in this paper. Extensive simulation experiments are preformed with a high-performance microscopic traffic simulation program, Paramics, and the preliminary results have proved the promising properties of our proposed system.

Key Words: vehicle re-identification, intersection delay estimation, traffic-responsive signal control, signal plan optimization

1. INTRODUCTION

A traffic control system seeks to minimize the delay experienced by vehicle traveling through a road network of intersections by manipulating the traffic signal plans. There are various levels of sophistication in traffic signal control system. Basically, modes of operation can be divided into three primary categories (USDOT, 1996): pre-timed, actuated and traffic responsive. Under pre-timed operation, the master controller sets signal phases and the cycle length based on predetermined rates. These predetermined rates are determined from historical data. Common practice to develop pre-timed signal plans utilizes offline tools such as TRANSYT, which are based on traffic flows and queues observed from field data collection (McShane, 1997). The pre-timed control frequently resulted in the inefficient usage of intersection capacity because of the inability to adjust to variations in traffic flow and actual traffic demand. An actuated controller overcomes the problem of pre-timed controller by operating signals based on traffic demands as registered by the actuation of vehicle detectors. The green time for each approach can be varied between minimum and maximum lengths depending on flows. Cycle lengths and phases are adjusted at intervals set by vehicle actuation of loop detectors. The main feature of various actuated controllers is the ability to adjust the signal phase lengths in response to traffic flow, but attempt no optimization. In the traffic responsive mode, the signal timing plan responds to current traffic conditions measured by a detection system. The general traffic responsive strategies in use are either selection of a background signal timing plan based on detector data, or online computation of a background timing plan. The computation time interval may range from one cycle length to several minutes.

With recent advances in communication network, computer, and sensor technology, there are increasingly interests in the development of traffic responsive signal control system. Numerous systems have been proposed. The most notable of these are SCOOT (Hunt, 1982), developed in England, and SCATS (Lowrie, 1982), developed in Australia. Both SCOOT and SCATS are adaptive-cyclic systems, meaning that updates for the signal timing plan are performed at certain time interval. Other known methods under development over the last decade include PRODYN (Henry, 1989), UTOPIA (Mauro, 1990), OPAC (Gartner, 1990), etc. These systems attempt to

optimize traffic on-line without being confined to a cyclic time interval; signal time plan may change at any time step depending on the optimization algorithm. Compared with pre-timed signal control, these systems undeniably have improvements in terms of total time delay in the controlled network. The usual improvements amount to some 10% (Boillot, 1992).

Despite the encouraging development in adaptive signal control research in recent years and the added efficiency that has been achieved through the deployment of adaptive signal control, the prevailing lack of accurate prediction of traffic demands over the projected time horizon continues to impede the realization of substantial additional savings. Most prediction models rely on flow data from point detectors such as conventional inductance loops, which limits the ways that traffic variables may be estimated. Therefore, the above models can not be easily modified for feedback real-time control schemes based on observation of variables other than flow, except indirectly (through ad-hoc prediction of queue lengths without using link flow models, for instance).

The need for wide area traffic surveillance to capture traffic dynamics has led to the growing interest in advanced vehicle re-identification methods. In most countries, especially in the United States, California, several researches have been conducted for automatic vehicle re-identification system using the latest detector technologies. The surveillance technology applied in this study is capable of estimating real-time intersection delay that can be directly used for optimal signal control. Using loop detectors with the additional capability of producing vehicles waveforms that are essentially signatures to be re-identified at downstream stations, this technology has proven its capability to re-identify individual vehicles and to estimate real-time intersection delay.

The basis of this research work is the introduction of a pro-active traffic responsive signalization scheme by integrating traffic control with vehicle re-identification technologies. A real-time algorithm to optimize traffic signals for individual intersection in the traffic network will be presented. Unlike conventional signal control systems, the proposed method employs a real-time delay estimation technology and an on-line signal timing update algorithm. Intersection delay is estimated in real-time based on the vehicle re-identification using an algorithm that matches individual vehicle waveforms obtained from advanced inductive loop detectors. The delay estimated from the algorithm is fed into the routine to optimize the signal plan. Performance of the proposed method is evaluated via microscopic traffic simulation experiments.

2. OVERVIEW OF VEHICLE RE-IDENTIFICATION TECHNOLOGY

2.1 Vehicle Re-identification

Detector technology has been enhanced to the degree where vehicle signature can be obtained by using advanced ILD (Inductive Loop Detector) cards. A vehicle loop signature actually represents a change in inductance in the electric current of the loop detector due to the magnetic material present in a vehicle. Different vehicle generates different vehicle signature, and this represents the main idea of the vehicle re-identification algorithm. By exploiting useful feature vectors from this vehicle

signature, vehicles can be re-identified from different stations. Figure 1 and Figure 2 show a passenger car signature and a truck signature, respectively.

The Current vehicle re-identification algorithm developed at California ATMIS testbed at University of California, Irvine is a lexicographical, sequential, multi-objective optimization method (Sun, 1999). This algorithm was tested in fully instrumented signalized intersection, in City of Irvine, California, USA. The study site is the intersection of Alton/Irvine Center Drive (ICD), an eight phase fully actuated intersection in which each approach has a set of double loops, referred to as approach loops. These loops are at 325 ~ 375 feet from the intersection, except for the eastbound Alton loops which are 800 feet from the intersection. Additionally there are sets of double loops right after the intersection, referred to as departure loops. This brings the total number of loops at the intersection to 48.

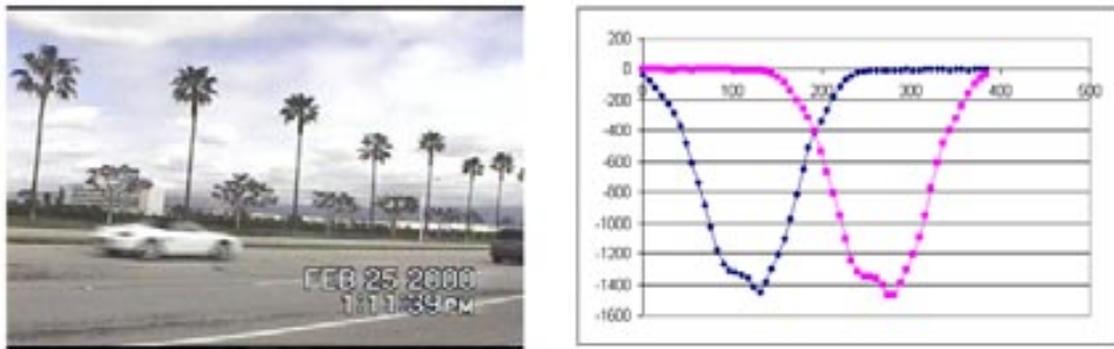


Figure 1. Sport Car Signature



Figure 2. Truck Signature

Vehicle signature data are collected in real-time and stored in the dedicated computer at Irvine Transportation Center (ITC). Those data can be accessed at Irvine Transportation Management Center via Local Area Network (LAN) and on-going Wide Area Network (WAN) construction will enable to get the data at University of California, Irvine Testbed. Because of current hardware limitations, vehicle signature data from one upstream and its corresponding three downstreams are collected in real-time. Figure 3 shows the Alton/ICD intersection and the existing network configuration. Unlike freeway case, the intersection flow is interrupted by signal control and this instability leads lower correct matching rate for the algorithm. In

intersection application, the vehicle re-identification technology was able to correctly identify more 40% of vehicles and provided average travel times with less than 15% of error.

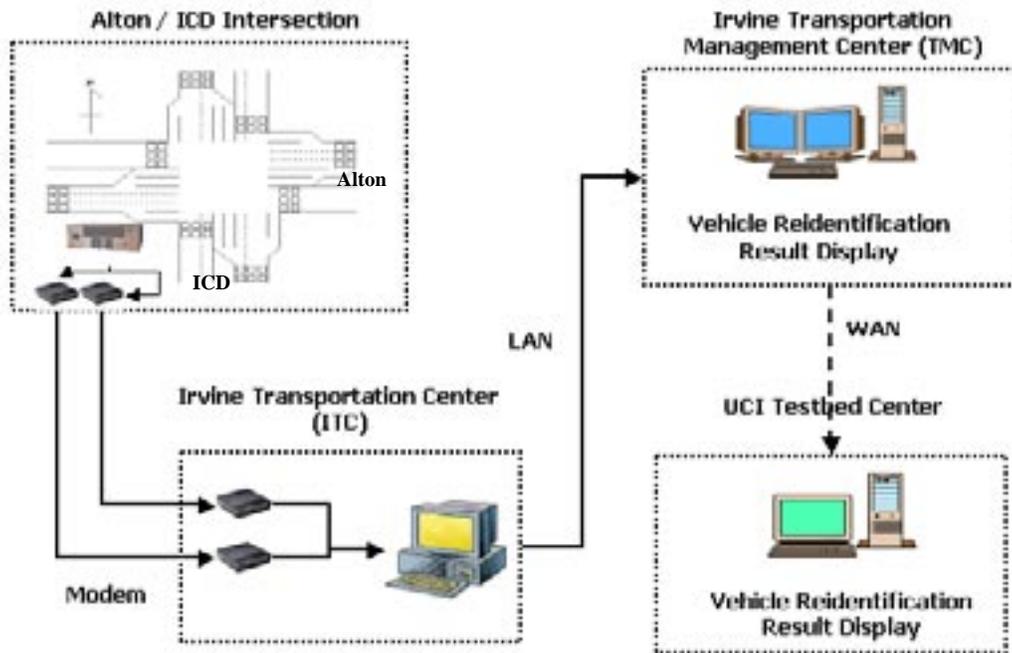


Figure 3. Alton / ICD Intersection and Network Configuration

2.2 Travel Time and Intersection Delay Estimation

Since vehicle travel delay is the main index for estimating intersection Level of Service (LOS), accuracy of the delay estimation directly affects the effectiveness of the signal control. The travel time for individual vehicle is referred to the time difference between detector hitting time of upstream and downstream station. Knowing the speed limit of this intersection, 55 mph and the detector distance between stations, minimum travel time for each movement can be derived. The delay of each vehicle is calculated by deducting the minimum travel time from vehicle's actual travel time. Since intersection flow is non-continuous one due to the signal control, the average travel time stability is highly correlated with the data aggregation method. A study (Oh, 2001) shows that cycle-based aggregation performs better in travel time aggregation than a moving average method. In this study, the vehicle re-identification algorithm estimates the average and total delay by movement every cycle, and these estimates are fed to the online signal control algorithm to find the optimal green split

3. FRAMEWORK OF FEEDBACK ADAPTIVE SIGNAL CONTROL

The adaptive signal control logic attempts to directly respond to real time demand variations from all intersections and allocates the green times on an "as needed" basis. Figure 4 presents the framework of the proposed adaptive signal control. The blocks above the dashed line are system blocks, in which signal parameters input to the controller to control the traffic light, and vehicle signatures will be captured through

vehicle re-identification algorithm. The blocks under the dashed line are online signal optimization module, which include the delay estimation from vehicle re-identification, and signal parameter optimization algorithm. This online signal optimization module works as complementary module to the existing signal controller, either pre-timed controller or vehicle actuated controller, by providing optimal signal timing parameters to adapt to time-variant traffic demands.

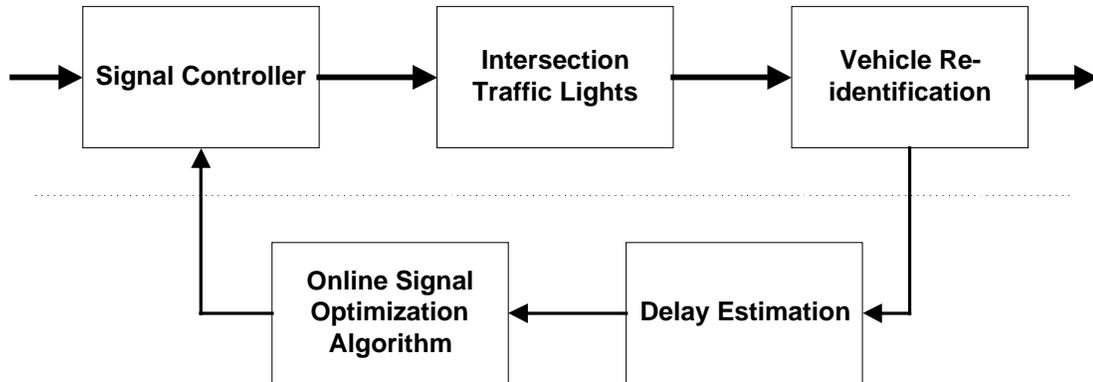


Figure 4. Framework of Feedback Adaptive Signal Control

A better understanding of the interaction between demand (i.e. vehicle arrivals) and supply (i.e. signal indications and types) at traffic signals is a prerequisite to the formulation of optimal signal control strategies. Performance estimation is based on assumptions regarding the characterization of the traffic arrival and service processes. Clearly, the delay estimation from vehicle re-identification well represents the current traffic demand. The proposed framework allows the optimization algorithm to take full advantage of this delay estimation, and provides the optimal signal timing over the projected time horizon. The optimization bears the responsibility to ensure the signal timing is consistent with control objective functions, in which both system optimal and user optimal are considered. The optimization algorithm will be presented in next section.

4. ONLINE SIGNAL CONTROL ALGORITHM

This section is to focus on presenting the local adaptive optimization module, including signal state description, delay estimation, mathematical formulation and computation procedures.

4.1 Signal State

A signal state at an intersection, denoted by the vector $(S(t))$, is defined by the following information: (1) the current green phase $(p(t))$, (2) the elapsed green time of current phase $(g(t))$, and (3) the vehicle delay by movements $(d(t) = [d^1, d^2, \dots, d^L])'$, here L is total number of movements in the intersection. So the signal state vector is represented by:

$$S(t) = \begin{bmatrix} p(t) \\ g(t) \\ d(t) \end{bmatrix}$$

4.2 Delay Projection

In many traffic control systems, the traffic-responsive control law should respond quickly and accurately to the deterministic data components. Because both the deterministic and random components appear together in delay projection, we use a projection equation to suppress the random components as follows:

$$d(t) = \alpha_1 \cdot d^r(t) + \alpha_2 \cdot d(t-1) + \alpha_3 \cdot d(t-2)$$

Where: $d(t)$ = filtered vehicle delay on all approaches

$d^r(t)$ = raw vehicle delay value from vehicle re-identification

$\alpha_1, \alpha_2, \alpha_3$ = filter coefficient in the range, and $\alpha_1 + \alpha_2 + \alpha_3 = 1$.

A signal timing plan for next time period is determined based on the projected delay. For the delay projection, filter coefficients need to be calibrated based on historical data. When α_1 equals to 1 ($\alpha_2 = \alpha_3 = 0$), the system relays on current estimation.

4.3 Control Objectives

The major considerations in the operation of an isolated intersection are: (1) Safe and orderly traffic movement, (2) Vehicle delay, and (3) Intersection capacity. Ideally, the objectives of minimizing total delay will: (1) maximize intersection capacity, and (2) reduce the potential for accident-producing conflicts. For each time step over a given time horizon, the main purpose of control is to minimize both the total vehicle travel delay and average vehicle delay for all movements during all signal stages at the target intersection. We seek a means to drive the user-equilibrium towards system equilibrium with improved performance, i.e. with reduced delay or reduced travel time. We conjecture that by weighting the opposing phases for each local intersection controller in some systematic manner. By introducing a weight in the calculation of delay when the controller seeks to compute an optimal signal plan.

Therefore, the objective functions are two folds, one is the system efficiency, which is represented by total vehicle delay on all approaches; and the other is the system fairness, which can be represented by the standard deviation of average delay on each movements. This multi-objective control function is to balance system optimal and user optimal, i.e. maximize the system throughput by minimizing total vehicle delay on all approaches, but taking average delay on each approach into consideration to avoid lengthy wait at light demand approach. Therefore, The multi-objective function is formulated as follows:

$$\text{System efficiency: } \min \sum_{k=k+1}^{k+N} \sum_{m=1}^M \sum_i D_i^m(k)$$

$$\text{System fairness: } \min \text{stdev}(\forall m, \sum_{k=k+1}^{k+N} \sum_i D_i^m(k))$$

Where:

$D_i^m(k)$: travel delay for vehicle i in movement m at each time step k

N: number of time steps in the projected time horizon

M: total number of movements

4.4 Feedback Optimal Control Model

4.4.1 Parameter Optimization for Vehicle-actuated Signal

In feedback control applications, the most widely used form for the control algorithm is proportional/integral/derivative (PID) controller. Applying PID controller in adaptive signal control, the equation is given below:

$$G(t) = G + K_c \left[e + \frac{1}{\tau_1} \int e dt + \tau_2 \frac{de}{dt} \right]$$

Where, $G(t)$: current signal parameter for projected time horizon

G : bias signal parameter, is assumed to be determined by some off-line analysis

and/or intuition about the historical traffic demand profile.

e : system output error, here is the difference of delay time

K_c, τ_1, τ_2 , control parameters

For actuated signal, the most important signal parameters are the minimal green time, the maximal green time and the unit extension time. The minimal green time is intended to provide sufficient time for all vehicles potentially stored between the detector and the stop line to enter the intersection. The unit extension time defines the maximum gap between vehicles arriving at the detector to retain a given green phase. And the maximal green is used to respond to demand variation during peak periods. At the light traffic demand, minimal green time and unit extension are more important than maximal green time, but it will be opposite at the high demand case. So these three parameters need to be optimized through feedback PID control.

4.4.2 Parameter Optimization for Fixed-timed Signal

There are three control variables in traffic signal control, such as cycle length, phase sequence, and phase split. The proposed algorithm can optimize both cycle length and phase split. While cycle lengths are derived from historical traffic data, phase splits are updated every cycle based on the projected delay. The optimal cycle length can be obtained from off-line optimization based on mid-term (say, 15 minutes) traffic data. The crucial part of the algorithm is optimizing phase split in real-time.

Given cycle length, we seek optimal green times for each movements. First, we determine split between approaches (E-W and N-S) based on critical movement delay. Then each green split is determined proportionally. Figure 5 illustrates the proportional green split model for fixed-timed signal.

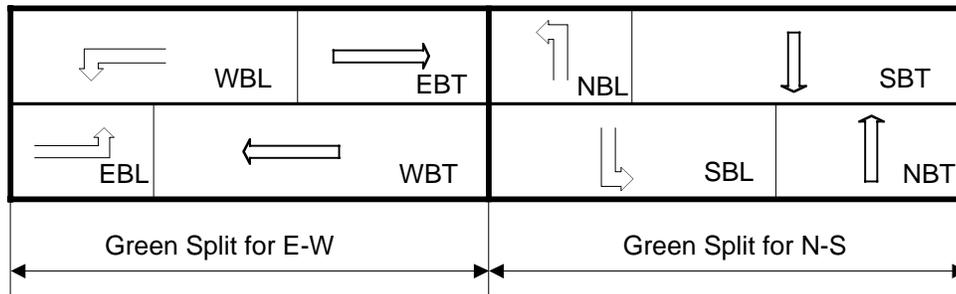


Figure 5. Proportional Green Split Model

5. A CASE STUDY

The proposed algorithm has been tested extensively with a high performance microscopic simulation, Paramics. This section shows performance of the proposed algorithm. In this experiment, we used on-line feedback control model for pre-timed signal controller. The model provides optimal green split every cycle based on the projected delay by movements. For the simple model implementation, we directly used estimated delay rather than projected one. In the experiment, total delay was used for the green time split.

We compared the model performance with fixed control and actuated control under different simulated traffic scenarios. The experiment showed that the on-line adaptive control provided more efficient control, especially at the high demand case.

5.1 Study Site and Data Preparation

The study site is the intersection of Alton/Irvine Center Drive (ICD) as described at section 2.1. The studied intersection was coded in Paramics for simulation. Traffic demand datasets were collected at two different time periods, from 12 to 2pm, which was the light demand case, and from 4 to 6pm, which was the high demand case. All the data collections were conducted at California ATMIS testbed at University of California, Irvine, through CCTV traffic monitoring system.

As the baseline study, optimal fixed timed signal plan was generated through SYNCHRO for each demand case and the parameters for actuated signal used in the real world were adopted in this study.

5.2 Paramics (PARAllel MICROscopic Simulation)

Paramics is a parallel, microscopic, scalable user programmable and computationally efficient traffic simulation model that has been used in many applications in the ATMIS Testbed (Duncan 1995). Individual vehicles are modeled in fine detail for the duration of their entire trip, providing comprehensive traffic characteristics and congestion information, as well as enabling the modeling of the interface between drivers and ITS facilities and strategies. Figure 6 shows Alton/ICD intersection in Paramics.

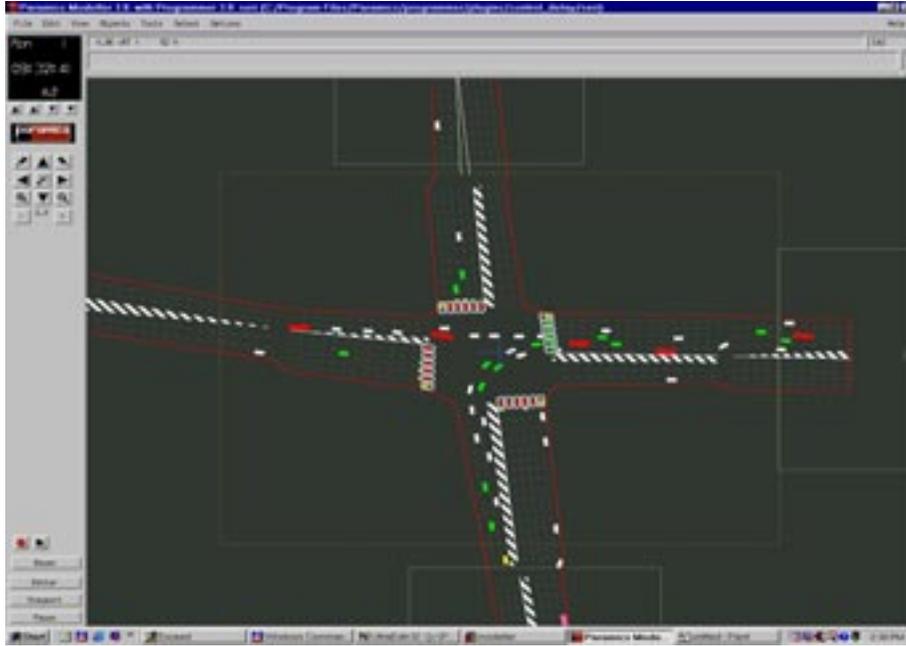


Figure 6. Alton/ICD Intersection in *Paramics*

Paramics provides a framework that allows the user to customize many features of underlying simulation model. Access is provided through a Functional Interface or Application Programming Interface (API). The capability to access and modify the underlying simulation model through API is essential for research. Such an API should have a dual role, first to allow researchers to override the simulator's default models, such as car following, lane changing, route choices for instance, and second, to allow them to interface complementary modules to the simulator. Complementary modules could be any ITS application, such as signal optimization, adaptive ramp metering, incident management and so on. In this way, new research ideas could be easily tested using simulator before the implementation in the real world.

All the signal control strategies used in this study, including the fixed-time signal controller, full-actuated signal controller, and online feedback signal control with intersection delay estimation, are coded in Paramics API.

5.3 Measure of Effectiveness (MOE)

Any new or modified traffic control system should satisfy a goal or set of goals. The goals here for the proposed online signal optimization algorithm is to minimize the vehicle delay, improve the intersection capacity and reduce traffic congestion. MOE provides a quantitative basis for determining the capacity of traffic control system and their strategies to attain the desired goals. For our purpose, the total time of vehicle delay appears to be the appropriate measurement for system efficiency; standard deviation of vehicle delay for different movements would be the one for system fairness; and intersection throughput is for system capacity. Section 4.3 shows details of the MOEs.

5.4. Simulation Results

Because the traffic pattern in the simulation is stochastic, a Monte Carlo simulation is used to obtain the estimates of system performance level. 30 simulation runs of 2

hours period for both high and low demand scenarios were conducted. Simulation results will be presented in the following.

The overall performance is summarized in Table 1. The simulation results show that the proposed adaptive algorithm is more efficient than the others at the high demand level. Compared with the other two control logics, adaptive control algorithm shows significant reductions of total vehicle delay, standard deviation of average vehicle delay from different movements, which indicate the improvement of system efficiency and system fairness. System throughput also increases greatly. However, the results also indicate that there is no performance improvement at the light demand case.

To further detail the performance improvement at high demand scenario, Figure 7 and 8 compare the results of three types of control logic based on the total vehicle delay for all movement at each time step and the cumulated delay over the 2 hour high traffic demand period. The results show the significant reduction of vehicle travel delay, which indicate the system efficiency improvement. Figure 9 and Table 2 compare the results of three types of signal control based on average vehicle delay for each movement (expressed in NEMA phase), and results indicate the system fairness improvement at high traffic demand.

Table 1. Comparison of Overall Performance

MOE		Effectiveness			Fairness
		Throughput (veh./hr)	Total delay (seconds)	Avg. delay (seconds)	Std.
High demand	Fixed Control	4426	324857.4	73.4	7.8244
	Actuated Control	4328	302898.8	69.9	9.6252
	On-line Control	4568	194895.8	42.7	1.5714
Low demand	Fixed Control	3064	103963.0	33.9	0.7322
	Actuated Control	3074	82245.1	26.8	0.5072
	On-line Control	3053	99599.1	32.6	0.7079

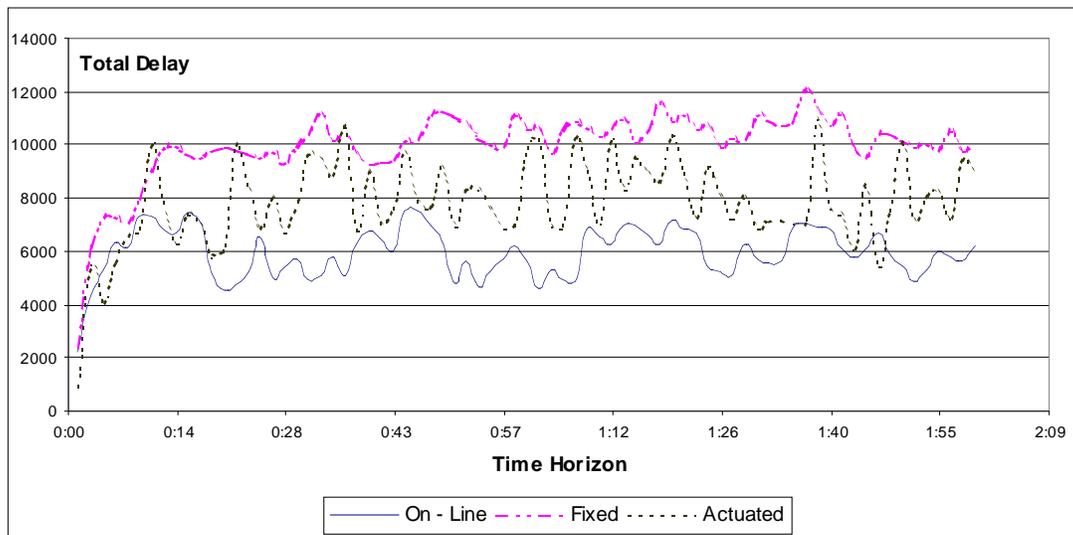


Figure 7. Comparison of Total Delay at Each Time Step (high demand case)

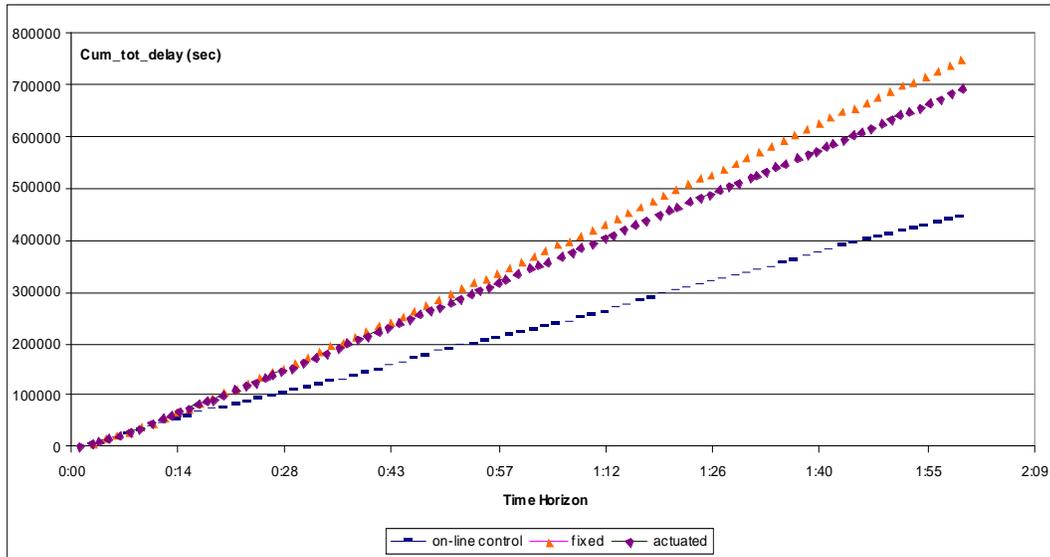


Figure 8. Comparison of Cumulated Total Delay (high demand case)

Table 2. Comparison of Average Delay and Average Green Time

NEMA Phase	Fixed Control			Actuated Control			On – Line Control		
	Avg. Delay (secs)	Avg. Green (secs)	Avg. Delay/Green	Avg. Delay (secs)	Avg. Green (secs)	Avg. Delay/Green	Avg. Delay (secs)	Avg. Green (secs)	Avg. Delay/Green
1	76.27	27	2.82	79.62	21.36	3.73	46.51	33.71	1.37
2	46.25	20	2.31	42.41	15.16	2.80	50.32	13.74	3.66
3	56.15	11	5.10	41.95	10.26	4.09	57.75	11.34	5.09
4	49.82	22	2.26	46.76	18.48	2.53	48.94	21.01	2.32
5	87.82	8	10.97	42.58	9.72	4.38	52.39	10.67	4.90
6	262.63	39	6.73	278.29	26.80	10.39	88.27	36.77	2.40
7	83.43	11	7.58	42.62	13.27	3.22	59.58	13.96	4.25
8	30.32	22	1.37	29.66	15.46	1.92	31.84	18.39	1.73
Overall	73.4	-	-	69.9	-	-	42.7	-	-

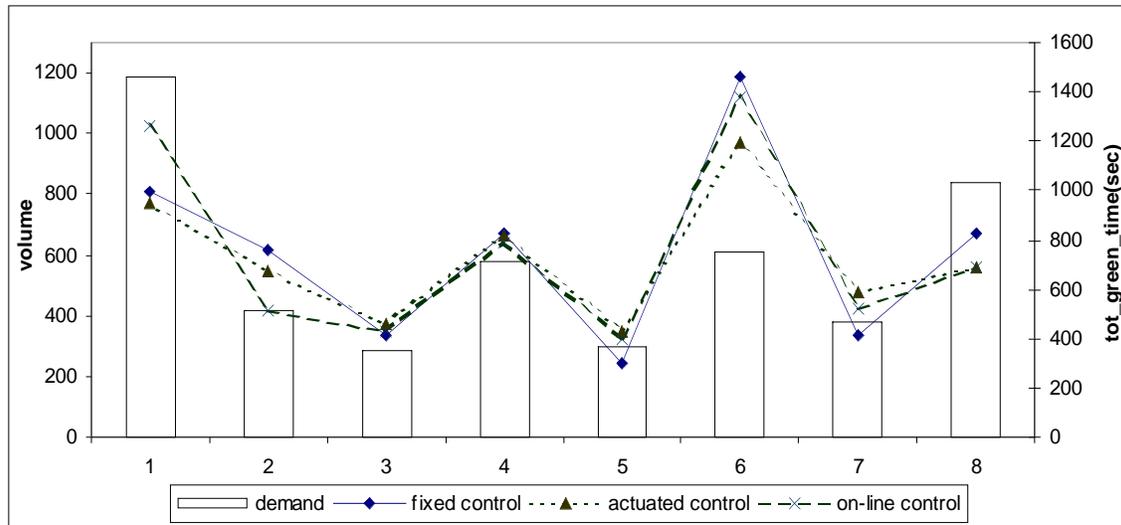


Figure 9. Comparison of Green Time Split by Movement

6. CONCLUSIONS AND FUTURE WORKS

This paper has dealt with the development of efficient techniques for the dynamic control of signalization in traffic networks in the context of Intelligent Transportation Systems. This online signal optimization module works as complementary module to the existing signal controller, either pre-timed controller or vehicle actuated controller, by providing optimal signal timing parameters. It comprises two elementary models: delay estimation model from vehicle re-identification, and on-line signal optimization model. We compared the proposed online feedback control model for pre-timed signal controller with fixed-time signal control and actuated signal control. The test results showed that the proposed adaptive control provided more efficient control, especially at the high demand case.

Note that the main purpose of this paper is to present an integrated adaptive signal control algorithm with vehicle re-identification technologies. Simulation experiment was conducted on a single intersection, rather than at the network level. A natural extension of local intersection signal control is to address coordination of intersections. Specifically, coordination of the proposed adaptive controller is sought in terms of maximizing the combined performance of all of the controllers.

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