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**ADAPTIVE SIGNAL CONTROL SYSTEM WITH ON-LINE PERFORMANCE
MEASURE FOR SINGLE INTERSECTION**

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Abstract:

This paper introduces an adaptive signal control system utilizing an on-line signal performance measure. Unlike conventional signal control systems, the proposed method employs real-time delay estimation and an on-line signal timing update algorithm. As a signal performance measure, intersection delay for each phase is measured in real-time via an advanced surveillance system that re-identifies individual vehicles both at upstream and downstream stations using vehicle waveforms obtained from advanced inductive loop detectors. In each cycle, the signal timing plan is optimized based on the delay estimated from the vehicle re-identification technology. The main thrust of the algorithm is the on-line control capability utilizing direct intersection delay measures. A description of the overall control system architecture and the optimization algorithm is addressed in this paper. Performance of the proposed system is evaluated with a high-performance microscopic traffic simulation program, Paramics, and the preliminary results have proven the promising properties of the proposed system.

Key Words: adaptive signal control; vehicle re-identification; intersection delay estimation; signal plan optimization

1. INTRODUCTION

A common function of a traffic control system is to seek to minimize the delay experienced by vehicles traveling through a road network of intersections by manipulating the traffic signal plans. There are various levels of sophistication in traffic signal control system applications. 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 such offline tools as TRANSYT, which are based on traffic flows and queues observed from field data collection (McShane, 1997). Pre-timed control frequently results in the inefficient usage of intersection capacity because of the inability to adjust to variations in traffic flow and actual traffic demand; this inefficiency is pronounced when flows are substantially below capacity. An actuated controller overcomes the problem of a 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 systematic 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 technologies, there is increasing interest in the development of traffic responsive signal control systems. 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, in that they update the signal time plan at pre-specified time intervals. Other known methods under development over the last decade include PROLYN (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; i.e., the signal time plan may change at any time step depending on the optimization algorithm. Compared to pre-timed signal control, these systems undeniably improve overall performance in terms of total 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 such point detectors as conventional inductance loops, which place severe limits on the estimation of traffic variables. Because of this feature, these models cannot be modified easily 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 example).

This paper introduces an adaptive signal control system utilizing an on-line signal performance measure. Unlike conventional signal control systems, the proposed method employs real-time delay estimation technology and an on-line signal timing update algorithm. Intersection delay is estimated in real-time based on vehicle re-identification using an algorithm that matches individual vehicle waveforms obtained from advanced inductive loop detectors. Such vehicle re-identification technology has proven its capability to re-identify individual vehicles (Sun *et al.*, 1999) and in estimating real-time intersection delay. In this approach, the signal timing plan is optimized each cycle based on the delay estimated from the vehicle re-identification technology.

This paper is outlined as follows. The next section provides a description of the overall architecture of the signal control scheme. Section 3 presents a delay estimation scheme based on vehicle re-identification technology. Section 4 shows how the signal timing plan is optimized using the estimated delay. Section 5 evaluates the performance of the proposed method via microscopic traffic simulation experiments. Finally, Section 6 presents conclusions and future research.

2. OVERALL SYSTEM ARCHITECTURE

This section provides the overall architecture of the proposed adaptive signal control system with on-line performance measure. The system consists of five components: 1) Surveillance System, 2) Vehicle Re-identification, 3) Delay Estimation and Projection, 4) Signal Timing Optimization, and 5) Traffic Signal Controller. Figure 1 presents overall framework of the proposed adaptive signal control and connectivity of these components. The blocks above the dashed line are system blocks, which represent the operational mechanism of traffic signal systems. The blocks below the dashed line are components of the online signal optimization module that include the delay estimation via vehicle re-identification and the signal parameter optimization.

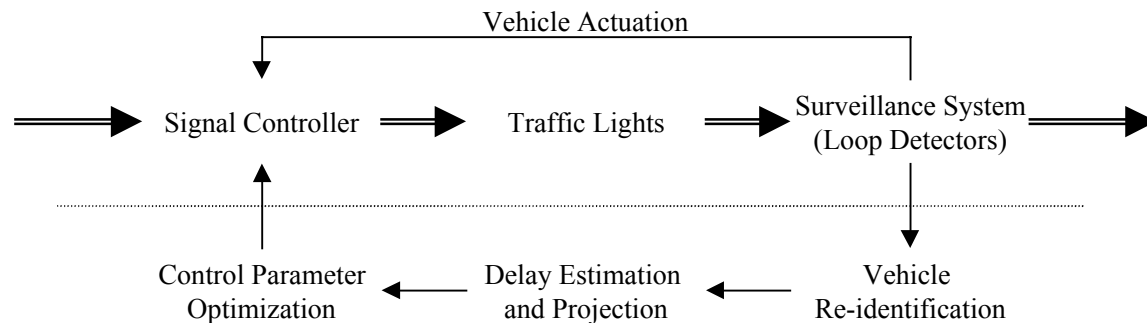


Figure 1. Overall Framework of Feedback Adaptive Signal Control

The main thrust of the proposed systems is to utilize a direct measure of delay for optimal 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. This online signal optimization module works as a complementary module to the existing signal controller (either pre-timed or vehicle-actuated controllers) by providing optimal signal timing parameters to adapt to time-variant traffic condition.

The formulation of optimal signal control strategies requires a rich representation of the interaction between demand (i.e., vehicle arrivals) and supply (i.e., signal indications and types) at the signalized intersection. Performance estimation itself is based on assumptions regarding the characterization of the traffic arrival and service processes. It is purported herein that the direct measure of delay from vehicle re-identification can be used effectively to represent 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. The procedure for delay estimation and signal timing optimization is presented in next two sections.

3. REAL-TIME INTERSECTION DELAY ESTIMATION

Inductive loop detectors have been used widely both for surveillance of traffic condition and for operation of control systems. Actuated signal control systems rely on actuation of loop detectors, and adaptive control systems use measurements from the loop detectors. In this study, the loop detectors are used not only for vehicle actuation but also for delay estimation.

Detection by loop detectors is represented by a change of inductance in electric current. More detailed waveforms can be obtained using advanced loop detector cards. The waveform produces an individual vehicle's signature that can be used for vehicle re-identification. Different types of vehicles produce correspondingly different waveforms (so-called vehicle signatures), as shown in Figure 2. Even though the same type of vehicle produces a similar form of signature, each vehicle generally has characteristics (such as number of passengers, luggage, speed, profile, etc.) that produce a locally unique signature due to differences in these characteristics. Using such characteristics, a vehicle can be re-identified from different detector stations; the time difference between the repeat signatures at two stations represents the vehicle's travel time.

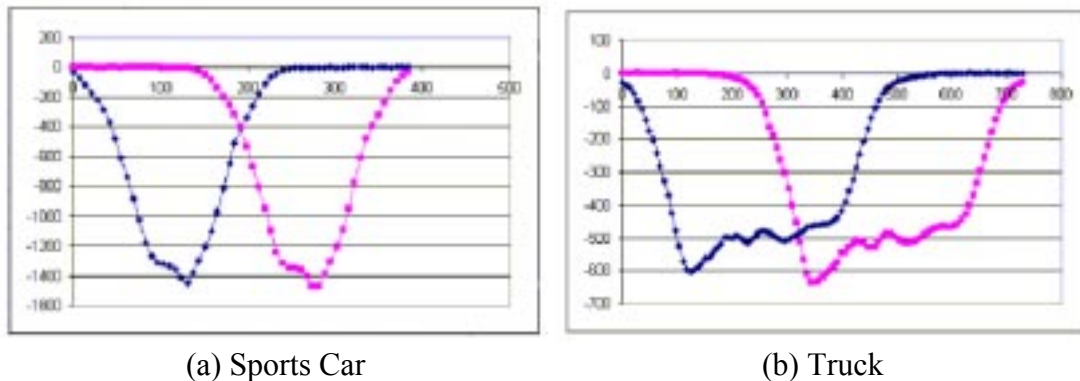


Figure 2. Typical Form of Vehicle Signature

This vehicle re-identification technology has been tested extensively at the California ATMIS Testbed at the University of California, Irvine. For vehicle signature matching, Sun *et al.* (1999) have developed a lexicographical, sequential, multi-objective optimization method. They also have shown successful performance of the loop-based vehicle re-identification on a

freeway section in California. The vehicle re-identification algorithm has also been applied at the Alton/ICD (Irvine Center Drive) intersection in the city of Irvine, California. The algorithm is currently being tested at a fully instrumented signalized intersection, using upstream and downstream advanced detector stations. According to preliminary results, the algorithm can correctly match more than 40% of vehicles passing through the intersection (throughs and turns), demonstrating its online capability of intersection delay estimation.

In this study, the vehicle re-identification algorithm is used to estimate the average and total delay by movement during each cycle, and these estimates are fed to the online signal control algorithm to find the optimal green splits. The travel time for each individual vehicle is referenced to the time difference between its identification at an upstream detector and its re-identification at one of the downstream detector stations. Knowing the prevailing free speed for the approaches, and the detector distance between stations, the 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. For each cycle, each movement's delay is estimated from the measured delays of re-identified vehicles.

Because both the deterministic and random components appear together in delay projection, we employ a projection equation to suppress oscillations due to the random components as follows:

$$d(t) = \alpha_1 \cdot d'(t) + \alpha_2 \cdot d(t-1) + \alpha_3 \cdot d(t-2) \quad (1)$$

where: $d(t)$ = filtered vehicle delay by movement

$d'(t)$ = raw vehicle delay value from vehicle re-identification

$\alpha_1, \alpha_2, \alpha_3$ = filter coefficients 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 relies on current estimation.

4. ONLINE SIGNAL CONTROL ALGORITHM

This section presents 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:

$$S(t) = \begin{bmatrix} p(t) \\ g(t) \\ d(t) \end{bmatrix} \quad (2)$$

4.2 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 utilization of intersection capacity, and (2) reduce the potential for accident-producing conflicts.

In this study, we consider two objectives: (1) minimization of total delay, and (2) fair treatment of each movement. The minimization of total delay, which allocates green time in favor of high demand movements, has been a well-accepted signal control objective. Such a strategy improves overall efficiency of the intersection; however, traffic from the minor approaches may suffer inordinate delay for the sake of overall system efficiency. This can result in a lengthy wait at light demand approaches. The second objective considers this fairness issue that can be caused when the system optimal strategy is applied. Based on these considerations, we adopt two-fold objective functions: the system efficiency, as represented by total vehicle delay on all approaches, and the system fairness, as represented by the standard deviation of average delay across each movement.

$$\text{System efficiency: } \min \sum_{k=1}^K \sum_{m=1}^M \sum_{n=1}^{N_m} D_n^m(k) \quad (3)$$

$$\text{System fairness: } \min \text{stdev} \left(\frac{\sum_{k=1}^K \sum_{n=1}^{N_m} D_n^m(k)}{N_m}, \forall m \right) \quad (4)$$

Where:

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

N_m : total number of vehicles in movement m during the time horizon

M : total number of movements

K : total number of time steps

These two objectives are conflicting in their nature. A multi-objective intersection signal control is adopted that is a compromise of these two objectives, balancing the system efficiency and fairness.

4.3 Parameter Optimization

There are three primary control variables in traffic signal control: 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 worth) traffic data. The crucial part of the algorithm is to adaptively seek the optimal phase split in real-time. In this paper, we consider two control policies in seeking the optimal green splits: (1) minimization of total delay, and (2) minimization of average delay. The total-delay-based on-line control is to maximize the efficiency of the system, but the fair treatment of each traffic movement is ignored. However, the average-delay-based on-line control tries to balance system efficiency and fairness in that it reduces the vehicle delays at one hand and keeps the system fair to each movement on the other, although it may gain less in terms of the system efficiency.

This adaptive control can be applied both to pre-timed signal control and actuated signal control. While the control parameter for pre-timed signal control is the green time allocated to each phase, control parameters for actuated control are initial green, minimum green, maximum green, gap, extension, etc. In the current study, for the on-line control under the actuated control system, only maximum green is used as a control variable to avoid complexity of the control problem. However, the procedures can be extended to other parameters without difficulty. The signal phase sequences follow the conventional NEMA (National Electrical Manufacturers Association) phase as in Figure 3. Numbers in the figure represents NEMA phase numbers.

In case of pre-timed control, given cycle length, we seek optimal green splits for each movement. First, we determine split between approaches (E-W and N-S) based on (total or average) delays on critical movements. Then each green split is determined proportionally. Figure 3 illustrates the proportional green split model for pre-timed signal. In this simple logic, more green time is allocated to the more congested phase.

For the actuated signal control, a similar method is applied for the maximum green allocation. Similarly, the maximum green of each phase is recalculated based on (total or average) movement delay and the background cycle length. Unlike the pre-timed case, the green time is affected by the gap and the unit extension time, so that the phase can be terminated earlier than the allocated maximum green, due to randomness in the traffic arrival pattern.

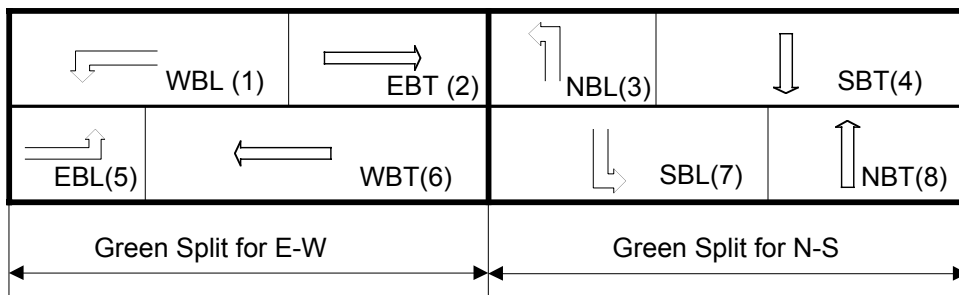


Figure 3. Proportional Green Split Model

The above method uses the current information for determining signal control in the next cycle. Although this simple method is used for the on-line adaptation of signal timing plan in this study, a more reliable system can also be designed by incorporating more complicated adaptive control logic. 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:

$$G(t) = G + K_c \left[e + \frac{1}{\tau_1} \int e dt + \tau_2 \frac{de}{dt} \right] \quad (5)$$

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

5. SIMULATION EXPERIMENTS

5.1 Simulation Scenario

This section compares the performance of the proposed systems via simulation experiments. The proposed system has been tested with Paramics, a high performance microscopic simulation. In this experiment, we used the on-line adaptive control model for both pre-timed signal controller and actuated signal controller. The model provides optimal green split every cycle based on the projected delay by movements. For the simple model implementation in this paper, we directly applied the estimated delay from the current cycle as the basis for determining the parameter settings for the subsequent cycle, rather than projecting one. In the experiment, two on-line control logics are applied for the green time update: total delay and average delay. A total of six cases is experimented and compared.

- 1) Pre-timed control (PTC)
- 2) On-line pre-timed control based on average delay (OPA)
- 3) On-line pre-timed control based on total delay (OPT)
- 4) Actuated control (AC)
- 5) On-line actuated control based on average delay (OAA)
- 6) On-line actuated control based on total delay (OAT)

The study site of the experiment is the intersection of Alton and Irvine Center Drive, Irvine, California, an eight phase fully actuated intersection where advanced detectors have been instrumented for a test of vehicle re-identification technology. Loop detectors are located at 325 ~ 375 feet upstream from the intersection, except for the eastbound Alton approach where detectors are located at 800 feet from the intersection. Traffic demand data were collected during p.m. peak hours from 4 to 6 p.m. The base signal timing plan for the pre-timed control was generated via SYNCHRO off-line signal timing optimization, and a set of field control parameters was adopted for the actuated signal control in this study.

5.2 Microscopic Simulation Model, Paramics (PARAllel MICROscopic Simulation)

Paramics is a parallel, microscopic, scalable user programmable and computationally efficient traffic simulation model (Duncan 1995) that has been used in many applications in the ATMIS

Testbed (Oh *et al.*, 2000). Individual vehicles are modeled in fine detail for the duration of their entire trips, providing comprehensive traffic characteristics and congestion information, as well as enabling the modeling of the interface between drivers and ITS facilities and strategies. Figure 4 shows Alton/ICD intersection in Paramics.



Figure 4. Alton/ICD Intersection in *Paramics*

Paramics provides a framework that allows users to customize many features of the 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. The APIs 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 an interface to 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 can easily be tested using the simulator before the implementation in the real world.

All of the signal control strategies employed 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 (Liu *et al.*, 2001).

5.3 Simulation Results

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 are to minimize the vehicle delay, improve the utilization of intersection capacity and reduce traffic congestion. Measures of effectiveness (MOEs) provide a quantitative basis for determining the capacity of traffic control system and their strategies to attain the desired goals. As described in Section 4.2, we consider two objectives: system efficiency and system fairness. For the system efficiency, three

measures of effectiveness (MOEs) are evaluated: total intersection delay, total throughput, and average delay. The fairness of system is measured via standard deviation of movement delays.

Because Paramics is a stochastic simulation model, a Monte Carlo simulation is used to measure the system performance. A total of 30 simulation runs, each comprised of a two-hour period, were conducted for each scenario. As summarized in Table 1, the proposed on-line adaptive control outperforms both pre-timed and actuated control. Compared to the pre-timed control case, on-line control systems show greater than a 10% reduction in average delay. However, the fairness measure, standard deviation of movement delays, worsens when the total delay is used for green time update, while the control system with the average delay-based update reduces the standard deviation. That is, the average-delay-based on-line control satisfies both objectives, although the system efficiency is slightly lower than that of total delay-based on-line control.

Since the overall performance is averaged based on 30 simulation runs, the performance of the system also can be evaluated probabilistically. Figures 5, 6, 7, and 8 depict the system performance measures as probability density functions (PDF). As we can see from these figures, the average-delay-based on-line control algorithms perform better for both pre-timed and actuated signal controls. The standard deviation of the performance measure can be regarded as a measure of system stability in real application. In general, the pre-timed control systems exhibit greater stability than do the actuated control systems, and could be verified easily by the shapes of their PDF as shown in these figures.

To further detail the performance improvement under a high demand scenario, Figures 9 and 10 compare changes in average intersection delay during the two-hour simulation period, showing significant reduction of the total intersection delay.

Table 1. Comparison of Overall Performance

MOEs		Pre-timed Controller			Actuated Controller		
		PTC	OPA	OPT	AC	OAA	OAT
Efficiency	Total Delay (hrs)	263.1 (5.5)	238.6 (6.7)	232.1 (4.6)	235.9 (10.9)	238.3 (10.5)	231.4 (9.1)
	Throughput (veh)	11072.0 (98.5)	11284.4 (76.5)	11057.7 (77.0)	10772.9 (116.5)	11250.3 (148.0)	11011.6 (243.0)
	Avg. Delay (sec/veh)	85.5 (2.0)	76.1 (2.1)	75.6 (1.4)	78.8 (3.6)	76.3 (3.5)	75.7 (3.9)
Fairness	Std. of Delays	35.0 (2.4)	30.8 (4.1)	40.4 (2.7)	48.4 (3.2)	31.4 (3.2)	37.8 (4.7)
Improve- ment (%)	Total Delay	-	-9.3	-11.8	-10.3	-9.4	-12.0
	Throughput	-	1.9	-0.1	-2.7	1.6	-0.5
	Avg. Delay	-	-11.0	-11.7	-7.8	-10.8	-11.5
	Std. of Delays	-	-11.8	15.4	38.3	-10.2	8.1

Note: Values in () represent standard deviations of 30 simulation runs.

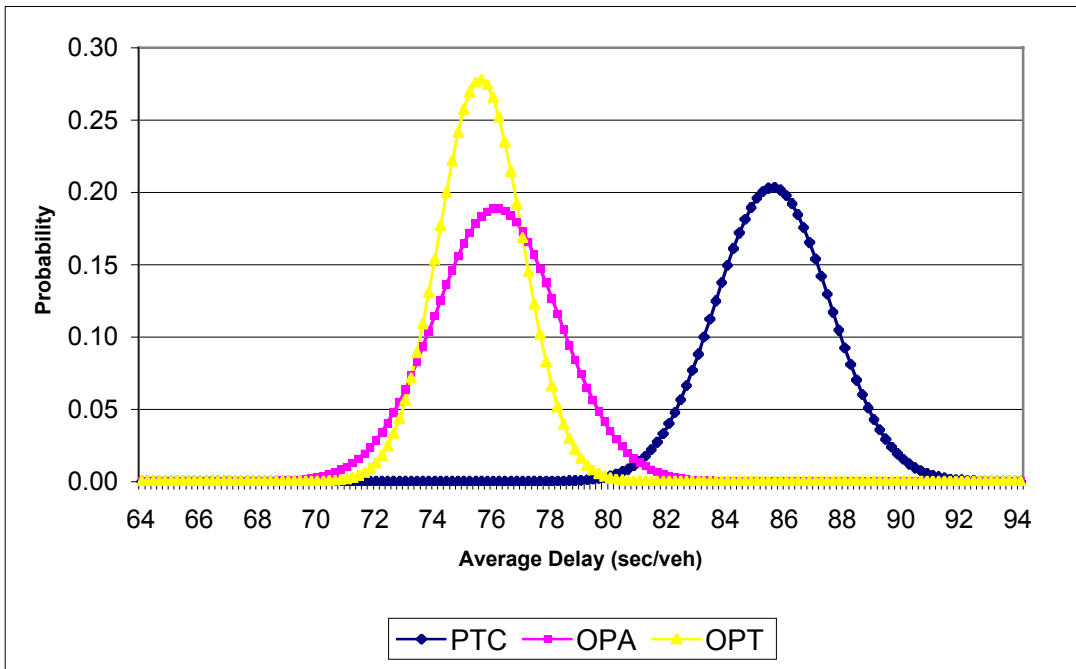


Figure 5. Probabilistic Distribution of Efficiency Measure (Pre-timed Control)

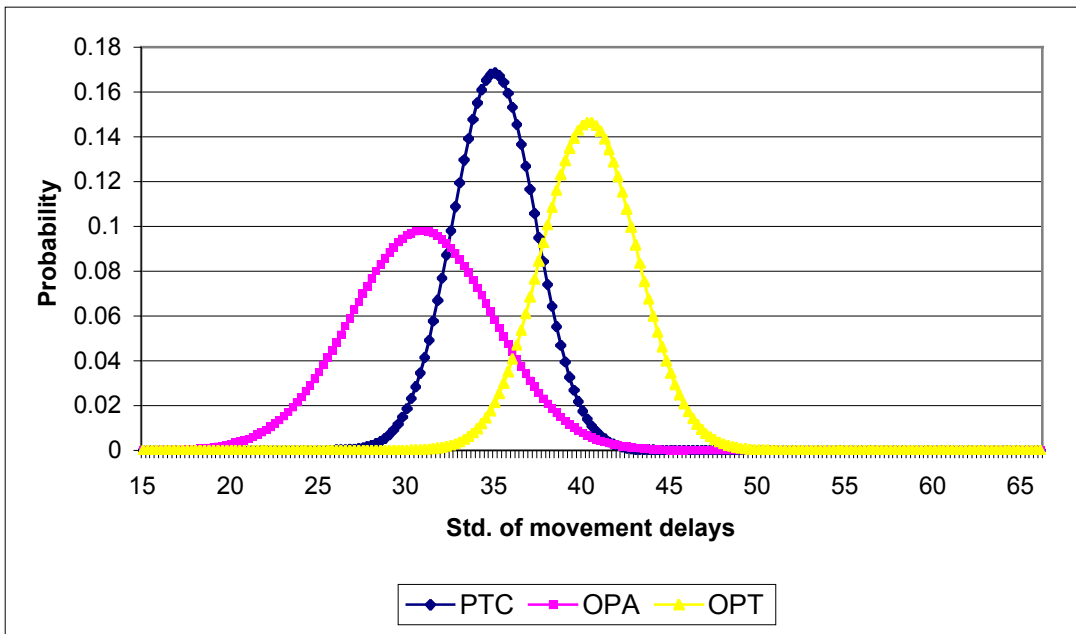


Figure 6. Probabilistic Distribution of Fairness Measure (Pre-timed Control)

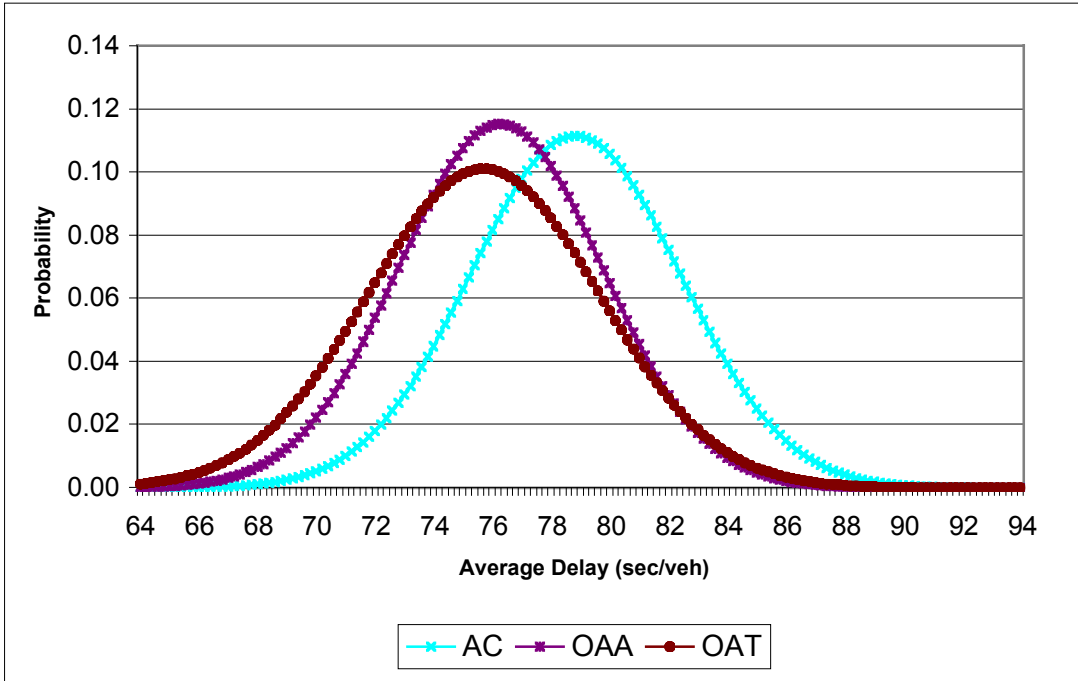


Figure 7. Probabilistic Distribution of Efficiency Measure (Actuated Control)

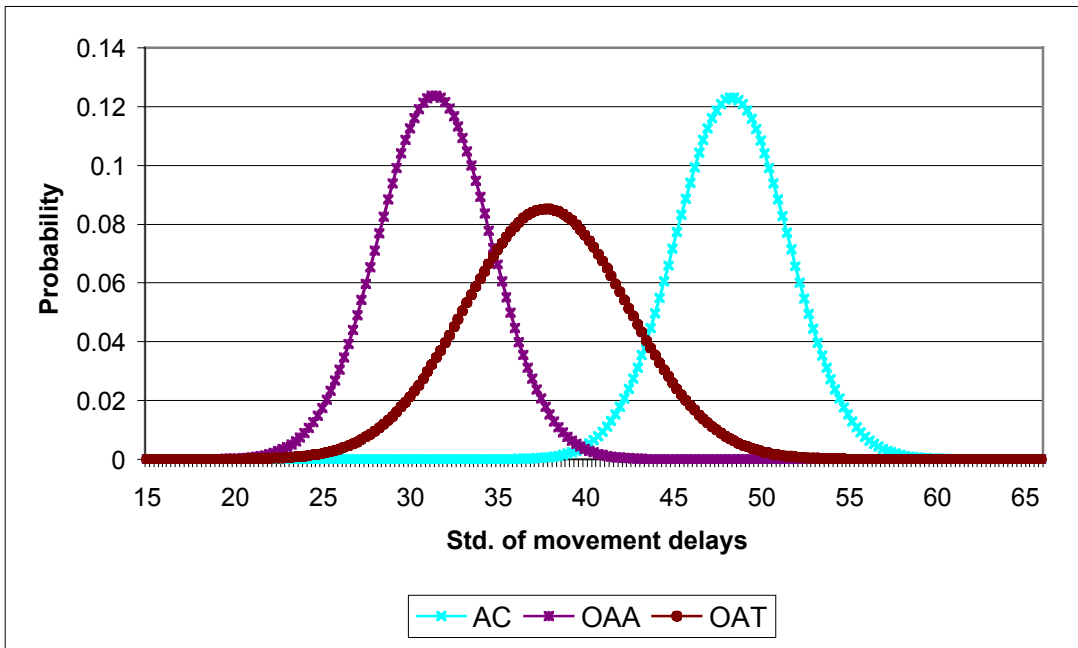


Figure 8. Probabilistic Distribution of Fairness Measure (Actuated Control)

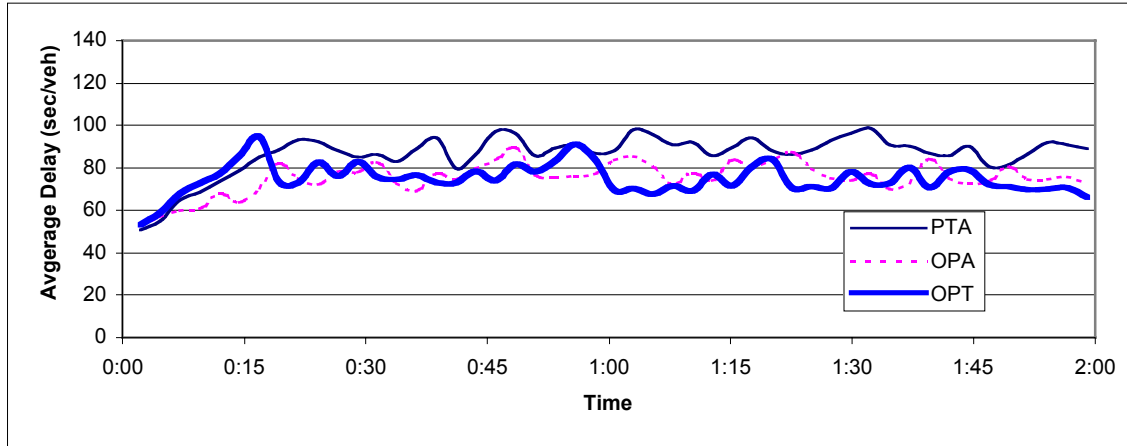


Figure 9. Comparison of Total Delay at Each Time Step (Pre-timed control)

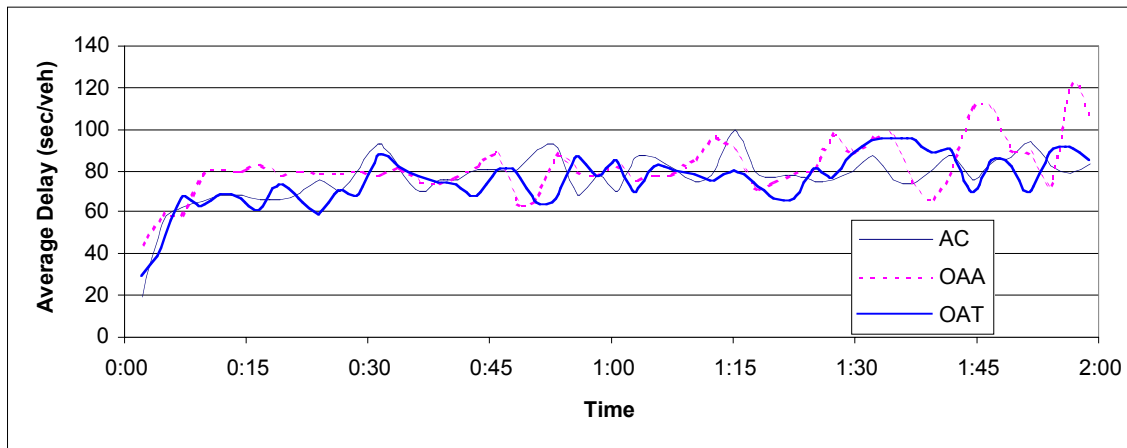


Figure 10. Comparison of Total Delay at Each Time Step (Actuated control)

6. CONCLUSIONS AND FUTURE WORK

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 a complementary module to the existing signal controller for both pre-timed and vehicle actuated controllers, by providing optimal signal timing parameters. It comprises two main components: real-time delay estimation via vehicle re-identification, and on-line signal parameter optimization. We applied the on-line adaptive control system to both pre-timed and actuated control, and compared the performance of the systems via microscopic simulation model. The simulation experiments showed that the proposed adaptive control system could be an efficient method even under the application of a simple algorithm for adapting the signal timing plan.

Note that the main purpose of this paper is to present an integrated adaptive signal control algorithm with vehicle re-identification technologies. Simulation experiments were 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. As addressed in the paper, the performance of the system can be improved by employing more complicated control logics.

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