THE SIMULATION OF ADAPTIVE SIGNAL CONTROLS ON URBAN ARTERIAL STREETS

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INTRODUCTION

In an urban road system, arterials and networks are very common geometric configurations, on which the traffic performances are receiving much and greater attention with increasing traffic demands in most cities. An arterial generally uses one of the three types of traditional traffic control strategies, i.e., the disutility, band-width, and combination methods. These methods are generally used in off-line generation of signal plans for the UTCS-1st generation type of control, or on-line generation for the UTCS-1 1/2 or 2 generation. Several problems in using UTCS control strategies include, at least, difficulties in obtaining accurate traffic flow data and traffic disturbance during the transition period between time plan changes. On the other hand, some research are underway to establish guidelines in the use of traffic-actuated controllers for signal coordination, however, there exist no such effective timing design tools yet.

The more advanced adaptive control logics utilize very short-term advance information for real-time optimization of signal operations at isolated intersections. Examples are, but not limited to, SCOOT, SCATS, OPAC, SAST, and TOL. An isolated intersection control logic called COMDYCS-III has been developed in some research by the authors, and extended to the signal operation of arterial streets [Ho, 1990 and 1991].

The conducted research aimed at, on one hand, to improve platoon progression along arterials, and on the other hand, to reduce travel delays of the system. With the help of a specific traffic simulation model, different coordinated adaptive control strategies were analyzed and evaluated. The more traditional arterial signal timing design methods of pre-timed and actuated controls were also included in this comparison study. This paper outlines the general background on, and the conceptual framework of, the proposed adaptive control strategies for arterial systems and thus some findings of that research.

1. GENERAL BACKGROUND

1.1. Arterial Signal Control Models

The more conventional arterial traffic control theories can be classified into three categories [Moore, et al, 1976; McGowan and Fullerton, 1980].

With the goal of maximum progression bandwidth, models such as PASSER-II, MAXBAND, and BANDTOP belong to the bandwidth method [Chang, 1985; FHWA, 1987a; Tsai, 1988a]. The disutility method includes softwares such as TRANSYT, SIGOP-III and T7F-T88 which are formulated to obtain minimum delay and stops [FHWA, 1987b; FWHA, 1983; Tsai, 1988b]. The third one called combination method, which combines the above two methods, can rely on the two-stage, integrated, and progressive opportunity solutions [Cohen, 1986; Cohen and Liu, 1986; Baass and Allard, 1984; Wallace and Courage, 1981; Hadi and Wallace, 1992].

1.2. Adaptive Controls Overview

In order to overcome the defects of most urban traffic control systems having existed since the 60's, several adaptive control theories have been developed, e.g., SCOOT [Hunt, et al, 1981], SCATS [Luk, 1984; Luk and Sims, 1982; Luk, et al, 1982], OPAC [Gartner, 1983 and 1985], SAST [Lin, 1988a and 1988b; Lin and Vijayakumar, 1988], and TOL [Bang, 1976]. These models or systems use different control strategies or logics, and accordingly different hardware features, such as detector locations. Among them, only the SAST concept, which has initiated this research, is briefly described.

SAST, Stepwise Adjustment of Signal Timing is developed by Lin, F.B. Its system components include detectors both upstream and at stoplines of approaches to acquire flow data, a traffic model that processes vehicle movement, and an optimal decision-making logic that assesses phase change options. The operation is to use four decision-making criteria to decide whether to extend the current green time or to terminate it within two seconds interval. It is a binary decission process.

2. Proposed Adaptive Traffic Control Strategies COMDYCS-III

An isolated intersection control logic called COMDYCS-III (COMputerized DYnamic traffic Control System - III), which is originated from the SAST, has been developed. Firstly, it divides the time span into discrete intervals or steps. In each step, a decision is made to either terminate or extend the current green phase at the end of that step. This timing adjustment procedure allows the use of a limited amount of information to achieve a high level of control efficiency. The proposed adaptive control method relies on a six-level decision-making process. The fourth level, i.e., gain and loss comparison for signal optimization, is the core of the said process, and all the others are based on simple decision rules. The information needed to reach a timing decision in each step includes queue lengths at the beginning of that step and the expected numbers of vehicle arrivals at the stop lines within each of the several steps to come. The queue lengths are estimated from a traffic model. The expected numbers of arrivals at the stop lines are derived from the data provided by upstream detectors. Lastly, the control logic uses predicted traffic data basing on vehicle arrivals of the latest cycle to supplement detector data.

2.1. Assumptions

COMDYCS-III has the following assumptions:

1. The decision interval is represented as Δt, which is equal to 2 seconds.
2. The clearance time is 5 seconds, with 2 seconds of all-red and 3 seconds of usable yellow.
3. The advance information is equal to the average link travel time of free flow traffic.
4. The signal controls are 2 phases, and the N value (comparative number of decision) is calculate as follows:
   $N = (I - Y - \Delta t)/\Delta t$
   $I = \text{Min}(IA, IB)$
   IA(IB) : The advance information in current green phase of approach A(B).
   Y : Yellow interval
5. For the vehicle arrival rate, if advance information is not long enough, it will adopt a smoothing method to predict the arrivals. The method is to use the average arrival rate of vehicles in the system, and the prediction period commences at the end point of advance information.
6. The expected time of vehicle arrival at the stop line is equal to the vehicle arrival time at the detector plus the average travel time.
7. The model uses travel time delay.
8. In the "gain-loss comparision", the expected green time is equal to the maximum value of the minimum green time and the time required for the queue length to dapart in the current green phase.

2.2. Signal Timing Decision-Making Process

The decision-making process of COMDYCS-III can be refered to in Figure 1, which is described below, following the notations.

The notations are:

(a) Gmin: Minimum green interval
(b) Gmax: Maximum green interval
(c) Gnow: Current time
(d) Gstop: Green termination point
(e) Li, i=A,B,C,D : Critical queue length of approach A(B,C,D)
(f) QA (QB): Queue length of approach A(B) in current green phase
(g) QC (QD): Queue length of approach C(D) in competitive phase
(h) Qmax=Max(QA,QB): Maximum queue length of current green phase
(i) Q'max=Max(QC,QD): Maximum queue length of competitive phase
(j) Tdec: Current decision-making point.
(k) TV: The total number of vehicles in approaches A and B in current green phase
(l) TV': The total number of vehicles in approaches C and D in competitive phase
(m) VTTD : Vehicle Travel Time delay
= Actual Departure Time - Expected Stopline Arrival Time

(n) $\sum_{A,B,C,D}$ VTTD(0) : The total VTTD of approaches A,B,C,D for the zero alternative (at Gnow+ Δt point)
(o) $\sum_{A,B,C,D}$ VTTD(K) : The total VTTD of approaches A,B,C,D for the Kth alternative (at Gnow+ $\Delta t(K+1)$ point)

First, COMDYCS-III processes initialization, it then proceeds to a green phase. When at a Δt interval before minimum green termination, it begins to execute the COMDYCS-III decision-making process. The process can be separated into six-level:

1. First level decision
   If the queue length of approach A or B in current green phase exceeds a critical value, in order to avoid spillover at the upstream intersection, it extends one Δt interval green time beyond the current decision-making point, but not exceeding the maximum green time.
2. Second level decision
   If no car arrives in the competitive phase, it extends one Δt interval green time, but not exceeding the maximum green time.
3. Third level decision
   If the queue length of approach C or D in the competitive phase exceeds a critical value, in order to avoid spillover, the current green phase must be cut off after one Δt interval.
4. Fourth level decision
   Perform the "gain and loss comparision" for signal optimization.
5. Fifth level decision
   If the maximum queue length of the current green phase exceeds that of the competitive phase, it extends one Δt interval green time, but not exceeding the maximum green time.
6. Sixth level decision
   If the minimum queue length of the current green phase exceeds 3 vehicles or the maximum exceeds 7 vehicles, then it extends one Δt interval, but not exceeding the maximum green time. This decision is to assure queued vehicles will pass through the intersection on the first green.

2.3. Gain & Loss Comparison Decision Logic

The gain & loss comparison decision logic is the fourth and most important level in the COMDYCS-III decision-making process. The entire process can be refered to in Figure 2, as follows:

1. The first step is to calculate $\sum_{A,B,C,D}$ VTTD(0), that is the total travel time delay of the zero alterative which cuts off the current green phase at Gnow+Δt point. The vehicles considered are those within a complete cycle.
2. The second step is to set $K = 1$ for $GK = Gnow + (K+1)\Delta t$ which represents the green time length when terminating the current green phase in the Kth alternative.
3. Compare GK with Gmax. If $GK >= Gmax$, that is, the green time in the Kth alternative exceeds the maximun green, terminate the fourth level decision logic.

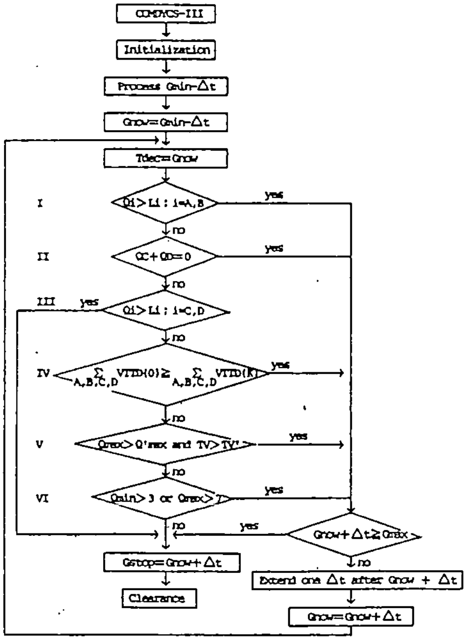

Figure 1. COMDYCS-III
Decision-Making Process

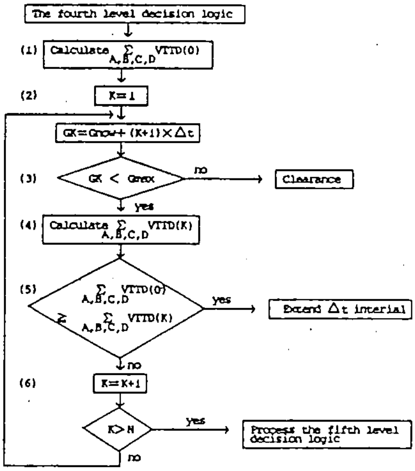

Figure 2. COMDYCS-III Gain & Loss Comparision Logic

4. If not, GK<Gmax, then calculate $\sum_{A,B,C,D} VTTD(K)$.
5. From results of 1 thru 4, if $\sum_{A,B,C,D} VTTD(K) - \sum_{A,B,C,D} VTTD(0) <= 0$, then the Kth alternative is a "gain"; otherwise, a "loss". If a "gain", it extends Δt; if a "loss", proceed to the next step.
6. Set K=K+1 and compare K with N (where N = (I-Y-Δt)/Δt, and I = Min{IA,IB}); if K>N, proceed to the fifth level decision process, otherwise go back to Step 2 with a new K.

2.4. Multuple Step Control Logic

The original COMDYCS-III logic of single-Δt interval extention was modified to extention of multiple Δt intervals. The method of modification can be classified into four models, which are described below:

2.4.1. Model 1 (continuing decreasing delay multi-step logic)

In addition to the delay improvement over the base alternative of no extension, the delay of any alternative must be lower than its previous one to be considered. The process stops at a step where additional time extension will incur more delay.

2.4.2. Model 2 (minimum delay multi-step logic)

The model selects one among all the alternative that has the minimum delay which is lower than that of the base alternative.

2.4.3. Model 3 (continuing lower-than-base-alternative delay multi-stop logic)

The model scans from the first alternative to the last and stops when the next extension will incur more delay than the base alternative.

2.4.4. Model 4 (last extension lower-than-base-alternative delay multi-step logic)

The model selects the longest extension alternative that has lower delay than the base alternative.

3. COMDYCS-III ADAPTIVE CONTROL STRATEGIES FOR ARTERIALS

3.1. Individual-Intersection Optimization

This method is to extend the isolated-intersection control strategy to intersections in series. Basically, it maintains the operation of the same logic at each intersection, assuming self optimization of all intersections approaching the global optimun, which however is seldom the case. This method has been applied to COMDYCS-III, Gain & Loss Comparision, SAST control strategies for single-step extension and the four models of multiple-step extension, as well as the OPAC control.

3.2. Differential Weighting

In order to let vehicles progress through intersections in series, the "gain and loss comparision" logic was changed to weigh vehicle delay more in the arterial direction, so the timing decision will favor that direction and incline to extend its green. This increase in the opportunity of arterial vehicle progression will cause a decrease in green time on the side street and increase its delay. Besides, it can not guarantee two-direction progression or complete progession from the first intersection to the last along the arterial.

3.3. Queue-Based Method

The queue-based method is similiar to a full-actuated control, using vehicles as a comparative basis, not delay. The method uses traffic flow data from detectors, and finds the maximun number of vehicles that can pass through an intersection in a defined interval to decide an extension or not. Besides, if vehicles still arrive in the two approaches of the current green phase, it will protect that phase and extend the green time until no vehicle arrival on either approach, subject to the limit of maximum green time. The logic is to compare the total number of vehicles passing through the intersection between the current and competitive phase in one Δt interval.

4. SIMULATION RESULTS

In order to compare the performance of various traffic control strategies, the SLAM II simulation langulage was used to construct a traffic simulation model and various above-mentioned control strategies, including OPAC and SAST [Pritsker, 1986]. Experiments were then conducted for comparison purposes.

Both the fixed-time and semi-actuated coordination controls were used as the bases for comparision. For the fixed-time coordination, TRANSYT-7F model was run to obtain timing plans of cycles, offsets, and splits, with predefined geometric, traffic flow and other parameter data. For the semi-actuated coordination, the concept of using TRANSYT-7F yield point and side-street spare green to obtain new yield point and thus reset offset point, suggested by Skabardonis, was employed [Skabardonis, 1988].

The simulation model has the following assumptions:

1. The model is macroscopic in nature and of discrete-event type.
2. Only cars with 10% larger vehicles, no motorcycles, are considered.
3. The arterial has 5 intersections in series.
4. The arterial and side street links are of the same length, each equal to 200 meters.
5. Average link travel time is 20 seconds, with travel speed of 10 meters per second.
6. Each arterial link has 15% left-turns and 10% right-turns, side-street link 15% respectively.
7. Vehicle arrivals follow the exponential distribution.

The simulation results are shown in Tables 1 and 2 and Figures 3, 4, 5, and 6, and are summarized below:

1. The average delay and queue length of different control strategies are increasing with flows. The fixed-time coordination and multiple-step extension methods increase the most, especially in high volumes.
2. The comparision shows that the performance of COMDYCS-III, OPAC, SAST, and Queue-based are more or less the same in low-middle volumes, but in high volumes, the performance of Queue-based, SAST and OPAC are worse than COMDYCS-III. The performance of differential-weighting is not as good as COMDYCS III both in average delay and queue length.

Table 1. Simulation Results of Average Delay

unit: sec/veh

Flows, vphs Average System Delay Control Strategies		600 100	600 200	600 300	600 400	700 100	700 200	700 300	700 400	800 100	800 200	800 300	800 400
COMDYCS-III		16.0	19.7	21.1	20.3	15.4	20.5	21.0	22.6	16.9	20.8	23.0	22.5
Gain & Loss		15.0	19.4	19.3	19.9	15.0	20.4	22.1	22.9	16.2	20.0	21.9	23.6
SAST		19.3	20.4	19.7	20.0	21.2	24.0	22.8	22.0	22.7	24.4	25.2	25.5
OPAC		17.1	19.3	20.8	22.7	17.8	19.6	22.3	23.5	18.2	21.5	23.1	26.2
Weighting		17.0	18.5	21.1	23.7	15.6	20.2	21.3	24.2	16.8	21.2	24.2	25.0
Queue-based		21.7	21.2	22.0	23.1	21.8	23.4	23.2	24.3	24.2	24.8	25.4	27.6
Multiple-step Adjustment	#1	21.0	19.8	20.8	22.1	21.7	23.4	22.6	21.9	23.1	28.8	26.1	26.1
	#2	16.0	19.8	20.7	22.4	14.8	20.3	23.8	24.2	16.6	20.9	24.2	25.6
	#3	20.7	23.7	23.0	25.3	21.5	26.2	27.3	28.3	24.9	29.7	29.9	30.6
	#4	18.9	23.5	25.2	25.6	16.7	24.1	27.6	28.6	17.4	24.6	29.3	30.2
Semi-actuated		17.8	16.6	17.2	17.9	16.8	19.5	18.2	20.5	20.2	20.2	19.7	24.3
Fixed-time		24.7	28.2	31.8	32.8	24.0	28.5	31.8	34.8	23.1	28.6	32.4	35.1

Table 2. Simulation Results of Average Queue Length

unit: vehicles

Flows, vphs Average Queue Length Control Strategies		600 100	600 200	600 300	600 400	700 100	700 200	700 300	700 400	800 100	800 200	800 300	800 400
COMDYCS-III		1.5	2.4	3.1	3.5	1.5	2.5	3.1	3.8	1.7	2.6	3.5	3.8
Gain & Loss		1.3	2.3	2.8	3.5	1.3	2.4	3.3	3.9	1.5	2.4	3.3	3.9
SAST		1.6	2.2	2.6	3.0	1.8	2.5	2.9	3.4	2.0	2.6	3.2	3.8
OPAC		1.5	2.1	2.7	3.5	1.6	2.2	3.0	3.4	1.7	2.4	3.2	3.9
Weighting		1.6	2.2	3.0	3.8	1.5	2.4	3.1	4.0	1.7	2.7	3.6	4.3
Queue-based		1.8	2.1	2.7	3.2	1.8	2.4	2.9	3.4	2.1	2.6	3.1	3.8
Multiple-step Adjustment	#1	1.5	2.0	2.6	3.3	1.6	2.4	2.9	3.3	1.7	2.9	3.3	3.8
	#2	1.4	2.3	3.0	3.9	1.3	2.4	3.5	4.1	1.5	2.6	3.6	4.3
	#3	1.5	2.4	3.0	3.7	1.7	2.8	3.6	4.3	1.9	3.0	3.9	4.8
	#4	1.6	2.8	3.7	4.4	1.6	2.9	4.1	4.9	1.7	3.0	4.3	5.1
Semi-actuated		1.8	2.1	2.6	3.1	1.8	2.4	2.8	3.5	2.1	2.6	3.0	4.1
Fixed-time		2.2	3.4	4.6	5.5	2.3	3.5	4.7	5.9	2.3	3.6	4.8	5.9

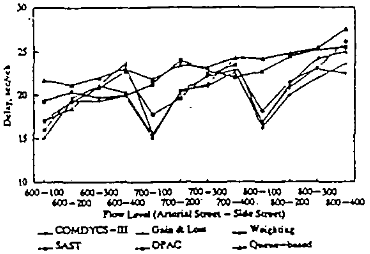

Figure 3 Average System Delay Comparision of Six Adaptive Control Strategies

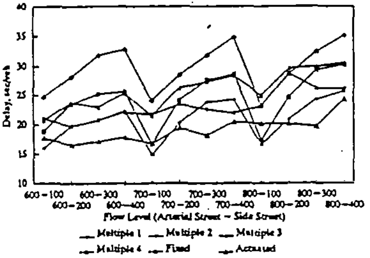

Figure 4 Average System Delay Comparision of Six Control Strategies

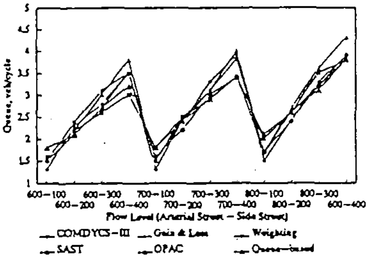

Figure 5 Average Queue Length Comparison of Six Adaptive Control Strategies

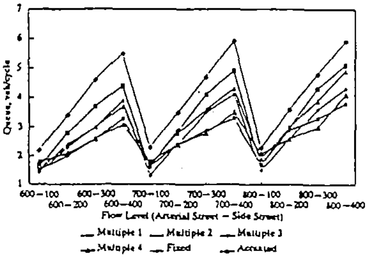

Figure 6 Average Queue Length Comparison of Six Control Strategies

3. Among the four models of multiple-step extension, the model 2 of minimum delay performs the best, which compares farorably with the other adaptive control strategies.
4. In low volumes, SAST model is not as good as COMDYCS-III in average delay and queue length, but more or less the same in high volumes.
5. Generally speaking, the performance of semi-actuated coordination is rather good, with the exception of extremely unbalanced arterial-side street volumes, such as 800-100, 600-100vphs.
6. In summary, the single-step binary decision logic of adaptive control strategies is better than the multiple-step extension logic, and the performance of fixed-time coordination is the worst. As regards to more through comparison among these control strategies, it demands further exploration on simulation results using more flow sets and different road configurations.

5. FUTURE DEVELOPMENT

Serveral methods are under development which are aimed at achieving better control efficiency in managing arterial traffic.

The progression method is first to decide cars within a platoon via the dectector headways, then to add a platoon extension criteria within the COMDYCS-III logic to let the platoon pass through intersections. Nevertheless, it must satisfy the constraint of maximum green time and the acceptable wait time limit of side street. The main objective is to maintain platoon movement in the arterial without being cut-off, so the traffic can flow smoothly and effectively.

The flexible adjustment of fixed-band method is to maintain a fixed-band operation, but adjusting the splits flexibly with the flow, and the cycle changes accordingly. The offset adjustment is kept within some limits while keeping the decision intelligence of the adaptive control logic.

Finally, most streets in cities of Taiwan have a very complicated traffic movement. In order to avoid missing data in the model or incorrect detector parameters, due to flow disturbance, it is essential to develop a self-calibration model of traffic flow information. The model can estimate correct number of cars in the system and calibrate the departure headways. The model development can rely on the point car method, fuzzy set method or better methods of estimating traffic detector parameters.

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