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OPAC: A Demand-Responsive Strategy for Traffic Signal Control

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Optimization Policies for Adaptive Control (OPAC) is a computational strategy for real-time demand-responsive traffic signal control. It has the following features: (a) It provides performance results that approach the theoretical optimum, (b) it requires on-line data that can be readily obtained from upstream link detectors, (c) it is suitable for implementation on existing microprocessors, and (d) it forms a building block for demand-responsive decentralized control in a network. Studies undertaken in the development of this strategy and the testing of its performance via the NETSIM simulation model are described.

Urban vehicle traffic as an expression of human behavior is variable in time and space. Therefore, a high degree of adaptiveness is required in the control of such traffic to provide a suitable response to this variability. Ever since the inception of modern traffic signal controls, traffic engineers and signal system designers have attempted to make them as responsive as possible to prevailing traffic conditions. The premise has always been that increased responsiveness leads to improved traffic performance. This premise applies, in broad terms, to single intersection signals as well as arterial and network systems. However, the extent to which traffic responsiveness is achieved depends on a variety of factors, including control hardware, software capabilities, surveillance equipment, and operator qualifications.

With the advent of computerized systems in the mid-1960s, many cities began to deploy centrally controlled and monitored traffic signal systems. Such systems have offered (and still do offer) significant advantages compared with the previously available electromechanical devices. But they also impose a certain rigidity that restricts the opportunities for traffic responsiveness. This has been quite evident in the Urban Traffic Control System (UTCS) experiments in Washington, D.C., as well as in similar experiments conducted in Canada and in Great Britain (1-3). A review of the causes of this failure and a prescription for its alleviation are presented elsewhere (4).

The emergence of microprocessor technologies is drastically changing the traffic signal control field and opening up new horizons and opportunities for demand-responsive control that were not imaginable in the past. It is now feasible to develop much more sophisticated systems than before, systems that would offer a great deal of responsiveness, would work automatically, and would almost eliminate the need for operator intervention.

This paper describes studies that have been undertaken in the development of a strategy that would serve as a building block for demand-responsive decentralized traffic signal control. The strategy, called Optimization Policies for Adaptive Control (OPAC), was developed in stages. First, a dynamic programming (DP) procedure was used to establish a standard of performance for demand-responsive control, since the DP technique is capable of generating optimal control strategies. Next, a simplified procedure was developed that replicates the performance of DP yet relinquishes its extensive computational requirements so that it becomes suitable for on-line implementation. In the third stage, the procedure was further refined by applying a rolling horizon approach. In this way, only readily available data are required and a practical method for demand-responsive control is obtained. This paper is based on a research report prepared for the U.S. Department of Transportation (5).

REVIEW

Forms of Traffic Signal Control

There are three basic forms of traffic signal control: pretimed, semiactuated, and fully actuated. The latter is further subdivided into fully actuated with volume-density control and without volume-density control. According to Orcutt (6), pretimed control is used primarily in the central business district, especially where a network of signals must be coordinated. This is not a good strategy where more than three phases are required. Orcutt defines actuated signals as equipment that responds to actual traffic demand of one or more movements as registered by detectors. If all movements are detected, the control is called fully actuated. He also states that fully actuated control should normally be used at isolated intersections.

The National Electrical Manufacturers Association (7) provides the following definitions for the four types of control:

1. The pretimed controller assembly is a controller assembly for the operation of traffic signals with predetermined fixed cycle length(s), fixed interval duration(s), and fixed interval sequence(s).
2. The semi-traffic-actuated controller assembly is a type of traffic-actuated controller assembly in which means are provided for traffic actuation on one or more but not all approaches to the intersection.
3. The full-traffic-actuated without volume density controller assembly is a type of traffic-actuated controller assembly in which means are provided for traffic actuation on all approaches to the intersection. The fully actuated controller without volume density has three settings for the determination of green timing on an actuated phase: (a) initial interval, the first timed portion of the green interval, which is set in consideration of the storage vehicles waiting between the sensing zone of the approach vehicle detector and the stopline, (b) extension interval (gap), a portion of the green interval whose timing shall be reset with each vehicle actuation and shall not commence to time again until the vehicle actuation signal is removed from the input to the controller unit, and (c) maximum extension, a time setting that shall determine the length of time that this phase may be held green in the presence of an opposing serviceable call.
4. In the full-traffic-actuated with volume density controller assembly, the volume-density operation shall include a form of variable initial timing and gap reduction timing. The effect on the initial timing shall be to increase the timing in a manner that depends on the number of vehicle actuations stored on this phase while its signal is displaying the yellow or red. The effect on the extensible portion shall be to reduce the allowable gap between successive vehicle actuations in a manner that is related to the delay of the first vehicle arriving on a conflicting phase.

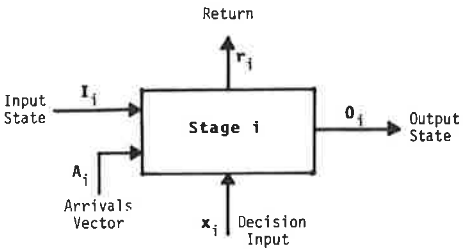
When properly calibrated, traffic-actuated signals in their various forms provide considerable advantages over fixed-time equipment and are widely used. Reports by Staunton (8) and Tarnoff and Parsonson (9) provide a comprehensive evaluation of actuated signal controls. It is apparent, however, that the methods of actuation are of an ad hoc nature and cannot provide the best possible performance. Moreover, these forms of actuation are not suitable for signal systems where demand-responsiveness and coordination are needed simultaneously.

Analytic Modeling of the Intersection Control Problem

There is a tremendous variety of modeling problems associated with the optimal control of traffic intersections, but only a limited number of special cases have been studied analytically. The most common approach is to determine settings for a fixed-cycle light that minimize the average delay per car, assuming constant arrival rates (10,11). Gazis and Potts (12) obtained conditions for the optimal control of an intersection that becomes oversaturated for some finite length of time, and the model has been extended by Gazis (13) to two intersections. The same modeling approach has also been studied by Michalopoulos and Stephanopoulos (14). Dunne and Potts (15,16) developed time-varying control algorithms for an undersaturated intersection with constant arrivals that guarantee that, for any initial state, the system will eventually reach a limit cycle for which the average equilibrium delay per car is a minimum. In all of these models, the dynamics of the control policy are not responsive to the dynamics of the traffic flow process since there is no real-time traffic flow information. The traffic flow process is represented by a single value (the expected flow rate), a statistical distribution (Poisson, binomial, etc.), and the initial conditions (the initial queue lengths) or, in case of oversaturation, by a smooth function of demand versus time. Obviously, none of these models can take advantage of the time-variant features of individual vehicle arrival times.

A dynamically self-optimizing strategy has been proposed by Miller (17). In this strategy, a decision whether to extend a phase is repeatedly made at very short fixed intervals h by the examination of a delay-based control function. This function estimates the difference in vehicle seconds of delay between the gain to the extra vehicles that will be allowed to cross the intersection during an exten-

Figure 1. Stage in the DP process.



sion of h seconds and the loss to the queuing vehicles on the cross street that results from the extension (h is 1-2 s long). A similar approach was also proposed by van Zijverden and Kwakernaak (18). Bang and Nilsson (19) implemented and field tested Miller's strategy and showed that significant gains can be obtained compared with fixed-time and vehicle-actuated control at isolated intersections. However, since this method has a very short projection horizon and corresponding optimization interval, it does not appear to lend itself to implementation in a network of intersections and furthermore does not ensure overall optimality of the control strategy. Because of its capability for multistage decisionmaking, dynamic programming is an attractive candidate technique for dynamic optimal signal control. Two DP models have been proposed in the literature for optimal signal control: Grafton and Newell (20) developed a continuous-time model, and Robertson and Bretherton (21) used a discrete-time model. The first model chooses to minimize an infinite-horizon total discounted delay function. The second model minimizes the total delay aggregated over all intervals of a finite horizon. This paper first develops and investigates a discrete-time version of DP similar to the second model.

DYNAMIC PROGRAMMING APPROACH

DP is a mathematical technique used for the optimization of multistage decision processes. In this technique, the decisions (or control values) that affect the process are optimized in stages rather than simultaneously. This is done by dividing the original decision-control problem into small subproblems (stages) that can then be handled much more efficiently from a computational standpoint. DP is a systematic procedure for determining the combination of decisions that maximizes overall effectiveness or minimizes overall disutility. It is based on the principle of optimality enunciated by Bellman (22): "An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision."

Consider a single intersection with signal phases that consist of effective green times and effective red times only. All traffic arrivals on the approaches to the intersection are assumed to be known for a finite horizon length. The optimization process is decomposed into N stages, where each stage represents a discrete time interval (such as 5 s).

A typical stage i is shown in Figure 1. At stage i we have an input state vector I_i, arrivals vector A_i, output state vector O_i, input decision variable x_i, economic return (cost) output r_i, and a set of transformations:

$$O_i = T_i(I_i, A_i, x_i)$$

$$r_i = R_i(I_i, A_i, x_i)$$

The state of the intersection is characterized by the state of the signal (green or red) and by the queue length on each of the approaches. Assuming a two-phase signal, the input decision variable indicates whether the signal is to be switched at this stage (x = 1) or remain in its present state (x = 0). The return cost output is the intersection index of performance (the total delay time), which has to be minimized. The functional relation between the input and output variables is based on the queuing-discharge processes at the intersection--i.e., the inflow and outflow relative to the signal settings.

DP optimization is carried out backwards--i.e., starting from the last time interval and backtracking to the first, at which time an optimal switching policy for the entire time horizon can be determined. The switching policy consists of the sequence of phase switch-ons and switch-offs throughout the horizon.

The recursive optimization function is given by the following equation:

$$f_i^*(I_i) = \min_{x_i} [R_i(I_i, A_i, x_i) + f_{i+1}^*(I_i, A_i, x_i)] \quad (1)$$

The return at state i is the queuing delay incurred at this stage and is measured in vehicle-interval units. Thus, when the optimization is complete at stage i = 1, we have $f_1^*(I_1)$, which is the minimized total delay over the horizon period for a given input state I_1. Since the initial conditions at stage 1 are specified (i.e., the queue lengths on all approaches are given as well as the initial signal status), the optimal policy can be retraced by taking a forward pass through the stored arrays of $x_i^*(I_i)$. The policy consists of the optimal sequence of switching decisions (x_i^*, i = 1, ..., N) at all stages of the optimization process.

An example of the demand-responsive control strategy calculated by this approach is shown in Figure 2 for a 5-min horizon length. The signal is two-phase and only two approaches are considered: A and B. The figure shows the arrivals on the approaches, the optimal switching policies, and the resulting queue-length histories. The signal timings appear as hatched (red) and blank (green) areas, including an all-red overlapping red interval at each switching point. The total performance index (PI) is 196 vehicle intervals. This is the best possible policy for the given arrival patterns.

SIMPLIFIED APPROACH

The DP approach for calculating demand-responsive optimal control policies requires advance knowledge of arrival data for the entire horizon period. This is far beyond what can reasonably be expected to be obtained from available surveillance systems. Moreover, the optimization requires an extensive computational effort and, since it is carried out backwards in time, it precludes the opportunity for updating the input data or correction of future control policies. Thus, although the DP approach ensures global optimality of the calculated control strategies, it is unsuitable for on-line use. This approach also produces a good deal of information that is not used. Optimal policies are obtained for all possible initial conditions, yet only one of these policies applies in practice.

Consequently, this research set out to develop a simplified optimization procedure that would be amenable to on-line implementation yet would provide results comparable in quality to those obtained via DP. The procedure has the following basic features:

1. The optimization process is divided into se-

Figure 2. Optimal demand-responsive control strategy for a two-phase signal generated by DP (5-min data, PI = 196 vehicle intervals).

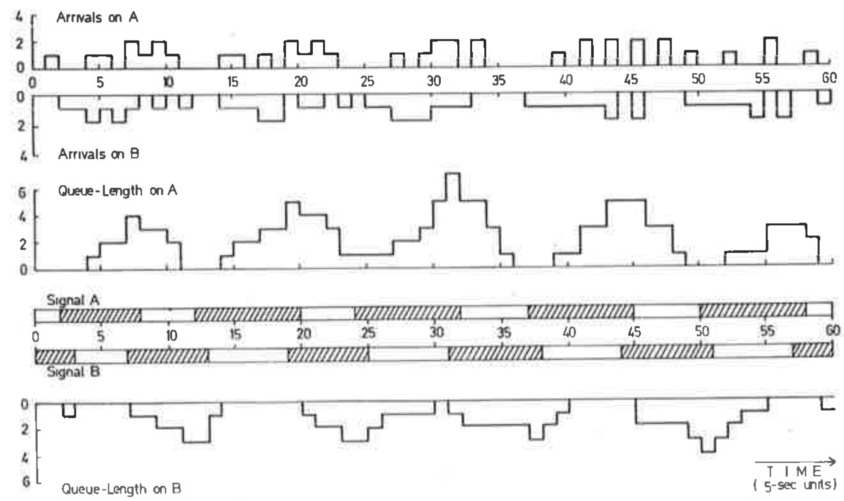
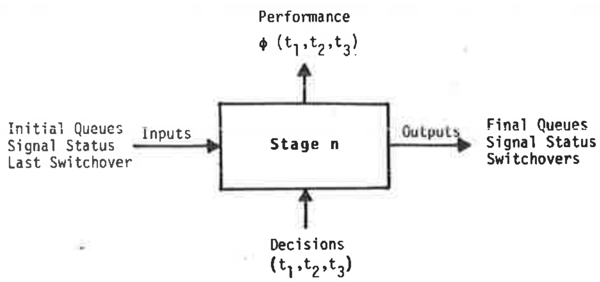


Figure 3. Information and decision flow at stage n of simplified optimization procedure.



quential stages of T seconds. The stage length is in the range of 50-100 s (i.e., similar to a cycle length for a fixed-time traffic signal) and consists of an integral number of the basic time intervals.

2. During each stage, at least one signal change (switchover) is required and up to three switchovers are allowed. This is designed to provide sufficient flexibility for deriving an optimal demand-responsive policy.

3. For any given switching sequence at stage n, a performance function is defined on each approach that calculates the total delay during the stage (in vehicle intervals):

$$\phi_n(t_1, t_2, t_3) = \sum_{i=1}^{k} (Q_o + A_i - D_i) \tag{2}$$

where

Q_o = initial queue,
A_i = arrivals during interval i,
D_i = departures during interval i, and
(t_1,t_2,t_3) = possible switching times during this stage.

Hence, ϕ measures the area enclosed between the cumulative arrivals and cumulative departures curves.

4. The optimization procedure used for solving the problem is an optimal sequential constrained search (OSCO) method (23). The objective function (total delay) is evaluated sequentially for all feasible switching sequences. At each iteration, the current PI (objective value) is compared with the previously stored value and, if lower, replaces it. The corresponding switching point times and final queue lengths are also stored. At the end of the search, the values in storage are the optimal solution.

The optimal switching policies are calculated independently for each stage in a forward sequential manner for the entire process (i.e., one stage after another). Therefore, this approach (unlike the DP approach) can be used in an on-line system. Figure 3 shows the information and decision flow at a typical stage n.

A comparison of computational results indicates that the simplified approach provides results that are very close to the optimum obtained by the DP approach. In most cases, the difference in the PI for the entire horizon is less than 10 percent. This is very encouraging, since the computational requirements (and the traffic data that are needed) are much reduced. An example is shown in Figure 4.

ROLLING HORIZON APPROACH

The previous section identified a basic building block for demand-responsive decentralized control, a simplified optimization technique for determining optimal switching policies in a time stage of T seconds. The technique requires future arrival information for the entire stage, which in practice is difficult to obtain with reliability. To reduce these requirements in such a way that one can use only available flow data and yet preserve the performance of the computational procedure, the rolling horizon (or rolling schedule) concept is introduced. This concept is used by operations research analysts in production-inventory control (24) and is here applied to the traffic control problem. The stage length consists of k intervals, which is the projection horizon, the period for which traffic flow information is needed. From upstream detectors, actual arrival data can be obtained for a near-term period of r intervals at the "head" of the stage. For the next (k-r) intervals, the "tail" of the stage, flow data are obtained from a model. An optimal policy is calculated for the entire stage but implemented only for the head section. The projection horizon is then shifted (rolled) r units ahead, new flow data are obtained for the stage (head and tail), and the process is repeated, as shown in Figure 5.

The basic steps in the process are as follows:

No.	Step
0	Determine stage length k and roll period r
1	Obtain flow data for first r intervals (head) from detectors and calculate flow data for next k-r intervals (tail) from model and detectors
2	Calculate optimal switching policy for entire stage by OSCO
3	Implement switching policy for roll period (head) only
4	Shift projection horizon by r units to obtain new stage; repeat steps 1-4

The computer program that implements this process has been named Optimization Policies for Adaptive Control or OPAC (5). The OPAC strategy was tested by using actual arrivals for the head of the stage and two types of models for the tail: (a) variable-tail, where projected actual arrivals are taken for the tail, and (b) fixed-tail, where the tail consists of a fixed flow equal to the average flow rate during the period.

The first model was used only to test the rolling horizon concept and compare the results with previous experimentations. The second model is of primary interest since it represents a practical approach to implementing OPAC. Measurements from upstream detectors can be used for head data and smoothed average flows for tail data, both of which are readily available. The head data are continuously updated in the rolling process. As one would expect, the variable-tail OPAC produces policies that are better than those produced by the simplified approach and, in most cases, replicate the standards obtained with the DP approach. Fixed-tail OPAC, although it uses smoothed data, comes very close to the optimal and represents a feasible and promising approach to real-time control. In particular, OPAC offers rather substantial savings in comparison with a fixed-time strategy such as Webster's (10) for the same total intersection volume (see Figure 6). These savings are impressive even when compared with strategies such as vehicle-actuated or Miller's (17), which are only 15-25 percent better than Webster's.

Another test of OPAC was conducted by using a special version of the NETSIM simulation model in which arriving traffic streams can be externally specified. The simulation logic was used to compare the performance of the original settings with that of the OPAC-generated control policies for the same arrival data. Five different 30-min data sets of a signal-controlled intersection in Tucson, Arizona, were tested. The results are given in Table 1. The OPAC policies provided a reduction of 30-50 percent of the initial delay. Corresponding improvements are noted in speed, which is averaged over all links of the simulated mininetwork. This contains large portions of travel time that are not subject to influence by the control strategy. Nevertheless, increases in average speeds ranged from 10 to 20 percent.

CONCLUSIONS

On-line traffic control strategies should be capable of providing results that are better than those produced by the off-line methods. The studies reported in this paper indicate that substantial benefits can be achieved with truly responsive strategies.

The OPAC strategy offers a feasible and very promising approach to real-time control. The strategy is designed to make use of readily available data, produces control policies that are almost as effective as those that would be obtained under ideal conditions, and has very reasonable computational requirements. It is well-suited for implementation via microprocessor technologies (25).

What is perhaps of even greater significance is the OPAC traffic flow model. It considers the entire projection horizon in the optimization process and therefore should be amenable for application in a demand-responsive, decentralized, flexibly coordinated system. In such a system, one would use the analysis capabilities of OPAC to structure the flows in the network so that one can preserve coordination on the one hand while taking advantage of the ever present variations in flows on the other. Thus, the system would require both local analysis capabilities and communication with adjacent controllers. A sketch of the envisioned information flow is shown in Figure 7. The development of such a system is the goal of the next phase of this research.

Figure 4. Demand-responsive policies generated by simplified approach with 60-s projection horizon.

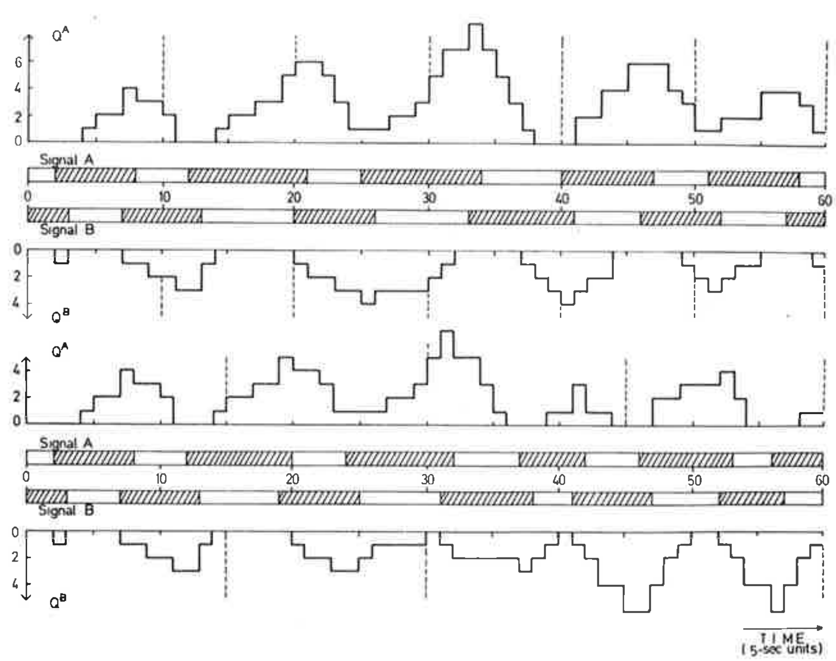


Table 1. NETSIM simulation results (30-min data sets) for a Tucson, Arizona, intersection.

	Avg Delay			Avg Speed		
Data Set	Original Settings (s/vehicle)	OPAC Policies (s/vehicle)	Percent of Original	Original Settings (mph)	OPAC Policies (mph)	Percent of Original
1	44.92	23.70	52.8	22.02	26.54	120.5
2	37.74	22.52	59.7	23.35	27.06	115.9
3	33.98	23.46	69.0	24.07	26.65	110.7
4	41.43	21.61	52.2	22.60	26.98	119.4
5	40.45	23.59	58.3	22.90	26.63	116.3

Figure 5. Rolling horizon approach.

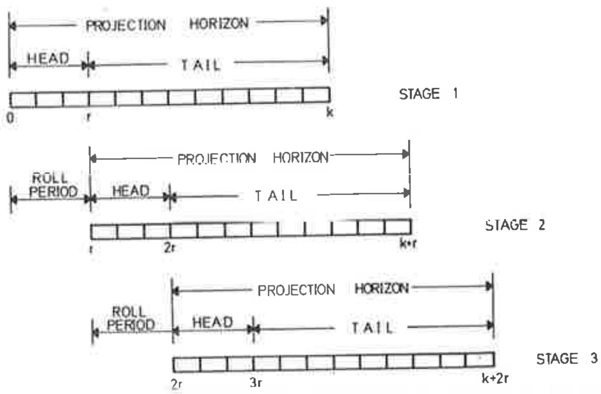


Figure 6. Comparison of average delay per vehicle at a single intersection for two strategies.

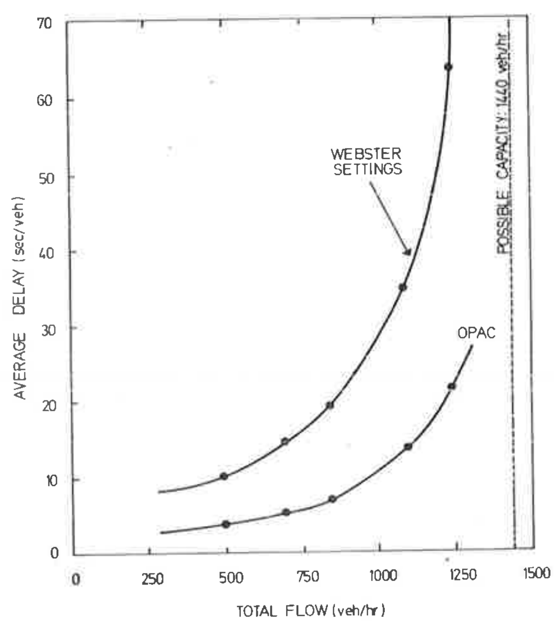
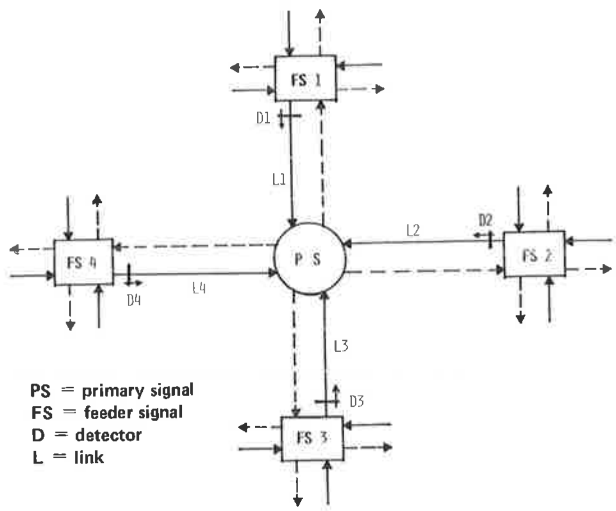


Figure 7. Information flow for demand-responsive decentralized control concept.



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Concurrent Use of MAXBAND and TRANSYT Signal Timing Programs for Arterial Signal Optimization

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A number of computer programs have been developed for the purpose of optimizing signal timing. All of the current programs, however, have some deficiencies. The TRANSYT program, which is the most widely used, has a good traffic model and optimizes green phase time. However, it does not get a globally optimal solution, optimize phase sequence, or really optimize cycle length. The MAXBAND program, which optimizes arterial bandwidth, does all of the above but is deficient in that green time is not optimized and the traffic model used is oversimplified. It is shown that a feasible way to overcome these deficiencies is to use the MAXBAND program to develop an initial timing plan for TRANSYT. This initial timing plan includes both cycle length and phase sequence optimization. The timing plans produced by the TRANSYT and MAXBAND programs separately were compared with the combined timing plans by using the NETSIM model. The results indicate that a substantial improvement in measures of effectiveness is obtained with the combined timing plans.

In recent years, there has been increasing emphasis on conserving energy, mostly due to the gasoline shortage crises of 1973 and 1979. One of the most cost-effective traffic engineering techniques for improving traffic flow and, hence, fuel efficiency is improvement of signal timing (1). In support of this goal, the Federal Highway Administration (FHWA) undertook the National Signal Timing Optimization Project (2). As part of this project, the TRANSYT 7 program (3) was modified so that it could be more easily used by American traffic engineers to develop signal timing plans for coordinated signal systems. The revised program is called TRANSYT 7F (4).

In parallel with the TRANSYT 7F activity, another approach to arterial signal timing, using the principal of maximal green bandwidth, has been pursued. This has resulted in the development of the MAXBAND program (5).

The purpose of the work described in this paper was to explore the advantages and disadvantages of the TRANSYT and MAXBAND programs as they are applied to arterials and to demonstrate that using both programs to develop timing plans can partly overcome the disadvantages of each of them.

DESCRIPTION OF PROGRAMS

TRANSYT

The TRANSYT program includes an excellent traffic model that uses network geometry and traffic flows