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 allow 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: pre-actuated, semiaudtuated, and fully actuated. The latter is further subdivided into fully actuated with volume-density control and without volume-density control. According to Orcutt (6), pre-actuated 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 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 pre-actuated controller assembly is a controller assembly for the operation of traffic signals with predetermined fixed cycle length(s), fixed duration(s), and fixed 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 time portion of the green interval, which is set in consideration of the storage vehicles waiting between the sensing zone of the approach vehicle lane 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 interval 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 Kulloff and Passerman (8) and Parson (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 is saturated for a finite time or over a period 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 demand-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 by a demand-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.

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:

\[
f^*_{i+1} = \min_{x_i} \{R_i(x_i, A_i, s_i) + f^*_i [R_i(i, A_i, s_i)]\}
\]

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 \(x^*_i(I_j)\). The policy consists of the optimal sequence of switching decisions \(x_i, i = 1, \ldots, N\) 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 hashed (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 s-
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.

quantum 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):

\[ d_n(t_1, t_2, t_3) = \sum_{i=1}^{3} (Q_0 + A_i - D_i) \] (2)

where

- \( Q_0 \) = 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, \( d \) 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 (GSCS) 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:
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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 detec-
   tors
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 con-
sists 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 previ-
ous experimentations. The second model is of pri-
mary interest since it represents a practical ap-
proach 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 continu-
ously updated in the rolling process. As one would
expect, the variable-tail OPAC produces policies
that are better than those produced by the simpli-
fied 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 particu-
lar, OPAC offers rather substantial savings in com-
parison 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 in-
fluence by the control strategy. Nevertheless, in-
creases in average speeds ranged from 10 to 20 per-
cent.

CONCLUSIONS

On-line traffic control strategies should be capable
of providing results that are better than those pro-
duced 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 strat-
ey 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 compu-
tational requirements. It is well-suited for imple-
mentation via microprocessor technologies (25).

What is perhaps of even greater significance is
the OPAC traffic flow model. It considers the en-
tire projection horizon in the optimization process
and therefore should be amenable for application in
a demand-responsive, decentralized, flexibly coordi-
nated 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 capabili-
ties 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 simpli-
fied approach with 60-s projection horizon.
Table 1. NETSIM simulation results [30-min data set] for a Tucson, Arizona, intersection.

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<th>Data Set</th>
<th>Original Settings (s/vehicle)</th>
<th>OPAC Policies (s/vehicle)</th>
<th>Percent of Original</th>
<th>Original Settings (mph)</th>
<th>OPAC Policies (mph)</th>
<th>Percent of Original</th>
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<td>116.3</td>
</tr>
</tbody>
</table>

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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REFERENCES

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 crisis of 1973 and 1974. 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...