Evaluation of Optimized Policies for Adaptive Control Strategy

NATHAN H. GARTNER, PHILIP J. TARNOFF, AND CHRISTINA M. ANDREWS

Optimization Policies for Adaptive Control (OPAC) is an on-line control algorithm designed to optimize the performance of individual traffic signals. It is a building block for demand-responsive control of a distributed signal system. OPAC-RT is a traffic signal control system that implements the OPAC strategy in real time. The system uses traffic data collected from detectors located well upstream (400 to 600 ft) of the stop bar on all approaches to an intersection. Signal timings are dynamically optimized in a demand-responsive manner using a rolling horizon scheme. Results of the first implementation and field testing of the on-line OPAC strategy at individual intersections indicate that OPAC performs better than well-timed actuated signals, particularly at greater demand levels. The payback period of the incremental costs of installing the current version of OPAC is estimated to be less than 1 year. Further enhancements of the OPAC system operation are likely to significantly increase its effectiveness.

Many different traffic signal control strategies are available to the traffic engineer. These strategies can be grouped into the following basic categories: isolated intersection control, arterial control, or network control (*1*). These categories are further distinguished between off-line strategies, which process manually collected data using batch computer programs to produce signal timing plans, and on-line strategies, which use detector inputs to calculate signal timings for immediate implementation.

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 the prevailing traffic conditions on the premise that increased responsiveness would lead to improved traffic performance. This premise was broadly applied to individual intersection signals as well as to area-wide systems. However, the extent to which traffic responsiveness can be achieved depends on a variety of factors, including the type of control hardware, software capabilities, surveillance and communication equipment, and operator qualifications.

The Optimized Policies for Adaptive Control (OPAC) strategy is an on-line traffic signal timing optimization algorithm that represents the most recent development in traffic control research. The development of this strategy was based on the following principles (*2–4*):

1. The strategy must provide better performance than off-line methods. Although it may seem self-evident, this principle was not always explicitly incorporated in the development of previous responsive strategies. Other less relevant criteria, such as "main-street platoon progression" or "variable cycle in time and in space," were often used.
2. The strategy must be truly demand-responsive, that is, it must adapt to actual traffic conditions and not be responsive to historical or predicted values, which are unreliable and may be far from actuality.
3. The strategy must not be restricted to arbitrary control periods but should be capable of providing continuously optimized controls. Effective responsiveness cannot be achieved by implementing off-line methods at shorter and shorter intervals.
4. Development of new control concepts that are better suited to the variability in traffic flows is needed, not merely the extrapolation of existing concepts. Thus, the conventional notions of cycle time, splits, and offsets, which are inherent in all existing signal optimization methods, are unsuited for demand-responsive control. On the other hand, direct minimization of the performance measures provides much improved performance.
5. The strategy should not be encumbered by a rigid network structure; rather, it should be based on decentralized decision making.

As a result, OPAC was developed as a distributed strategy featuring a dynamic optimization algorithm for traffic signal control without requiring a fixed cycle time. Signal timings are calculated to directly minimize performance measures, such as vehicle delays and stops, and are only constrained by minimum and maximum phase lengths. The strategy was originally developed at the University of Lowell under sponsorship of the U.S. Department of Transportation and is well documented in the literature (*5–8*). The following section briefly describes the OPAC methodology.

Following comprehensive simulation studies (*9*), a field implementation and evaluation of the method was sponsored by FHWA (*10*). Because OPAC is a distributed strategy, it was decided to initially test the operation of the single-intersection module. The same module serves as a building block of a multi-intersection system. The following specific objectives of the study were formulated:

- To develop a system that would enable the real-time OPAC program to interface with a full-actuated, modern, solid-state controller, so that the signal phase times would be determined by the OPAC optimization algorithm;
- To determine, in terms of traffic performance, how effectively the OPAC algorithm controls traffic at isolated intersections as compared with well-timed full-actuated control;
- To make recommendations, based on the observed performance of the existing OPAC control algorithm, for

N. H. Gartner, Department of Civil Engineering, University of Lowell, Lowell, Mass. 01854. P. J. Tarnoff and C. M. Andrews, Farradyne Systems, Inc., 3206 Tower Oaks Blvd., Rockville, Md. 20852.

modifications and enhancements that would improve its effectiveness;

- To estimate the cost-effectiveness of using OPAC instead of full-actuated control at isolated intersections;
- To produce a strategy that can be offered to the signal industry for commercial implementation; and
- To develop features that minimize the amount of fine-tuning required by local traffic engineering personnel.

The results of this study are described in a report prepared by the contracting agency (*10*). This paper discusses primarily the technical issues involved in the first field implementation of the OPAC strategy and the analysis of the traffic performance results.

DEVELOPMENT OF OPAC STRATEGY

Dynamic Programming: OPAC-1

The OPAC strategy evaluated in this study is the culmination of a research effort that included the development of three optimization algorithms (*5*). The first, designated OPAC-1, was designed as a basis for future OPAC strategy development. OPAC-1 uses dynamic programming techniques for the solution of the traffic control problem. Dynamic programming is a global optimization strategy for multistage decision processes (*11*). As such, it provides an absolute standard against which all other strategies can be compared.

When applying dynamic programming to the signal control problem, each interval of time is designated as a stage (with a typical length of 5 sec). For each stage, the initial state is defined by the initial queues on each approach and the signal status. The initial signal status for each approach is either green (0) or red (1). The input decision variable for each approach is either 0 (no signal change) or 1 (change). The output of the algorithm at each stage consists of the new queue values and signal indications that will result on each approach from the implementation of the specific decision. The performance measure (delays and/or stops) is calculated to be the sum of the minimized performance associated with the corresponding intersection state at the succeeding interval (which has already been calculated because the procedure moves backwards), the initial queues, and the arrivals minus the departures during the stage.

The dynamic programming procedure as applied to the traffic signal control problem can be summarized as follows:

1. Select an intersection state at Interval i; that is, select a specific queue length and signal status within the valid ranges for each approach.
2. Calculate the total performance (e.g., delay) for intervals i to n (the last interval in the stage) for each input decision (i.e., calculate the delay assuming the signal changes in Interval i and recalculate the delay assuming there is no change).
3. Choose the policy for Interval i to be "change" or "no change" based on which produced the best total performance.
4. Repeat Steps 2 and 3 for all valid input states at Interval i.

The procedure is terminated when Interval 1 has been reached and yields values for the optimum policy and minimized total performance for each initial intersection state.

Although this procedure ensures globally optimal solutions, it requires complete knowledge of arrivals over the entire control period. It cannot be used for real-time implementation because of the amount of processing involved. Much of the output from the program is never implemented because optimized policies are generated for all possible combinations of initial conditions at each stage of the control period. If an "entire optimum policy" is defined as the complete sequence of optimized policies throughout the control period that corresponds to a particular initial state at Interval 1, then the algorithm could produce hundreds of such policies. However, in practice, only one initial state at Interval 1 exists; hence, only one "entire optimum policy" would be implemented. By being able to produce the theoretically optimal control strategy for each input state, OPAC-1 is a standard for the evaluation of the relative effectiveness of other, more practical strategies.

Sequential Optimization: OPAC-2

The second optimization algorithm, OPAC-2, is a simplification of the OPAC-1 algorithm. It was designed as a building block in the development of a distributed on-line strategy. OPAC-2 has the following features:

- The control period is divided into stages T sec long. In this case, T is approximately equal to a typical cycle length, although it could be longer. (It should be remembered that there is no fixed cycle length in OPAC.)
- Each stage is divided into an integral number of intervals s sec long. For development of the algorithm, $s = 5$ sec was chosen.
- Each stage must include at least one signal phase change and may include as many as three. The phase change (switching) times are measured from the start of the stage in time units of s.
- For any given switching sequence at stage n, the performance function for each approach is defined to be the sum over all intervals in the stage of the initial queue length plus the arrivals minus the departures during each interval.

The optimization problem in OPAC-2 is stated as follows: For each stage, given the initial queues on each approach and the arrivals for each interval of the stage, determine the switching times, in terms of intervals, which yield the least delay to vehicles over the whole stage.

The procedure used for solving the problem is an optimal sequential constrained search method. It is an exhaustive search of all possible combinations of valid switching times within the stage to determine the optimum set. Valid switching times are constrained by minimum and maximum phase durations.

Rolling Horizon Approach: ROPAC

Although the OPAC-2 optimization procedure lends itself more readily to operation in real time than OPAC-1, it still requires knowledge of arrivals over the whole stage. Depending on minimum phase durations, the stage might be 1 or 2 min long. Obtaining actual arrivals over this length of time might be difficult. However, OPAC-2 could be imple-

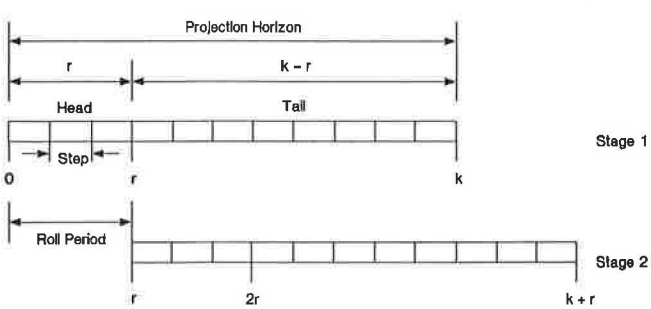
mented with a traffic prediction model that predicts the traffic pattern over the entire stage. Although using a prediction model might simplify the optimization, research and experimentation with predictors has shown that they are less effective than historical data and are unreliable as estimators of traffic arrival patterns. In essence, it is difficult to predict what will happen during the next cycle based on what happened during the previous cycle (*3*).

In order to use only available flow data without degrading the performance of the optimization procedures, a "rolling horizon" concept was applied to the OPAC-2 algorithm; it was renamed ROPAC (*5*). In this version, the stage length consists of k intervals. The stage is called the projection horizon (or simply horizon) because it is the period over which traffic patterns are projected and optimum phase change information is required. The horizon is typically equal to the average cycle length. With intervals of 4 sec and an average cycle length of 60 sec, the horizon would be approximately 15 intervals.

From detectors placed upstream of each approach, actual arrival data for r intervals can be obtained for the beginning, or head, portion of the horizon. For the remaining $k - r$ intervals, the tail of the horizon, flow data may be obtained from a model. A simple model consists of a moving average of all previous arrivals on the approach. An optimal switching policy is calculated for the whole horizon, but only those changes occurring within the head portion are actually being implemented. Thus, there is a chance for dynamically revising the decisions when more recent real-time data are being obtained.

It is important that the detectors be placed well upstream of the intersection (10 to 15 sec travel time) in order to obtain actual arrival information over the head period. As indicated earlier, traffic prediction models have proven unreliable in determining optimum signal timing. Knowing actual arrivals, however, allows for the exact calculation of delay based on particular phase change decisions. Hence, it is important to have actual arrival data over the period for which phase changes will be implemented.

At the conclusion of the current head period, a new projection horizon containing new head and tail periods is defined, with the new horizon beginning at (rolled to) the termination of the old head period. The calculations are then repeated for the new projection horizon. Figure 1 illustrates the procedure. The roll period can be any multiple number of steps, including one. It does not necessarily have to equal the head period. A smaller roll period implies more frequent calculations and, generally, closer to optimum (i.e., ideal) results.



1 Step = n Seconds ($n \geq 1$)
k = The Number of Steps or Intervals in the Projection Horizon
r = The Number of Steps for Which Actual Arrival Data Is Known

FIGURE 1 OPAC algorithm rolling horizon concept.

Real-Time OPAC: OPAC-RT

The real-time traffic control system developed for implementing the OPAC strategy uses the OPAC software as the signal timing optimization algorithm. The system developed for this study is designated as the Real-Time OPAC Traffic Signal Control System (OPAC-RT).

OPAC-RT Version 1.0: Two-Phase Operation

Version 1.0 of the OPAC-RT Traffic Signal Control System uses the ROPAC software with no modifications or enhancements that would affect its phase change decisions. The primary objective of Version 1.0 of the OPAC-RT system is to effectively control the signal timing at a two-phase, fully actuated, isolated intersection.

OPAC-RT Version 2.0: Dual-Ring, Eight-Phase Operation

Based on the observed performance of Version 1.0, various enhancements were identified. These enhancements were expected to increase its effectiveness and make it more generalized in terms of the locations for which the system could be used. These enhancements were incorporated into Version 2.0. The primary objective of Version 2.0 of the OPAC-RT system is to effectively control the signal timing at an isolated intersection controlled by a dual-ring, eight-phase controller. Only the major phases, typically the through phases, are actually controlled by the system. The minor phases, typically the left-turn phases, are treated by OPAC as part of the intergreen period. The minor phases are controlled by the usual "gap out/max out" strategy.

The system collects vehicle arrival information from upstream detectors as well as signal indications, which are supplied as inputs to a modified version of the ROPAC strategy. The system then implements the switching decisions produced by the optimization algorithm. The system also stores system conditions throughout the control period. This information includes phase returns, HOLD release times, walk requests, the time of the occurrence of any errors, detector occupancies, and arrival patterns. A detailed description of the OPAC-RT software structure is given elsewhere (*10*).

EVALUATION OF REAL-TIME OPAC STRATEGY

Three field tests were conducted to evaluate OPAC-RT: two for evaluating Version 1.0 and one for Version 2.0. Each field test consisted of two phases. In the first phase, the values of three parameters required by the algorithm were fine-tuned to yield the best possible performance. The parameters are

- Saturation flow per approach (Field Tests 1 and 2) or per phase (Field Test 3),

- Travel time in seconds from the OPAC-RT detectors to the stop line, and
- Horizon length.

The horizon is the time period over which the OPAC-RT optimization algorithm calculates its switching decisions. It consists of a head and a tail portion. In the head portion of the horizon, the algorithm has available real-time vehicle arrival information. In the tail portion, the flows are estimated from previous measurements. This estimation requires a "smoothing factor" which was calibrated prior to the field tests.

The second phase of the test plan was performed as a before-and-after study. Two measures of effectiveness were selected for comparing the operation of the intersection under full-actuated and OPAC-RT control. These were delay, defined as vehicle-seconds of delay per vehicle, and percentage of stopped vehicles. Average cycle lengths under both modes of operation were also recorded and compared.

In the before study, a well-timed actuated controller was in control of the intersection. The test plan called for the collection of volume counts, stops, and delay data on each of 3 days for approximately 3 hr each day. Data were to be collected in 25-min segments, yielding 18 sets of observations. An observation consisted of volume counts, stops, and delay by approach per cycle. Delay was calculated by recording the number of stopped vehicles on each intersection approach at a fixed data collection time interval and multiplying this number by the time interval.

The after study was conducted in the same manner, with the OPAC-RT algorithm in control of the intersection. The plan specified that the before and after data collection would be conducted on the same days of the week. Allowances were made for adverse conditions such as bad weather so that a particular field test could be completed in 2 weeks, even if the before and after data were not collected on the same days of the week.

In evaluating the OPAC-RT system, a simple comparison of the observations of delay and percent stops under full-actuated and OPAC-RT control was determined to be inadequate to develop a full understanding of the algorithm's operation. It was postulated that the performance of the OPAC-RT algorithm would be better understood if measured as a function of volume conditions on the major and minor streets. This approach to the evaluation was based on some inherent characteristics of both Version 1.0 of the OPAC algorithm and the actuated controller. Version 1.0 requires at least one phase change per horizon length. Thus, even if there are no calls from the side street, OPAC-RT services the side street once per horizon and causes delay to the major street. The actuated controller does not change phases unless there is a call from the side street, causing no delay to the major street when there is no volume on the side street. This handicap to the OPAC operation was only later removed for Field Test 3.

On the other hand, an actuated controller cannot distinguish one call on the minor street from many calls on the major street. In other words, if flows are high on the major street and low on the minor street, the actuated controller may cause excessive delay to the major street because it assigns the same value to the single vehicle on the minor street as it assigns to the many vehicles on the major street. Such myopia is an inherent handicap of vehicle-actuated control. In this respect, the OPAC-RT algorithm is "smarter" because it counts the many vehicles and considers them more important than a single vehicle on the minor street.

Moreover, because there is no preference to "major" or "minor" directions in the OPAC terminology, what actually counts is the total volume approaching the intersection. It became clear that the performance measure (average delay) should be evaluated as a function of the total volume. To seek a meaningful functional relationship between the two variables, a further decision had to be made about what basic data unit to use in the statistical analysis. Data were collected on a per cycle basis; however, because the phase lengths vary with the changing arrival rates, the cycle length is also variable. Consequently, we have a chain reaction in which the volume per cycle and the average delay are not independent. The statistical data unit must consist of a fixed-time interval that is independent of the resulting control parameters. Therefore, it was decided to aggregate all data into a constant interval approximately 10 min long (600 sec.). These basic data units were then used to compare the performance of OPAC-RT versus actuated control and to derive regression models of average delay versus total volume.

Field Test 1

The location chosen for the first field test, the initial testing of the on-line OPAC strategy, was the intersection of North George Mason Drive and North 16th Street in Arlington, Virginia. This intersection offers low to moderate volume levels and is controlled by a two-phase, full-actuated traffic signal. The north and south approaches are multilane. Detectors supplying information to the OPAC-RT system were located approximately 600 ft (180 m) from the stop lines. Call-only detectors at the stop line in each lane were 6 ft by 50 ft (1.8 m by 15 m). The intersection is normally operated under loop/occupancy control using stop-bar detectors.

OPAC-RT input parameters were calibrated as specified by the test plan. Saturation flow rates were calculated by measuring the discharge rate of standing queues on each approach with adjustments for start-up lost times. Because some of the approaches had very low volumes, the saturation flow rates are thought to be overestimated. This was a further handicap for the OPAC algorithm, because it alone explicitly requires these rates in the optimization procedure. This effect was partly mitigated by the fact that the lowest-volume approaches have only a minor influence on the overall intersection performance optimization. Travel times from the OPAC-RT detectors to the stop lines were all 12 sec. The horizon length was 12 steps or 48 sec. The step size was 4 sec. The head period of the projection horizon was 3 steps.

Delay

Figure 2 shows the scatter plots of the aggregated data under actuated and OPAC-RT control. A hyperbolic model was chosen for the regression analysis. The regression results, summarized in Table 1, indicate a weak correlation, probably

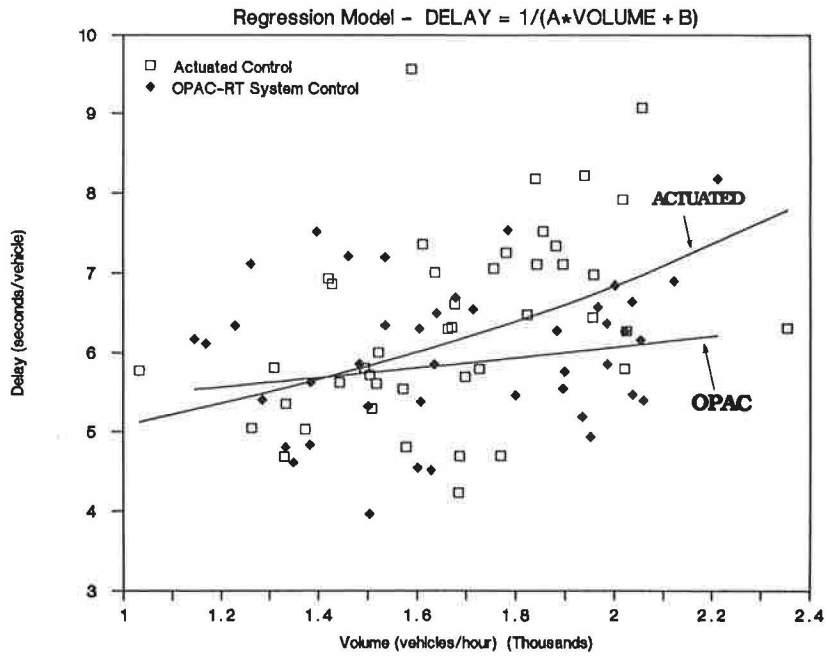


FIGURE 2 Field Test 1 aggregated delay data—regression results.

TABLE 1 SUMMARY OF REGRESSION RESULTS FOR DELAY, FIELD TEST 1, NONLINEAR (HYPERBOLIC) REGRESSION—DELAY = $(A_0 * \text{VOLUME} + A_1)^{-1}$

REGRESSION COEFFICIENTS

VARIABLE	ACTUATED CONTROL	OPAC-RT CONTROL
Volume (A_0)	-0.00005	-0.00001
Constant (A_1)	0.2427	0.2018

OTHER STATISTICS

	ACTUATED CONTROL	OPAC-RT CONTROL
R SQUARED	0.1916	0.0386
SAMPLE SIZE	43	42

because of the small range in values for the independent variable, the flows. These data were later combined with those from Field Test 2, and the resulting regression equation proved much more satisfactory. The average delay for the aggregated data under actuated control was 6.29 sec. Under OPAC-RT system control, the average delay was 6.04 sec. On the average then, OPAC-RT yielded a 3.9 percent reduction in delay to vehicles.

The results of the first field test indicate that OPAC-RT Version 1.0 has the potential to improve the operation of isolated intersections. At the lower volumes at this intersection, the average delays under actuated and OPAC-RT system control were essentially identical. At the higher volumes, however, the difference became larger. It must be recognized in this case, however, that the OPAC-RT Version 1.0 worked under two handicaps: the requirement that the minor side street be serviced even though there are no vehicle calls, and the upward bias of the saturation flow values. To make more definitive statements regarding the operation of the OPAC-RT system, an analysis of an intersection with a wider range in flows—particularly higher flows—was required. This requirement was taken into consideration in selecting the second field test site.

Percent Stops

In a manner similar to the delay data, the stops data (total vehicles and stopping vehicles) were aggregated into time periods of approximately 600 sec. Despite the fact that OPAC-RT Version 1.0 does not optimize for stops, the percentage of stopping vehicles was decreased under OPAC-RT control on the average of 1.6 percent. This decrease is almost insignificant but may be due, in part, to the slightly higher average cycle length observed under OPAC-RT system control. In general, research has shown that shorter cycle lengths increase stopping percentages.

Average Cycle Length

On the average, the cycle lengths under actuated and OPAC-RT control were similar. Under actuated control, the average cycle length was 40 sec. Under OPAC-RT system control, the average cycle length was 44 sec. Despite the slightly higher average cycle length, both delay and stops were decreased on the average under OPAC-RT system control. Although the improvements in performance were modest, it must again be recognized that several requirements of the Version 1.0 system, including required servicing of the minor side street and equal minimum and maximum greens for each phase, degrade the performance of the OPAC algorithm, particularly at low volumes. Another source for degradation is the estimated saturation flow rate.

Field Test 2

The location chosen for the second field test was the intersection of Flowing Wells Road and Prince Road in Tucson, Arizona. At the time of the second field test, it was a two-phase semiactuated intersection with both phases serving multilane approaches. This intersection offered moderate to high volume levels. As part of a computer-controlled network, the intersection was placed off-line during the data collection period.

The remote OPAC detectors were located between 600 and 650 ft from the stop lines. The OPAC-RT input parameters were calibrated according to the test plan. Travel times from the OPAC-RT detectors to the stop lines were all 12 sec. The horizon length was 15 steps, or 60 sec. The step size was 4 sec. The head period of the projection horizon was 3 steps.

Delay

Figure 3 shows the scatter plots of the aggregated data under actuated and OPAC-RT control. Of several linear and nonlinear models, a hyperbolic model yielded the best results for the regression analysis. The regression results, summarized in Table 2, indicate weak correlation. But, when combined with the data from Field Test 1, the resulting regression equation provides a satisfactory explanation. The average delay for the aggregated data under actuated control was 15.81 sec. Under OPAC-RT system control, the average delay was 13.29 sec. In addition, the volumes under OPAC-RT control were found to be higher by an average of 4.12 percent. On the average then, OPAC-RT yielded a 15.94 percent reduction in delay to vehicles despite an increase in volume.

As noted earlier, the intersection in Tucson is part of a computer-controlled network and was placed off-line during the field study. Traffic patterns at the intersection were platooned because surrounding intersections were still on-line.

TABLE 2 SUMMARY OF REGRESSION RESULTS FOR DELAY, FIELD TEST 2, NONLINEAR (HYPERBOLIC) REGRESSION—DELAY = $(A_0 * \text{VOLUME} + A_1)^{-1}$

REGRESSION COEFFICIENTS

VARIABLE	ACTUATED CONTROL	OPAC-RT CONTROL
Volume (A_0)	-8.39×10^{-6}	-2.09×10^{-5}
Constant (A_1)	0.09494	0.1568

ANALYSIS OF VARIANCE - ACTUATED REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.00033	0.00033	3.13238	0.0876
Residual	0.00299	0.00011		

ANALYSIS OF VARIANCE - OPAC-RT REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.00188	0.00188	9.48554	0.0053
Residual	0.00456	0.00020		

OTHER STATISTICS

	ACTUATED CONTROL	OPAC-RT CONTROL
R SQUARED	0.1006	0.29199
SAMPLE SIZE	30	25

The reduced delay under OPAC-RT control indicates the degree to which the OPAC strategy responds to platooned traffic.

The results of the second field test support the findings from the first field test and indicate that OPAC-RT Version 1.0 has considerable potential for improving the operation of isolated intersections. It must be recognized, however, that the OPAC-RT Version 1.0 requirement that the minor side street be serviced, even though there were no vehicle calls, degraded OPAC's performance in this case as well. Despite the considerable reduction in delay, it was postulated that the

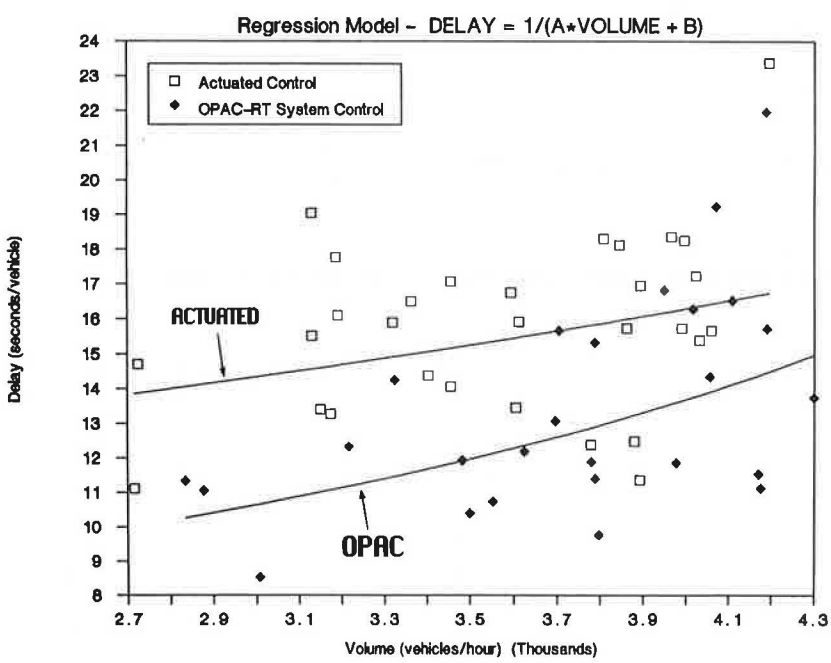


FIGURE 3 Field Test 2 aggregated delay data—regression results.

OPAC-RT system could do much better if certain constraints on the algorithm were removed. Some of these constraints were later removed, and the resulting system was evaluated in Field Test 3.

Percent Stops

Similar to the per cycle delay data, the per cycle stops data (total and stopping vehicles) were also aggregated into intervals of approximately 600 sec. Despite increased volumes and the fact that Version 1.0 of the algorithm does not optimize stops, OPAC-RT increased stops by only 3.9 percent. The increase in stops may be due, in part, to the significantly shorter average cycle length under OPAC-RT control. In general, past research has shown that shorter cycle lengths increase stopping percentages.

Average Cycle Length

On the average, the cycle lengths under actuated and OPAC-RT control were very different. Under actuated control, the average cycle length was 86 sec. Under OPAC-RT system control, the average cycle length was 55 sec. This difference in cycle length was expected because the OPAC algorithm forces the termination of a phase at the calculated optimum time by issuing a FORCE OFF command to the controller. The actuated controller may dwell in a particular phase if there is sufficient demand because the variable green interval will be extended by the passage of each detected vehicle.

Field Tests 1 and 2 Combined

An additional analysis was conducted on the delay data combined from the first and second field tests. To obtain a common basis for the two data sets, the volume/saturation flow ratio was used as the independent variable. Figure 4 shows the aggregated data and the resulting regression equations. Table 3 summarizes the regression results. As indicated in the table, the hyperbolic regression equations were adequate models for the relationship between delay and volume. These models provide a much better fit to the combined data than do the regression models for the individual field tests. This is due primarily to the greater number of data points and the wider range available for the independent variable in this case. The average delay under actuated control for the combined data was 8.13 sec. The average delay under OPAC-RT control for the combined data was 7.41 sec. Thus, there was a 9 percent decrease in average delay under OPAC-RT control.

The combined analysis supports the conclusions from the first and second field tests that the real-time OPAC system has considerable potential for decreasing delay at isolated intersections. As expected, under low volume conditions the benefits of the OPAC-RT system over the actuated controller are small; however, the benefits increase dramatically at higher volumes. As can be seen in the figure, the reduction in delay at volume/capacity ratios of 0.90 and up can be 30 percent or higher.

Field Test 3

The location for the third field test was also at the intersection of Flowing Wells Road and Prince Road in Tucson, Arizona. This intersection was chosen because it was being converted to eight-phase, dual-ring operation and the OPAC detectors required for the OPAC-RT system were already in place. As indicated in the discussion of the second field test, the intersection is part of a computer-controlled network and was placed off-line during the field study.

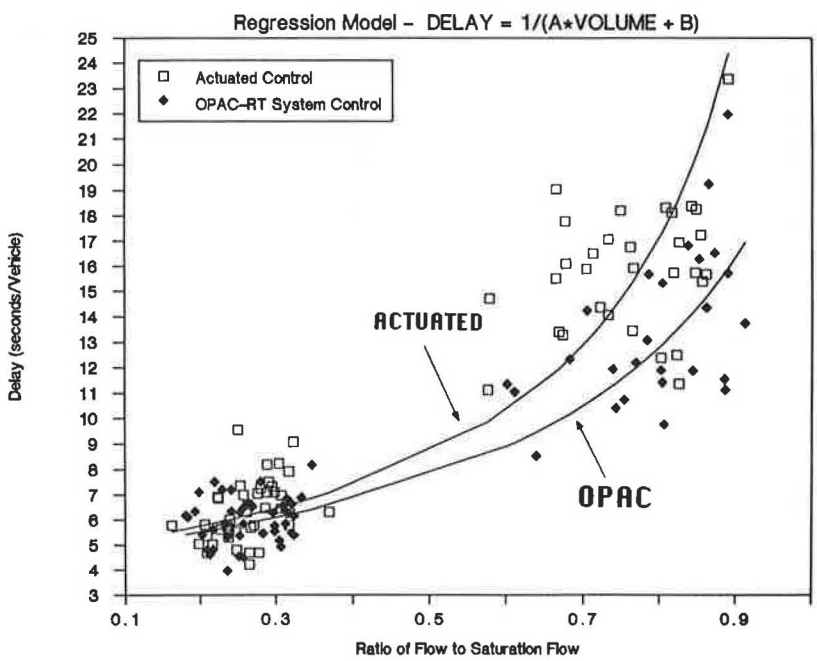


FIGURE 4 Aggregated delay data for Field Tests 1 and 2 combined—regression results.

TABLE 3 SUMMARY OF REGRESSION RESULTS FOR DELAY, FIELD TESTS 1 AND 2 COMBINED, NONLINEAR (HYPERBOLIC) REGRESSION—DELAY $= (A_0 * \text{VOLUME} + A_1)^{-1}$

REGRESSION COEFFICIENTS

VARIABLE	ACTUATED CONTROL	OPAC-RT CONTROL
Volume (A_0)	-4.87×10^{-5}	-4.17×10^{-5}
Constant (A_1)	0.2427	0.2378

ANALYSIS OF VARIANCE - ACTUATED REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.16964	0.16964	293.3791	0.0000
Residual	0.04047	0.00058		

ANALYSIS OF VARIANCE - OPAC-RT REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.1268	0.1268	219.3086	0.0000
Residual	0.0370	0.00058		

OTHER STATISTICS

	ACTUATED CONTROL	OPAC-RT CONTROL
R SQUARED	0.8074	0.7741
SAMPLE SIZE	72	66

Figure 5 shows the physical layout of the intersection. The operation was eight-phase with lagging left turns on all approaches. The left-turn phases were treated by OPAC-RT as part of the intergreen period. The logic maintains an exponentially smoothed average duration for each minor (typically, left-turning) phase for use in calculating the optimum durations of the major (typically, through) phases. Call-only and OPAC detectors and their locations with respect to the stop lines at the intersection are shown in the figure.

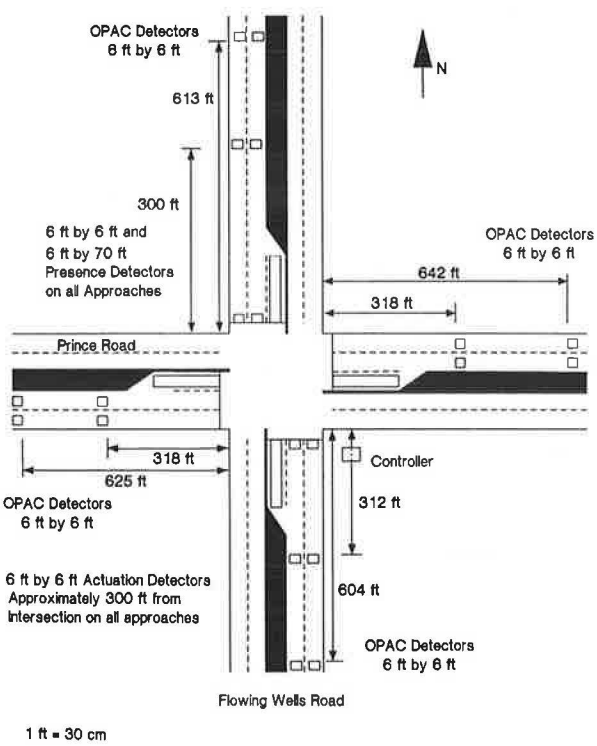


FIGURE 5 Field Test 3 site—Tucson, Arizona.

Saturation flows were recalculated for the third field test. Because left-turning vehicles were permitted during the through phases, it was impossible to determine saturation flows for the turning phases according to the procedures of the test plan. Saturation flows of 1,800 vehicles per hour were assumed for these minor phases. Travel times from the OPAC-RT detectors to the stop lines were all 12 sec. In order to accommodate the new phasing, the horizon length was increased to 20 steps, or 100 sec. The step size was 5 sec. The head period of the projection horizon was 3 steps. Also, the passage time for the through phases was 5 sec. under actuated control. The horizon length was extended to accommodate the new eight-phase configuration.

Delay

Figure 6 shows the aggregated field test data and the hyperbolic curves resulting from the regression analysis. Table 4 summarizes the regression and analysis of variance results. As indicated by the table, the hyperbolic models show weak correlation between delay and volume. As with both Field Tests 1 and 2, this is probably due to the limited range of volume data observed during the field test.

The average delay under OPAC-RT control was 19.23 sec. The average delay under actuated control was 20.83 sec. Operation under OPAC-RT yielded a 7.7 percent reduction in delay overall. The reduction in delay under OPAC-RT control indicates the responsiveness of the algorithm to platooned traffic. As indicated earlier, the intersection is part of a system. Although this intersection was off-line during the field study, the surrounding intersections remained on-line, producing platooned traffic at the intersection of Prince Street and Flowing Wells Street.

The benefits of OPAC-RT, with respect to delay, are not as impressive as those observed during Field Test 2. However, the results do indicate that the enhanced OPAC algorithm has the potential for improving the operation of isolated intersections. As indicated earlier, Version 2.0 uses several averaging functions for information required by the signal timing optimization algorithm. For example, the minor (typically, left-turning) phases are treated as part of the intergreen period. Hence, the algorithm must have estimates of the durations of these phases in order to perform its optimization. The estimates of these phases are made via an exponential smoothing function using a user-input smoothing factor. Errors in these estimates could greatly degrade the performance of the intersection under OPAC-RT control. It is expected that better calibration procedures of the various user-input parameters and smoothing values will further increase the benefits of the OPAC-RT system.

Percent Stops

Although stops were included in the optimization function, OPAC-RT increased percent stops by an average of 9.5 percent. However, the weighting of stops relative to delay was only 1; in reality, this weighting favors delay. A weighting of 15 or 20 should have caused a decrease in stops. If the trends observed during the three field tests are to be taken as valid,

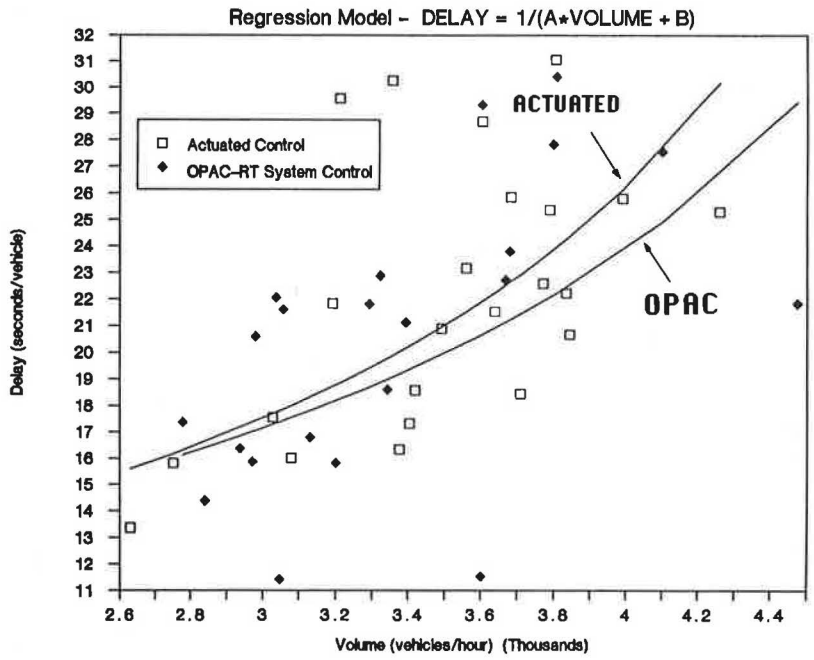


FIGURE 6 Field Test 3 aggregated delay data—regression results.

then shorter cycle lengths reduce delay and increase stops, and longer cycle lengths increase delay and reduce stops. For some combination of weighting factors for delay and stops, both will be optimized. Another factor affecting the performance of the algorithm with respect to stops is the estimation of minor phase (left-turning) volumes. Errors in this estimation may cause errors in the calculation of stops. This could be improved by better calibration procedures.

Average Cycle Length

Again, for the third field test, the cycle lengths under actuated and OPAC-RT control were very dissimilar. Under actuated control, the average cycle length was 110 sec. The average cycle length under OPAC-RT control was only 80 sec. This difference was not unexpected, given the results of the second field test. As indicated, research has indicated that shorter cycle lengths decrease delay and increase stops, and longer cycle lengths tend to increase delay and decrease stops. Because the weighting of stops relative to delay during this field test favored delay, it was expected that the average cycle length under OPAC-RT control would be shorter.

TABLE 4 SUMMARY OF REGRESSION RESULTS FOR DELAY, FIELD TEST 3, NONLINEAR (HYPERBOLIC) REGRESSION—DELAY = $(A_0 * \text{VOLUME} + A_1)^{-1}$

REGRESSION COEFFICIENTS

VARIABLE	ACTUATED CONTROL	OPAC-RT CONTROL
Volume (A_0)	-1.90×10^{-5}	-1.65×10^{-5}
Constant (A_1)	0.11397	0.10787

ANALYSIS OF VARIANCE - ACTUATED REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.00121	0.00121	15.9983	0.0007
Residual	0.00159	0.00008		

ANALYSIS OF VARIANCE - OPAC-RT REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.00108	0.00108	5.81276	0.0256
Residual	0.00372	0.00019		

OTHER STATISTICS

	ACTUATED CONTROL	OPAC-RT CONTROL
R SQUARED	0.4324	0.2252
SAMPLE SIZE	23	22

SUMMARY AND CONCLUSIONS

Three field tests of the real-time OPAC traffic signal control system were conducted. The first two tests evaluated the first version of the OPAC system, which was limited to the control of two phase intersections. Based on the observed performance of this version, various enhancements were identified both to increase the effectiveness of the system and to permit installation of OPAC for control of a broad range of controller phasing configurations. After making the required modifications, the second version was evaluated during the third field test, which was conducted at a site operating with an eight-phase, dual-ring controller.

The principal measures of effectiveness selected for comparison of the performance of an actuated controller and the OPAC systems were delay and percentage of vehicles forced to stop. During the first field test, both delay and percent of stops were decreased when the intersection was under OPAC control. The improvements were modest; on the average, delay was decreased by 3.9 percent and stops were decreased by 1.6 percent. However, the observed volumes during this field test were extremely low and the OPAC algorithm was

handicapped in its operation. More definitive statements regarding the performance of OPAC required the analysis of stops and delays at higher volume levels.

During the second field test, delay was considerably reduced under OPAC control. On the average, delay was reduced by 15.9 percent despite an increase of 4 percent in average volumes. The percentage of vehicles forced to stop, on the other hand, was increased only by 3.9 percent. Because stops were not an OPAC measure of effectiveness in the first version of the system, and because there was also an increase in volume during OPAC operation, this minor increase in stops was to be expected. During the third field test, which was conducted at an eight-phase intersection, delay was decreased on the average by 7.7 percent and the percentage of stopped vehicles was increased by an average of 9.5 percent.

The first version of the OPAC traffic control system was handicapped by several constraints. Despite these limitations, it has demonstrated a potential for significantly improving intersection performance as measured by delay and percentage of stopping vehicles. The results of the third field test indicate that the enhanced OPAC system also improves the operation of multiphase signalized intersections.

The OPAC strategy represents a new dimension in traffic signal control, the potential of which has not yet been fully realized. It carries out sophisticated optimization in real time and adapts to varying traffic conditions. This study has shown that it works well in a field environment and can provide significant benefits over well-timed actuated controllers. A preliminary economic analysis has shown that the incremental costs associated with its implementation as is can be recovered within less than 1 year of operation (*10*). This conclusion was reached notwithstanding the fact that it is only a first implementation of a previously untested method. It can be expected that further enhancements of the method and, especially, the development of improved calibration procedures will help to further improve the performance of the real-time OPAC system.

Because OPAC is a smart controller, it forms a building block for a distributed intelligence traffic control system. Unlike conventional actuated control logic, the OPAC model can communicate with neighboring controllers so as to form a flexibly coordinated traffic control system (*12*). It can similarly be used for critical intersection control within otherwise fixed-cycle coordinated systems. Herein lies the greatest potential of this method. Further research in these areas is now being conducted.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance and encouragement provided by Stephen L. Cohen of the Office of Research, FHWA, in the conduct of this research.

REFERENCES

1. *Traffic Control Systems Handbook*. Report FHWA-IP-85-11. FHWA, U.S. Department of Transportation, 1985.
2. N. H. Gartner. On-Line and Off-Line Urban Traffic Control. *Computing in Civil Engineering 1981*. ASCE, 1981, pp. 503–513.
3. N. H. Gartner. *A Prescription for Demand-Responsive Urban Traffic Control*. In *Transportation Research Record 881*, TRB, National Research Council, Washington, D.C., 1982, pp. 73–76.
4. N. H. Gartner. Demand-Responsive Traffic Signal Control Research. *Transportation Research*, Vol. 19A, 1985, pp. 369–373.
5. N. H. Gartner. *Demand-Responsive Decentralized Urban Traffic Control, Part I: Single-Intersection Policies*. Report DOT/RSPA/DPB-50/81/24. U.S. Department of Transportation, 1982.
6. N. H. Gartner, M. H. Kaltenbach, and M. M. Miyamoto. *Demand-Responsive Decentralized Urban Traffic Control, Part II: Network Extensions*. Report DOT/OST/P-34/85/009. U.S. Department of Transportation, 1983.
7. N. H. Gartner. Development and Testing of a Demand-Responsive Strategy for Traffic Signal Control. *Proc., 1982 American Control Conference*, June 1982, pp. 578–583.
8. N. H. Gartner. OPAC: A Demand-Responsive Strategy for Traffic Signal Control. In *Transportation Research Record 906*, TRB, National Research Council, Washington, D.C., 1983, pp. 75–81.
9. H. Chen, S. L. Cohen, N. H. Gartner, and C. C. Liu. Simulation Study of OPAC: A Demand-Responsive Strategy for Traffic Signal Control. In *Transportation and Traffic Theory* (N. H. Gartner and N. H. M. Wilson, eds.). Elsevier Science Publication, 1987, pp. 233–249.
10. Farradyne Systems, Inc. *Evaluation of the Optimized Policies for Adaptive Control Strategy*. Report FHWA-RD-89-135. FHWA, U.S. Department of Transportation, 1989.
11. D. P. Bertsekas. *Dynamic Programming: Deterministic and Stochastic Models*. Prentice-Hall, 1987.
12. N. H. Gartner. Adaptive Control of Traffic Signal Networks. *Proc., 1st International Conference on Applications of Advanced Technologies in Transportation Engineering*, San Diego, Calif., ASCE, 1989, pp. 373–377.

Publication of this paper sponsored by Committee on Traffic Signal Systems.