A Rule-Based Real-Time Traffic Responsive Signal Control System with Transit Priority:
Application to an Isolated Intersection

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ABSTRACT

Previous experience has shown that real-time, traffic-responsive signal control has the ability to improve traffic operations in urban areas when compared to traditional fixed-time control. However, most of these experiences have focused primarily on the impact on private automobiles. This paper describes the development and evaluation of a fully distributed, real-time, traffic-responsive model named SPPORT (Signal Priority Procedure for Optimization in Real-Time) that explicitly considers the impacts of transit vehicles. This model is unique in two ways. First, the model explicitly considers the interference caused to the general traffic by transit vehicles stopping in the right of way to board and discharge passengers. Second, when considering priority passage for transit vehicles, the potential effects that such preferential treatment might have on other traffic is explicitly quantified.

This paper describes the structure of the model and demonstrates it capabilities on an isolated intersection for a range of traffic demands and with and without transit vehicles. The rule-based signal optimization procedure provided delay reductions for most of the traffic conditions examined when compared to both fixed-time and traffic actuated control. While the results reported in this paper are limited to an isolated intersection, the model is capable of being applied to a network of signals. Evaluation of its performance on a corridor has been conducted and will appear in the literature in the near future.

INTRODUCTION

Past research and experience have clearly demonstrated the ability of real-time, traffic-responsive signal optimization techniques to reduce the stops and delay incurred by motorists at individual signalized intersections (see for example Henry and Farges, 1989; Kelman et al., 1993; Wood, 1993; Mauro and Di Taranto, 1989; Remer and Minge, 1999; Gartner et al., 1991). However, these techniques have typically not explicitly considered the unique characteristics of transit and other high-occupancy vehicles.

The Signal Priority Procedure for Optimization in Real-Time (SPPORT) model was created specifically with the objective of explicitly considering the unique nature of transit vehicles (Yagar et al., 1992, 1994; Conrad et al., 1998). The model is designed to provide effective transit priority while still giving appropriate consideration to other traffic. It is unique in that it employs a rule-based optimization process to generate candidate signal timing plans. Phase plans are generated using generic lists of rules that allocate different priorities to key traffic events at each intersection. For each anticipated event, a request is generated calling for either a green or a red signal indication on a given link at a given time. Using a heuristic decision-making process, phase plans are then generated for each intersection to best accommodate the requests that were generated.

The research described in this paper differs from the earlier work of Yagar, Han, and Conrad in three ways. First, the SPPORT signal-control system has been enhanced. The heuristic rules used to determine the optimal signal control strategy have been assigned numeric priority levels and several additional rules have been incorporated. Second, the scenarios used to evaluate the system are more challenging and a wider range of conditions have been evaluated with respect to the impact that stopped transit vehicles have on the general traffic stream. Third, in this paper, the SPPORT model performance is compared to both fixed-time control (Webster) and actuated control.

Following a more detailed description of the model, this paper presents the results of a series of simulation tests that were conducted to evaluate the model's ability to efficiently control traffic in real-time at individual intersections under various control conditions. More precisely, these tests evaluate the operation of the model under constant and peaking traffic demands, as well as in scenarios in which transit vehicles are provided priority of passage on a conditional basis.

THE SPPORT MODEL

Notation

α_R = User-specified coefficient defining the relative importance of stopped vehicles on an approach with a green signal in relation to stopped vehicles on an approach with a red signal ($\alpha_R \geq 0$).

$d_{car\,i}$ = Total delay incurred by passenger car i (seconds).

$d_{transit\,i}$ = Total delay incurred by transit vehicle i (seconds).

d_n = Total delay incurred by vehicle n in the controlled system (seconds).

I = Number of intersections in controlled network.

k_d = User-specified coefficient defining the relative importance of delay ($k_d \geq 0$).

k_S = User-specified coefficient defining the relative importance of stops ($k_s \geq 0$).

k_{TC} = User-specified coefficient defining the relative importance of the terminal cost ($k_{TC} \geq 0$).

k_{TT} = User-specified coefficient defining the relative importance of travel time ($k_{TT} \geq 0$).

N_{cars} = Total number of passenger cars entering the controlled network.

N_L = Number of approach links to intersection i.

$N_{transit}$ = Total number of transit vehicles cars entering the controlled network.

N_v = Total number of vehicles of type v entering the controlled network during a given period of time.

o_v = User-specified coefficient representing the average occupancy or relative importance of a vehicle of type v ($o_v \geq 0$).

PI = Performance index.

$Q_{end\,j}$ = Queue size on link j at end of decision horizon (passenger car units).

$q_{sat\,j}$ = Saturation flow rate on approach link j (passenger car units/second).

$R_{min\,j}$ = Shortest remaining red duration on approach link j (seconds).

s_n = Total number of stops incurred by vehicle i in the controlled system.

TC_i = Terminal cost for intersection i at end of the performance evaluation period.

TT_n = Total travel time of vehicle i in the controlled network (seconds).

U_j = Signal display on approach link j (0 if green, 1 if red).

V = Number of different vehicle types.

Real-Time Signal Operation

The SPPORT model provides real-time, traffic-responsive signal control using a discrete time, rolling horizon process. As illustrated in Figure 1, the model typically generates a new phase plan for the next minute or so of signal operation every few seconds. Signal optimization frequency is specified by the user and is typically in the range of 5 to 10 seconds. At each optimization stage, a timing plan for the next 40 to 120 seconds of signal operation is built by evaluating at constant intervals whether the current phase should be terminated immediately or extended for another decision interval up to the next decision point. At the end of the process, only the first few seconds of the newly generated plan are implemented, but the unimplemented portion of the plan is used as a first estimate of future timing decisions.

Similar to other control systems, including OPAC (Gartner, 1983; Gartner et al, 1990 & 1995; Pooran et al, 1999), RHODES (Head et al, 1992; Head, 1995; Dell'Olmo and Marchandani, 1995), PRODYN (Wood, 1993; Henry and Farges, 1989) and UTOPIA (Mauro, 1991) and unlike SCOOT (Robertson,

1986; Bretherton, 1996) and SCATS (Lowrie, 1982), the SPPORT model is acyclic, implying that the traditional concepts of cycle time and green allocation are not used. At each decision point, the control decisions are whether or not to end the current phase and which phase to go to next if the current phase is to be terminated. While a cyclic operation facilitates the analysis of traffic behavior around controlled intersections by ensuring the repetitiveness of signal timings over time, it may not provide the necessary flexibility to respond to large unexpected changes in traffic demands or to efficiently accommodate transit priority requests.

Traffic Detection

As with most traffic-responsive signal control systems, the SPPORT model relies heavily on projected vehicle arrival information to make signal-switching decisions. This information is obtained from traffic detectors installed at strategic points along the approaches to the intersection under control. The model allows the placement of one or more traffic detectors at any point along intersection approaches.

Each time a vehicle passes over a detector, the detection time and type of vehicle are recorded by SPPORT. This information is then used to project vehicle arrival times at the intersection stop line of every approach link. Projections are made within the model using a discrete-event microscopic simulation model that has been explicitly designed to operate with the SPPORT model (Conrad et al., 1998). The simulator is object-oriented and considers three object types, namely *vehicles*, *segments*, and *vehicle activities*. The user defines the number of segments and vehicle activities. Vehicles are automatically generated during simulation on the basis of user-defined flow parameters (e.g., statistical distributions of inter-arrival times, platoon characteristics, arrival lists, etc.). The simulator has the ability to model the effects that transit vehicles have on the general traffic when they stop in the right of way to board and discharge passengers.

Rule-Based Signal-Switching Decision Process

The SPPORT model makes signal-switching decisions following a heuristic rule-based signal optimization procedure. This procedure, which is illustrated in Figure 2, was originally developed by Yagar, Han and Greenough (1992) in response to concerns that exhaustive optimization procedures such as dynamic or linear programming may be too computationally demanding for real-time signal control applications in networks with highly variable demands.

The procedure is based on the recognition that signal switches usually occur after the realization of specific discrete events such as after a queue of vehicles has reached a certain size, after a queue has just

finished dissipating, or after the detection of an incoming transit vehicle. By ignoring all events that have no importance for the signal operation, the procedure allows the SPPORT model to significantly reduce the number of potential switching combinations that need to be considered to find a near optimal solution. Specifically, the model considers the following responses to key traffic events occurring on a given intersection approach:

- If a stopline queue of *n* vehicle exists and is not being served, start serving the queue as soon as possible.
- Switch the signal display to green if the stopline queue exceeds a user-defined length.
- Maintain the current green signal indication on an approach on which the reach of the upstream queue exceeds a user-defined location.
- Switch the signal to red if a queue on one of the approach's user-defined major exit links threatens to spill back across the intersection.
- If a platoon of *n* vehicles or more is approaching the intersection, switch the signal display to green at a time that will allow the platoon to cross the intersection without being affected by vehicles stopped at the stopline.
- If a queue of vehicles is being served, continue serving the queue.
- If a platoon of vehicles is being served, continue serving the platoon.
- If a transit vehicle is approaching its transit stop, switch the signal display to green at a time that will allow the vehicle to proceed uninterrupted up to its loading point.
- If a transit vehicle is approaching the stopline, switch the signal display to green at a time that will allow the vehicle to cross the intersection without having to stop.

To account for the fact that different traffic events do not carry the same importance, each event is assigned a priority or weighting. The signal optimization algorithm then generates requests calling for either a green or a red signal indication on specific approaches at specific times in response to the identification of any prioritized event within the period during which traffic arrivals are projected at the intersection. After all the requests have been generated, the model generates signal switching decisions using a multi-objective decision-making process so as to accommodate as best as possible the list of requests for green and red signal indications obtained at the end of the demand evaluation step.

Multi-Objective Optimization Process

While the use of prioritized lists of events allows the SPPORT model to determine the relative importance of various traffic events, it is often difficult to determine beforehand which event should have the highest priority. For example, it may be established very easily that starting to serve a queue of 50 vehicles is more important that starting to serve a queue of only 10 vehicles. However, it may not be as easy to decide if providing priority to a transit vehicle should have a higher priority than serving a queue of private automobiles.

To solve the above problem, the user is permitted to provide more than one prioritized list of events for consideration by the model. When more than one list is provided, the signal optimization algorithm generates a candidate timing plan for each list and then selects for implementation the one yielding the best performance measures (Figure 3). The best phase plan is selected on the basis of a generalized performance function (Equation 1) that can linearly combine stops, delay, and travel time incurred by all vehicles travelling across the controlled intersection within the evaluation period. The user is permitted to define the relative weights associated with stops, delay and travel time (k_d, k_s, k_{TT}). For all evaluations within this paper, travel time is not considered (i.e. $k_{TT} = 0$). The function also includes a terminal cost element (Equation 2) that estimates the delays incurred beyond the end of the decision horizon by all the vehicles left in queue at that time under the assumption that no other vehicles join the queue beyond the end of the decision horizon and that queue discharge occurs at a maximum rate. The purpose of the terminal cost is to counteract a bias that could lead the signal optimization process to select signal-switching decisions that yield a low cost in the near future but a high cost thereafter.

$$PI = \sum_{v=1}^{V}\left[\sum_{n=1}^{N_v}\left(o_v\left(k_d d_n + k_s s_n + k_{TT}TT_n\right)\right)\right] + \sum_{i=1}^{I}\left(k_{TC}TC_i\right) \qquad [1]$$

$$TC_i = \sum_{j=1}^{N_L}\left(\frac{Q_{end\,j}^{\,2}}{2\,q_{sat\,j}}\cdot\left[U_j + \alpha_R(1-U_j)\right] + Q_{end\,j}\,R_{min\,j}\left[U_j\right]\right) \qquad [2]$$

DESCRIPTION OF SCENARIOS USED FOR MODEL EVALUATION

Traffic Demands

Figure 4 illustrates the intersection that was modeled to evaluate the ability of the SPPORT model to control an isolated intersection. The behavior of the model is examined for 12 scenarios. These scenarios are differentiated on the basis of three characteristics, namely whether or not the demand is temporally constant, the magnitude of traffic demand, and whether or not transit priority is to be provided.

For the temporally constant demand scenarios, the average rates at which vehicles are assumed to enter the control area from each entry link are constant over time. This is the type of demand usually assumed to exist in fixed-time signal optimization methods. In the peaking demand scenarios, the rates at which vehicles are assumed to enter the control area at the northern and southern boundary of the control area vary over time according to Figure 5, while the arrival rates at the eastern and western boundaries remain fixed. In Figure 5, rates are expressed in relation to the overall average arrival rate to indicate that the

overall one-hour demand for all peaking scenarios is the same as the overall demand in the corresponding fixed-demand scenario. The same overall demands are used to allow direct comparisons to be made between each scenario.

For each type of traffic demand, three demand levels are defined: low, medium and high. In the low demand scenarios, the demand of private automobiles is 25% lower than in the medium demand scenarios. Similarly, there is a 25% increase in demand between the medium and high demand scenarios. From a functional point of view, the low demand scenarios allow the effectiveness of the model to be tested in situations in which minimum green interval constraints greatly affect the signal operation, while the high demand scenarios allow evaluations to be made when the test intersection is operating near or at capacity. On the basis of the optimum fixed signal timings selected for the evaluation of the SPPORT model (see explanation further below), the low, medium and high demand scenarios correspond to situations in which the highest volume to capacity ratio of all the approaches to the controlled intersection is 0.73, 0.84 and 0.96, respectively. All passenger car demands are assumed to enter the network with inter-arrival times that follow a shifted negative exponential distribution. For all scenarios considering transit operations, a transit vehicle is assumed to approach the controlled intersection from both the northbound and southbound approach every 10 minutes.

Signal Control Parameters

In each scenario, the following phase sequence is imposed on the signal operation:
- Phase 1: Protected left-turn phase, serving both northbound and southbound left-turners with a 5-second minimum green interval, 10-second maximum green interval and 2-second amber interval.
- Phase 2: Main-street green interval, serving all northbound and southbound traffic with a 10-second minimum duration, 90-second maximum duration, and 5-second amber interval.
- Phase 3: Cross-street green interval, serving all eastbound and westbound traffic with a 10-second minimum duration, 60-second maximum duration, and 5-second amber interval.

For each phase, a 2-second start-up lost time is simulated. A 2-second green interval extension into the amber interval is also simulated for the main-street and cross-street green intervals. As a result of these settings, the only role of the rule-based decision making process implemented in SPPORT is to determine the best duration of each phase in the imposed sequence on the basis of current traffic conditions and given signal control parameters.

The main control parameters used by SPPORT to generate signal-switching decisions in each of the 12 scenarios are as follows:
- Length of decision horizon: 60 seconds;
- Decision interval: 5 seconds;

- Length of commitment period: 5 seconds;
- Period over which future vehicle arrivals are projected at each decision point: 45 seconds;
- Minimum queue size triggering the generation of green signal display requests: 1 vehicle;
- Minimum platoon size triggering the generation of green signal display requests: 10 vehicles;
- Maximum allowed stopline queue reach: 75% of length of individual links.

Table 1 provides the different prioritized lists used by SPPORT to perform the signal optimizations. In total, six different lists were defined. They differ from each other in the way that incoming platoons and transit vehicles are handled on individual approaches. The first two lists, labeled *1np* and *1tp*, consider approaching platoons from the northbound approach only. The next two lists, labeled *2np* and *2tp*, consider approaching platoons from the southbound approach only. The last two lists, *3np* and *3tp*, consider incoming platoons on both the northbound and southbound approaches. The labels *1tp*, *2tp*, and *3tp* refer to lists providing priority to approaching transit vehicles on both the northbound and southbound approaches, while the labels *1np*, *2np*, and *3np* refer to lists that do not provide priority treatment to transit vehicles.

Depending on the scenario being simulated, different combinations of prioritized lists are submitted to SPPORT to generate signal-switching decisions. In the scenarios with no transit vehicles, only the lists labeled *1np*, *2np* and *3np* are provided. In the scenarios in which transit activities are simulated, all six lists are provided. This allows the SPPORT model to evaluate objectively at each decision point whether or not priority should be given to an approaching transit vehicle, or whether or not the currently proposed priority scheme should be maintained.

The priority weights that appear in Table 1 were chosen on the basis of the relative importance of the events described by the rule. For example, when the down stream link (i.e. the link onto which vehicles will be discharged) is full of vehicles (experiencing queue spillback), then regardless of other considerations, it is usually wise to provide green to some other phase. Therefore, this rule has the highest priority level. The relative value of the priority weightings are important, not the absolute magnitude. Thus, the same performance would be achieved if all priority weightings were multiplied by 10, or were divided by 10. A sensitivity analysis of the impact that the relative weights has on the performance of the SPPORT model has not yet been carried out.

Fixed-Time and Actuated Reference Timings

To evaluate the ability of the SPPORT model to effectively control traffic in real-time at an isolated intersection, its performance is compared against the performance of a fixed-time signal operation based on the delay minimization principles established by Webster (1958) and against traffic actuated control.

Webster's principles state that the total delay incurred by motorists at a single intersection is minimized by allocating the total available green time during each signal cycle in proportion to the vehicular demand for each phase.

To provide a similar optimization within SPPORT only delay was considered within the Performance Index. As illustrated in Equation 3, the Performance Index consisted of three components; the person delay experienced by cars within the decision horizon, the person delay experienced by transit vehicles within the decision horizon, and the terminal cost computed for all vehicles facing a red signal at the end of the interval.

$$PI = \sum_{n=1}^{N_{cars}} \left(1.5\, d_{car\, n}\right) + \sum_{n=1}^{N_{transit}} \left(60.0\, d_{transit\, n}\right) + \sum_{j=1}^{N_L} U_j \left(\frac{Q_{end\, j}^{\;2}}{2\, q_{sat\, j}} + Q_{end\, j}\, R_{min\, j} \right) \qquad [3]$$

In Equation 3, weighting coefficients of 1.5 and 60.0 are assigned to the passenger cars and transit vehicles, respectively, to reflect differences in person occupancy between these two types of vehicles. These values allow SPPORT to compile performance measures on a person basis and to provide transit priority on the basis that 1 second of transit vehicle delay is equivalent to 40 seconds of passenger car delay.

Figure 6 illustrates the relationship between person-delay and cycle length obtained from the simulation model. For each of the 15 cycle times examined, the simulation model was executed 8 times using a different seed value each time to initiate the random number generator, and the mean delay computed. The cycle length that results in the minimum mean delay (105 seconds) is substantially lower that that predicted by Webster's method (155 seconds). This difference in optimal cycle lengths results from the use in SPPORT of a shifted negative exponential headway distribution (shift = 1 second), while Webster's method is based on a shift = 0. As a result, the optimal cycle length used as the base case to which the SPPORT model results were compared was determined by constructing the delay-cycle time relationship for each scenario.

For actuated control, a decision to extend the green was made every second. A green extension of 1 second was used. The phase sequence was fixed as for the Webster and SPPORT control. The same maximum and minimum phase durations were used for actuated control as for SPPORT control.

EVALUATION RESULTS

Since the simulation results are subject to stochastic variation that arise in the vehicle generation process, each scenario was evaluated 10 times, each time using a different seed value to initiate the stochastic process.

All simulation results are based on a one-hour simulation of the fixed-time, actuated, and SPPORT operations. In order to allow the evaluation process to start with a realistic set of initial traffic and queuing conditions, each simulation was first run for a five-minute warm-up period before starting to compile the delays incurred by vehicle passengers over the next 60 minutes.

Scenarios without Transit Vehicles

Figure 7 illustrates the changes in total passenger delays that were achieved by SPPORT with respect to the reference optimal fixed-time operation. Stops were not considered in this analysis as Webster's signal optimization focuses only on delay. The results of Figure 7 indicate that on average SPPORT was able to reduce delays over the reference fixed-time operation by as much as 13% for the temporally constant demand and 25% for the temporally peaking demand scenarios. SPPORT provides reductions in delay for all scenarios except for the Constant Medium Demand scenario. In this scenario, the SPPORT timings results in delay that is, on average, 10% larger than under fixed time control. Figure 8 illustrates the signal timings implemented by SPPORT and the corresponding fixed time cycle length and main street green duration. The timings illustrated in Figure 8 indicate that the SPPORT timings exhibit persistent variation, but that the mean of the cycle times implemented by SPPORT (48.2 sec) is approximately equal to the optimal fixed-time cycle length (50 sec), and the mean of the main street green intervals implemented by SPPORT (23.1 sec) is approximately equal to the optimal fixed-time green duration (24.5 sec). It can be noted that the variation in cycle length and main street green occurs in discrete time steps of multiples of 5 seconds (i.e. only cycle lengths of 40, 45, 50, and 55 seconds were implemented). SPPORT was executed with a decision horizon of 5 seconds, implying that once a decision was made to extend a green, a commitment was made to extend the green for a minimum of 5 seconds. It is speculated that, if a decision horizon duration of 1 second had been chosen, the finer resolution available would have enabled SPPORT to provide a more efficient set of timings.

In Figure 7, the results obtained from the individual model runs give an indication of the variability of the results. On the basis of these individual results, SPPORT provided delay reductions ranging from -11.8% to 28.6%. It is observed that for the peaking demand scenarios, the average benefit provided by SPPORT increases with increases in demand.

Figure 9 illustrates the changes in total passenger delays that were achieved by SPPORT with respect to traffic actuated signal operation. As expected, the actuated signal control is more effective than fixed time control, especially for temporally changing traffic demands. Consequently, the benefits of using SPPORT, as compared to actuated control, are smaller than the benefits computed when compared to fixed time control. On average, SPPORT only provides benefits for three of the six scenarios (ranging from 2% to 6%). For the other three scenarios, the actuated control strategy provides better performance, with benefits ranging from 3.6% to 8% on average.

Scenarios with Transit Vehicles

Not only do transit vehicles carry more people than do passenger cars, resulting in the use of heavier weights for the evaluation of delay to transit vehicles in the overall performance evaluation of a given intersection, but these vehicles can also impede the flow of the general traffic stream when they stop in the right of way to board and discharge passengers. Figures 10 and 11 illustrate the ability of the SPPORT model to react to sudden changes in traffic demands for conditions when transit vehicles are assumed to have varying impedance on the general traffic stream.

Figure 10 shows the changes in total passenger delay resulting from the utilization of the SPPORT model with respect to a fixed-time traffic signal operation based on Webster's delay minimization principles. The results are shown as a function of the level of interference to the general traffic caused by transit vehicles stopping in the right of way to board and discharge passengers. The use of SPPORT resulted in average delay reductions over the corresponding optimal reference fixed-time operation ranging between 13% and 49%. In addition to the average delay reductions, the figure illustrates the results from each individual model run, providing an appreciation for the variability in the results.

While the results presented in Figure 10 are based solely on delay, similar results were obtained when the results of the simulation were compiled on the basis of a performance index combining stops and delay.

Figure 11 illustrates a comparison of the SPPORT results to those obtained under actuated signal control. On average, SPPORT provided reductions in person-delay for all scenarios, with benefits ranging from 0.4% to 20.6%. These benefits are smaller than those associated with Figure 10 as a result of the improved performance provided by the actuated control.

Figures 10 and 11 indicate a general tendency of larger benefits for high traffic demands. Similar to the results obtained for the scenarios without transit vehicles, the smallest benefits are obtained for the medium demand scenarios. Figure 10 indicates improved benefits with increasing levels of transit

interference. However, the results in Figure 11 do not support this observation. In fact, the results in Figure 11 for the peaking high-demand scenario indicate an opposite trend. These results can be interpreted as follows. Transit interference introduces additional variability in arriving traffic. The performance of the fixed time signal plan is most susceptible to these variations as it does not respond to traffic demand variations. Thus, while the performance of the SPPORT model improves relative to the performance of the fixed time plan as the traffic variation increases (i.e. saturation flow reduction increases), this improvement is due in large part to poorer performance of the fixed plans as transit interference increases rather than improved performance of SPPORT. In Figure 11, the actuated control strategy is able to respond to variations in traffic demands and therefore its performance is much less impacted by the interference caused by the transit vehicles loading and discharging passengers in the right-of-way.

The benefits that can be obtained using SPPORT result from the model's ability to provide priority to transit vehicles on a conditional active basis and to respond to the changes in traffic conditions induced on general traffic by the implemented preferential treatments. This ability is illustrated in Figure 12, which depicts the green intervals and cycle length implemented by SPPORT in response to transit priority requests. In Figure 12, six distinct spikes are observed in the curve illustrating the implemented cycle time and green intervals over the one-hour simulated control period. Each one of these spikes corresponds to an increase in the main-street green interval to accommodate an incoming transit vehicle. Following each main-street green interval extension, it can also be observed that SPPORT temporarily increased the duration of the cross-street green interval. These extensions were not awarded to accommodate incoming transit vehicles, but rather to serve the longer queues that have formed on the cross-streets as a result of the implementation of extended red intervals to accommodate the transit vehicles on the main-street approaches.

Effectiveness of SPPORT in Providing Transit Priority

Since one of the main motivation for developing SPPORT was to address the unique nature of transit vehicles, it is of interest to examine the performance impacts of considering transit priority versus not considering priority. The SPPORT model was applied to the medium peaking demand scenario with two different configurations of rule priority lists (traffic cops). The first configuration used 6 lists as defined in Table 1 and was able to explicitly provide conditional transit priority when it was advantageous to do so. The second configuration consisted of only 3 lists (*1np*, *2np*, and *3np*), none of which provided transit priority. Both SPPORT configurations were executed ten times for each of the three levels of transit interference, each time with a difference random seed. Figure 13 illustrates the benefits that are associated

with providing conditional transit priority (6 lists) versus providing traffic responsive signal control, but not providing transit priority (3 lists). The benefits are computed as the total person delay obtained when transit priority is provided minus the total person delay obtained when transit priority is not provided, and then divided by the total delay obtained when transit priority is not provided. Thus, negative values represent conditions in which providing transit priority has resulted in reduced person delay.

Figure 13 illustrates that, on average, the consideration of transit priority resulted in additional benefits for all three transit interference levels. The benefits ranged from 1.5% to 3.7%. However, Figure 13 also depicts the results from each of the individual model runs. These individual results indicate that there is substantial variation in benefits for each level of transit interference, with benefits ranging from -4.2% to 10.2%.

While Figure 13 has demonstrated that the consideration of the provision of transit priority provides additional benefits, it does not give an indication of what proportion of the total benefits are attributable to the provision of transit priority. Figure 14 illustrates the proportion of total benefits that are obtained when transit priority is not considered (i.e. 3 lists) and when transit priority is considered (6 lists). Total benefits are considered to be the largest reduction in person delay obtained using either 3 lists (no transit priority) or 6 lists (considering transit priority). It should be noted that for all cases, the minimum person delay resulted from the consideration of transit priority. The proportion of the benefit associated with only traffic responsive control (no transit priority) was computed as the difference between the total person delay associated with SPPORT using 3 lists and the reference timings (either fixed time or actuated), divided by the total benefit. The proportion of benefit associated with the provision of transit priority was simply the remainder.

The resulting allocation of benefits is provided in Figure 14 separately for comparison to fixed time control and actuated control. For fixed time control, the inclusion of transit priority provides only a small proportion of the total benefit (ranging from 9% to 20%). This result is not surprising, as significant improvements can be made over the fixed time control simply by providing traffic responsive control. When comparing to actuated control, the benefit of providing transit priority is much greater, in fact it is larger than 100% for all cases. The provision of traffic responsive SPPORT control alone (i.e. 3 lists), results in higher person delay than does the use of actuated control. When transit priority is considered, on average SPPORT provides benefits over actuated control (see Figure 11), and all of these benefits are attributable to the consideration of transit priority. These results indicate that the conditional active provision of transit priority within SPPORT is effective at reducing person delay, especially when compared to traffic actuated signal control.

CONCLUSIONS AND RECOMMENDATIONS

The results of the experiments indicate that the SPPORT model can provide effective real-time traffic signal control at individual isolated intersections with time varying traffic demands. In scenarios involving temporally varying traffic demands, transit priority and transit interference on general traffic, the application of the SPPORT model to an isolated intersection reduced total passenger delays by as much as 43% when compared to an optimal fixed-time operation and by 20.6% when compared to actuated signal operation. By simultaneously considering requests attempting to prevent queue spillbacks, serve existing queues, serve incoming platoons and provide priority of passage to transit vehicles, the heuristic rule-based signal optimization process allows the SPPORT model to automatically adjust its signal control strategy to prevailing traffic conditions. For example, by simultaneously considering general traffic and transit needs, SPPORT is able to quickly dissipate the queues of vehicles that often form on the cross-streets when the main-street green is extended to accommodate incoming transit vehicles.

The results further indicate that when existing signal control is assumed to be fixed time control, then the majority of delay reductions that can be achieved through SPPORT are achieved by the implementation of traffic responsive control, not the provision of transit priority. However, when existing signal control is assumed to be actuated control, then the majority of delay reductions that can be achieved through SPPORT are achieved by the provision of transit priority.

Having demonstrated the ability of the SPPORT model to efficiently control traffic signals at isolated intersections, it is necessary to determine the model's network control abilities. Therefore, it is recommended that the model be applied to a corridor containing several signalized intersections, for a range of traffic and transit demands.

To ensure an optimal operation of the model, additional experiments should be conducted to establish guidelines regarding the selection of appropriate priority levels for each rule of the optimization process, and evaluate the effectiveness of the signal-switching decision-making process.

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REFERENCES

Bretherton, D. (1996). "SCOOT Current Developments: Version 3." Presented at the 75th Annual Meeting of the Transportation Research Board, Washington, D.C., USA.

Conrad, M, F. Dion and S. Yagar (1998). "Real-Time Traffic Signal Optimization with Transit Priority: Recent Advances in the SPPORT Model." Presented at the 77th Annual Meeting of the Transportation Research Board, Washington, D.C., USA.

Dell'Olmo, P. and P. Marchandani (1995). "An Approach for Real-Time Coordination of Traffic Flows on Network" Presented at the 74th Transportation Research Board Annual Meeting, Washington, D.C.

Gartner, N. H. (1983). "OPAC: A Demand Responsive Strategy for Traffic Signal Control." In Transportation Research Record 906, Transportation Research Board, National Research Council, Washington, D.C., USA, pp. 75-81.

Gartner, N.H., P.J. Tarnoff, and C.M. Andrews (1990). "Evaluation of Optimized Policies for Adaptive Control Strategy." In Transportation Research Record 1324, Transportation Research Board, National Research Council, Washington D.C., U.S.A., pp. 105-114.

Gartner, N.H., C. Stamatiadis, and P.J. Tarnoff (1995). "Development of Advanced Traffic Signal Control Strategies for IVHS: A Multi-Level Design." Presented at the 74th Annual Meeting of the Transportation Research Board, Washington, D.C., USA.

Head, K.L., P.B. Mirchandani, and D. Sheppard (1992). "Hierarchical Framework for Real-Time Traffic Control." In Transportation Research Record 1360, National Research Council, Washington, D.C., pp. 82-88.

Head, K.L. (1995). "An Event-Based Short-Term Traffic Flow Prediction Model." Presented at the 74th Transportation Research Board Annual Meeting, Washington, D.C.

Henry, J.J, and J.L. Farges (1989). "PRODYN." Proceedings, 6th IFOC/IFIP/IFORS Symposium on Control Computers, Communications in Transportation, Paris, September 1989, pp. 253- 255.

Kelman, W.L., J.C. Greenough, and B.Y. Quan (1993). "A Performance Report on the Metropolitan Toronto SCOOT System: An Advanced Traffic Adaptive Control System. Metropolitan Toronto Department of Transportation, Toronto.

Lowrie, P.R. (1982). "The Sydney Coordinated Adaptive Traffic System - Principles, Methodology, Algorithms." Proceedings, International Conference on Road Traffic Signaling, Conference Publication No. 207, Institution of Electrical Engineers, London, United Kingdom, pp. 67-70.

Mauro, V., and C. Di Taranto (1989). "UTOPIA." Proceedings, 6th IFAC/IFIP/IFORS Symposium on Control, Computers, Communication on Transportation, Paris, September 1989, pp. 245-252.

Mauro, V. (1991). "Road Network Control." In Concise Encyclopedia of Traffic & Transportation Systems, Pergamon Press, Oxford, pp. 361-366.

Pooran , F. J., C. Andrews, and N. Gartner (1999) "Implementation of the OPAC Adaptive Control System in RT-TRACS". Presented at the 6th ITS World Congress held in Toronto, Canada November 1999.

Remer, M. K. and E. D. Minge (1999) "Evaluation of SCOOT In the Adaptive Urban Signal Control and Integration (AUSCI) Project" Presented at the 6th ITS World Congress held in Toronto, Canada.

Robertson, D.I. (1986). "Research on the TRANSYT and SCOOT Method of Signal Coordination." In ITE Journal, January 1986, pp. 36-40.

Webster, F.V. (1958). "Traffic Signal Settings." Road Research Technical Paper No. 39, Her Majesty's Stationary Office, London, United Kingdom.

Wood, K. (1993). "Urban Traffic Control, Systems Review." Project Report 41, Transport Research Laboratory, Crowthorne, United Kingdom.

Yagar, S., B. Han and J. Greenough (1992). "Real-Time Signal Control for Mixed Traffic and Transit Based on Priority Rules." In Traffic Management, Engineering Foundation Press, pp. 147-166.

Yagar, S. and B. Han (1994). "A procedure for Real-Time Signal Control that Considers Transit Interference and Priority." In Transportation Research, Vol. 28B, No. 4, pp. 315-331.

Table 1 - Rule Control Parameters for Test Scenarios

Rules	Priority Level	Traffic Cop					
		1np	1tp	2np	2tp	3np	3tp
Do not Feed Downstream Spillback	300 - 750 [a]	All	All	All	All	All	All
Begin Serving Upstream Spillback	200 - 500 [b]	All	All	All	All	All	All
Continue Serving Upstream Spillback	200 - 500 [b]	All	All	All	All	All	All
Bring Transit Vehicle to Transit Stop	100	--	NS	--	NS	--	NS
Bring Transit Vehicle to Stopline	100	--	NS	--	NS	--	NS
Begin Serving Excessive Wait	50	All	All	All	All	All	All
Continue Serving High Volume	40	XL	XL	XL	XL	XL	XL
Continue Serving Platoon	40	N	N	S	S	NS	NS
Begin Serving Platoon	$0.04 \times (\text{Platoon Size})^2$ Maximum: 40	N	N	S	S	NS	NS
Continue Serving Queue	$0.03 \times (\text{Onset Queue Size})^2$ Maximum: 30	All	All	All	All	All	All
Begin Serving Queue	$0.01 \times (\text{Queue Size})^2$ Maximum: 20	All	All	All	All	All	All

Notes: N = Northbound approaches only
S = Southbound approaches only
NS = Both northbound and southbound approaches
All = All approach links
XL = All approach links, except left-turn bays.
[a] 750 on approaches on which platoons are considered, 300 otherwise.
[b] 500 on approaches on which platoons are considered, 200 otherwise.
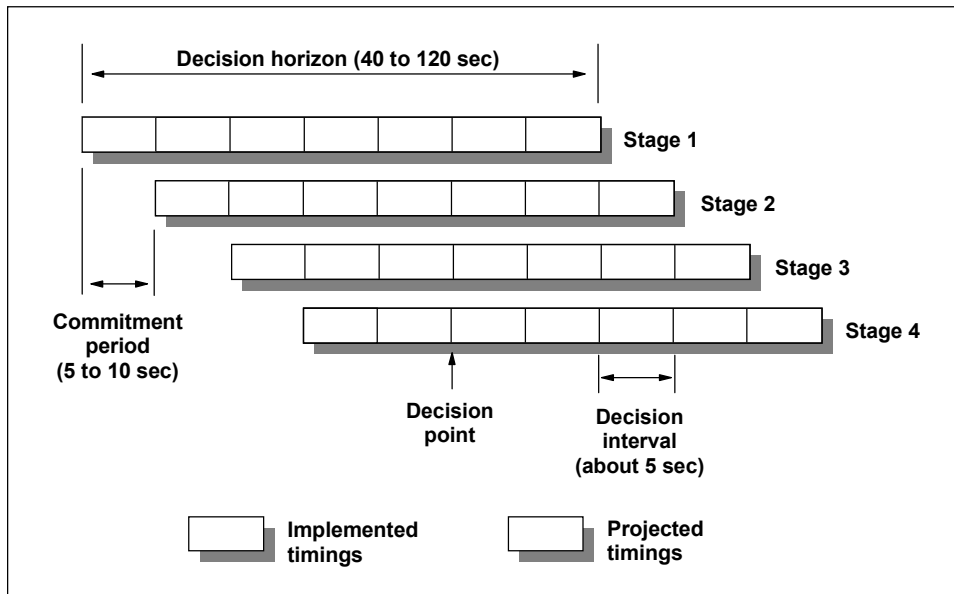
Figure 1 - Rolling Horizon Concept
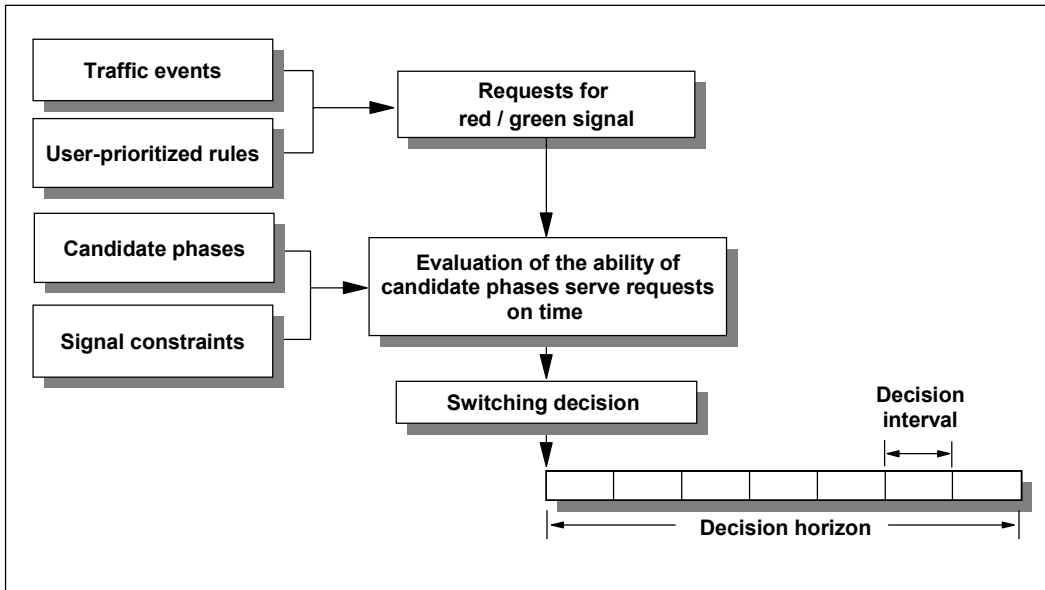
Figure 2 - Rule-Based Decision Process
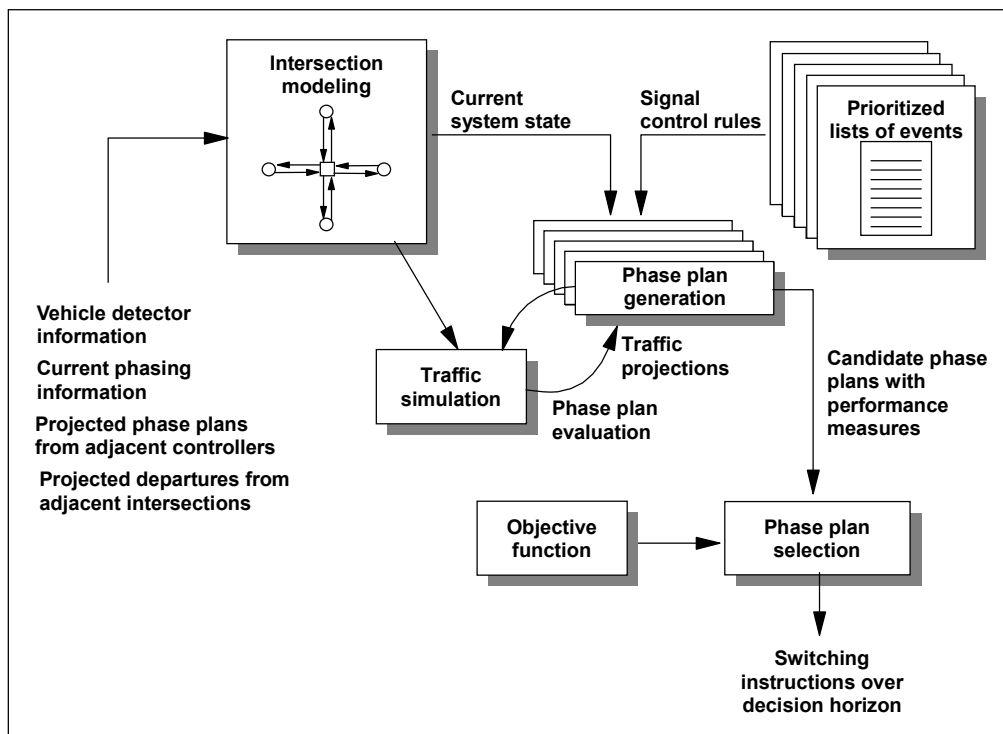
Figure 3 - Multi-objective Optimization Process
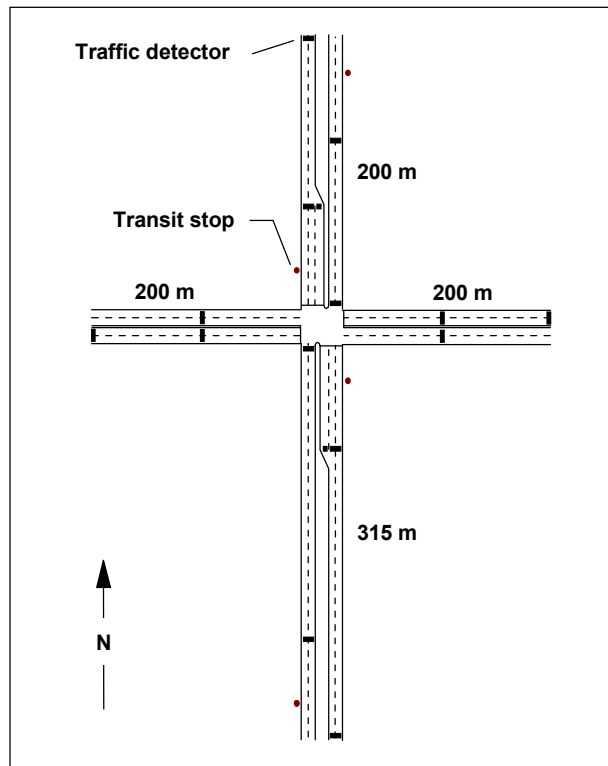
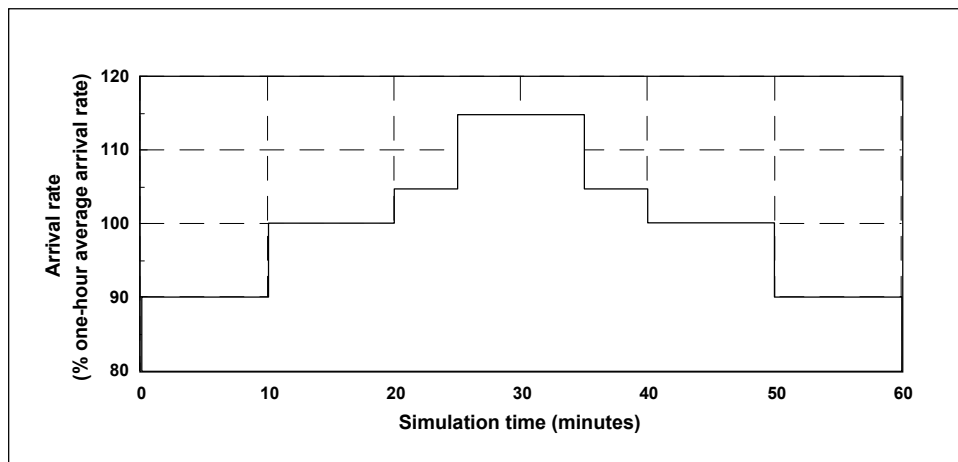**Figure 4 - Isolated Intersection Test Network Configuration**

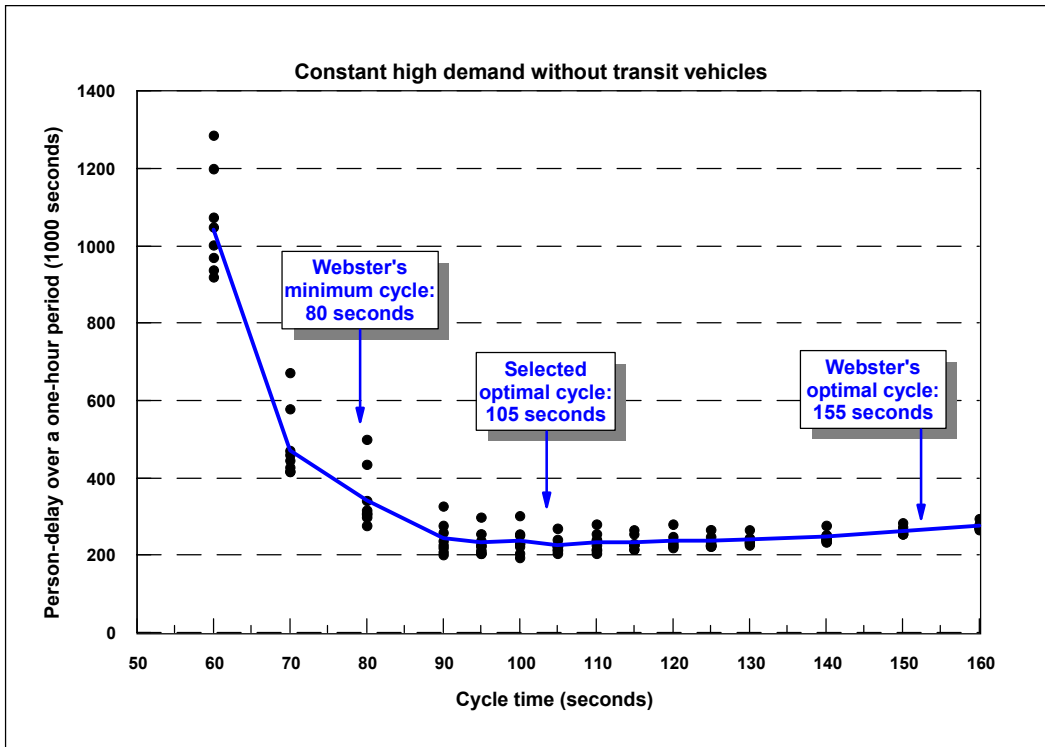**Figure 5 - Temporal Variation in Traffic Demand for Peaking Demand Scenarios**

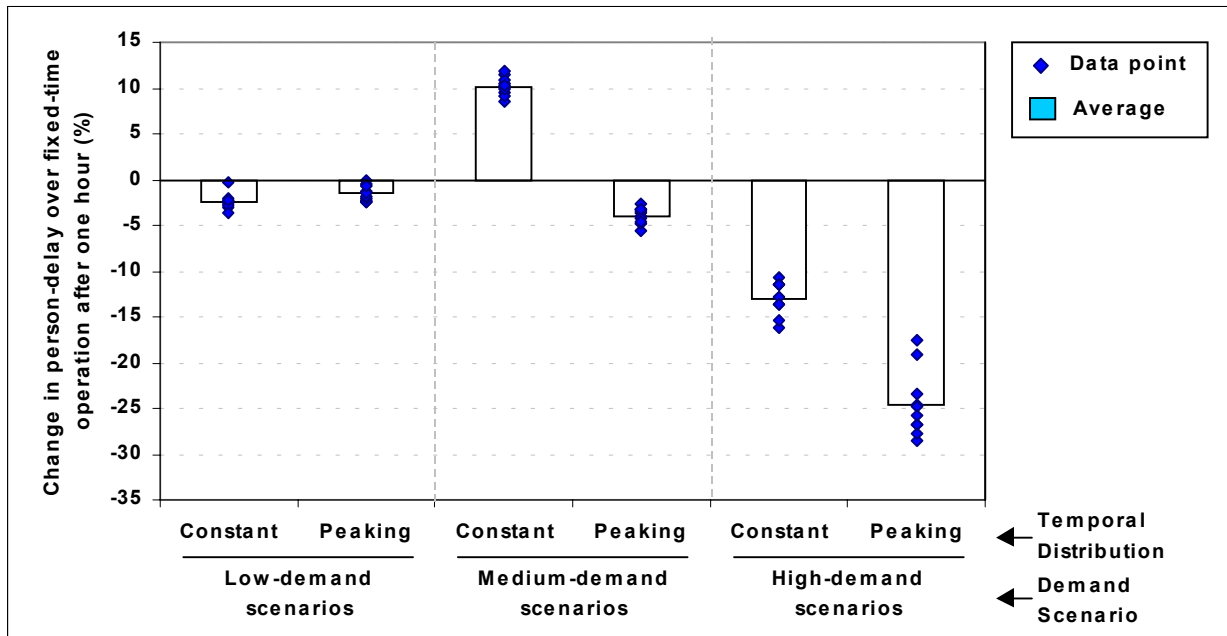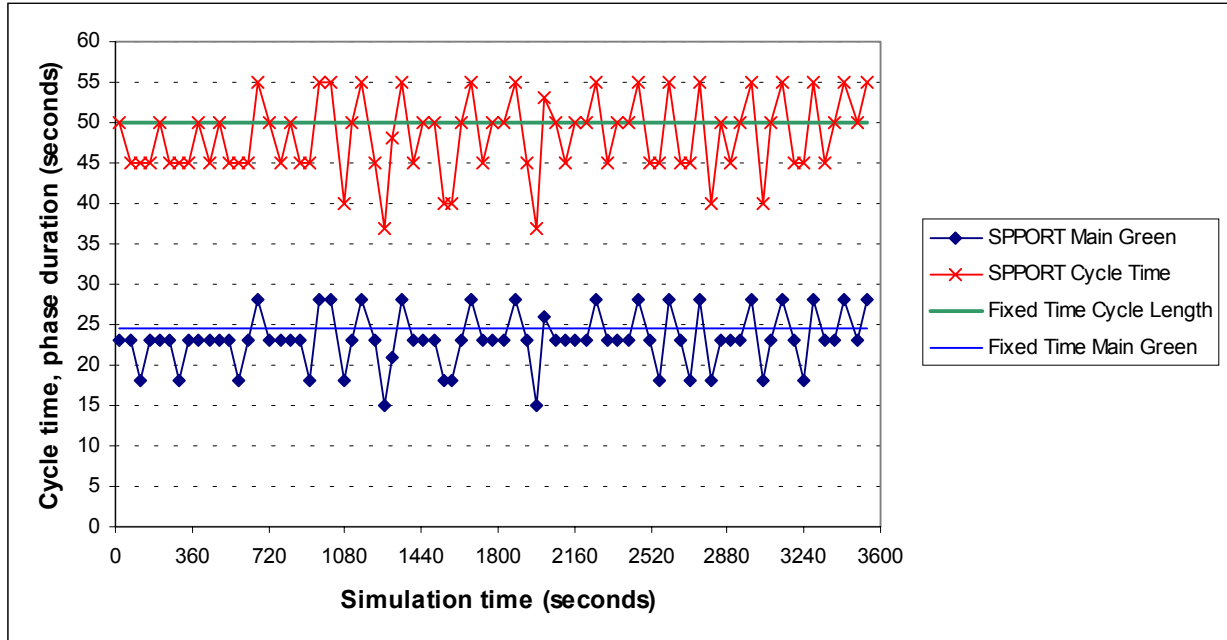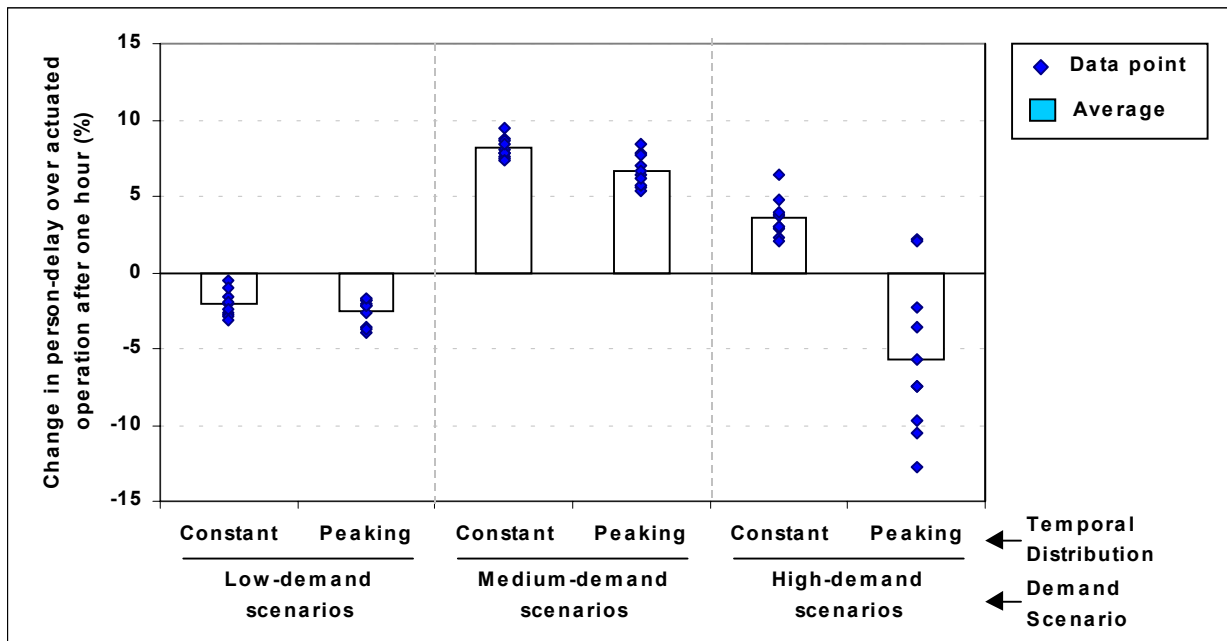**Figure 6 - Examination of Simulated Delay versus Cycle Time Relationship**

Figure 7 - SPPORT Performance Compared with Fixed Signal Timings (No Transit Vehicles)

Figure 8 - Comparison of SPPORT Signal Timings with Fixed Timings

(Constant Medium Demand - No Transit)

Figure 9 - SPPORT Performance Compared with Actuated Signal Timings (No Transit Vehicles)
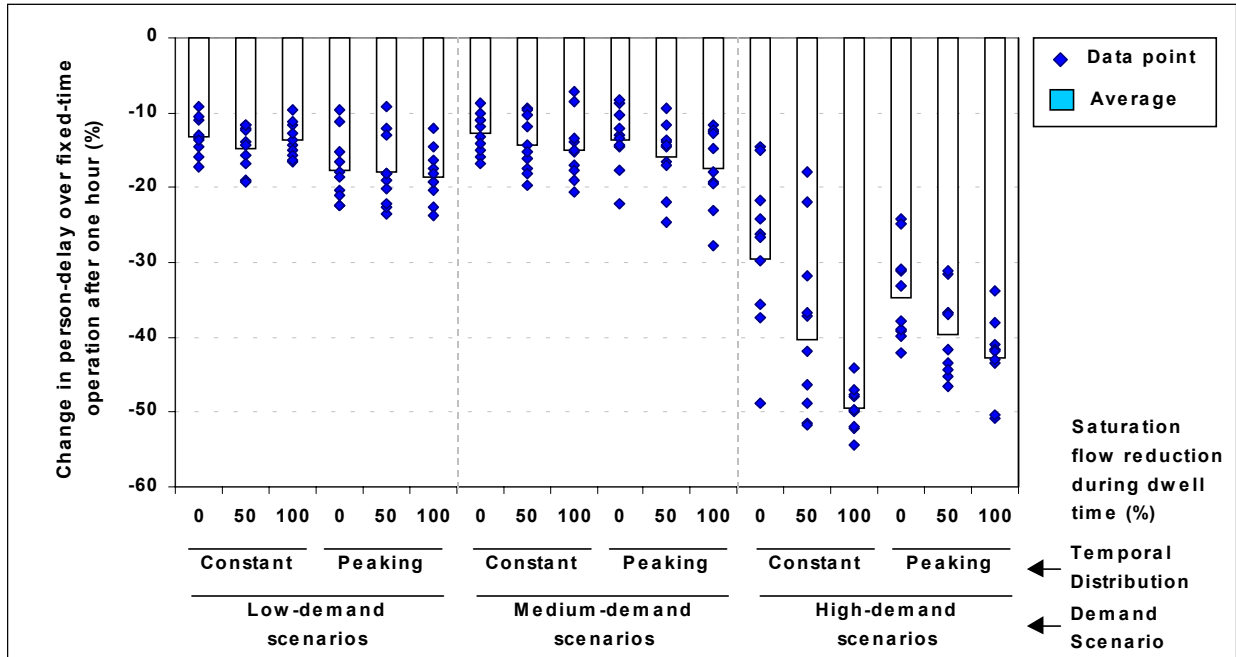
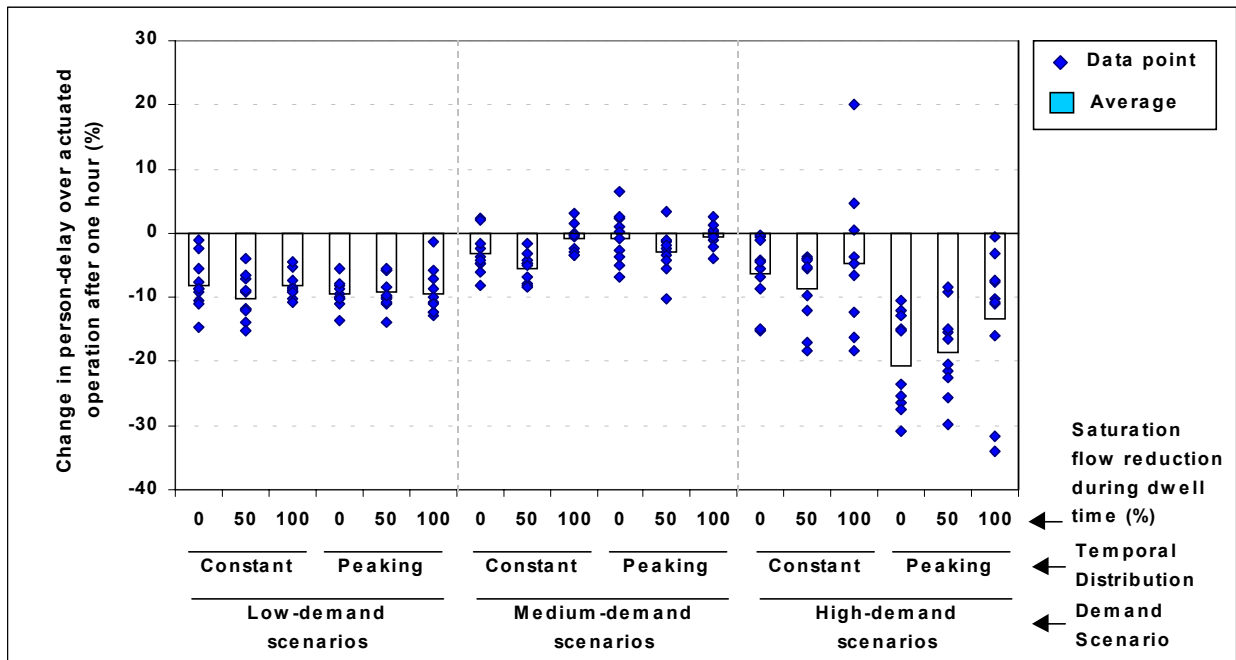**Figure 10 - SPPORT Performance Compared with Fixed Signal Timings (Transit Vehicles)**

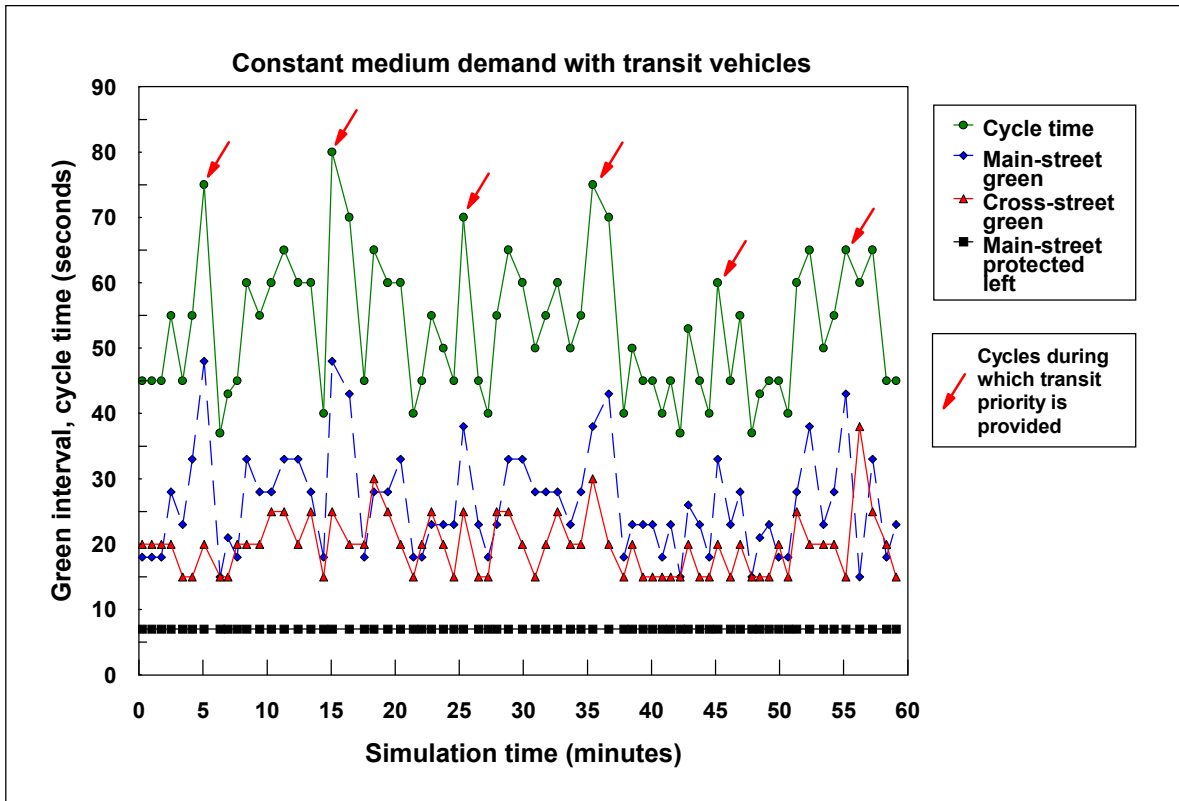**Figure 11 - SPPORT Performance Compared with Actuated Signal Timings (Transit Vehicles)**

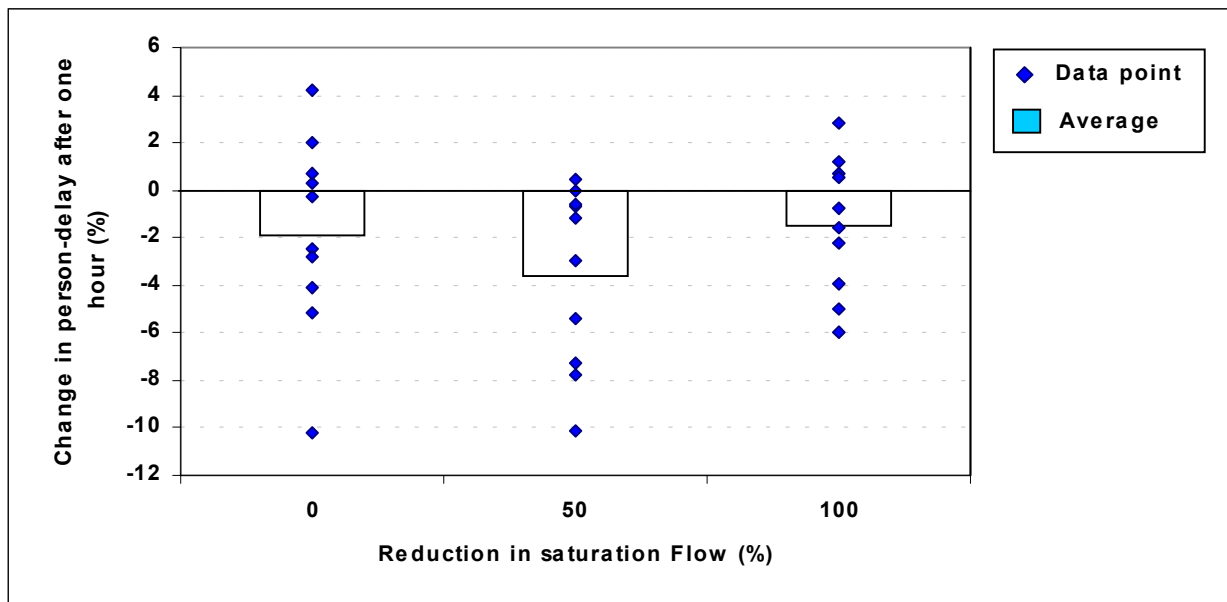**Figure 12 - Variation of SPPORT Signal Timings in Response to Transit Priority Requests**
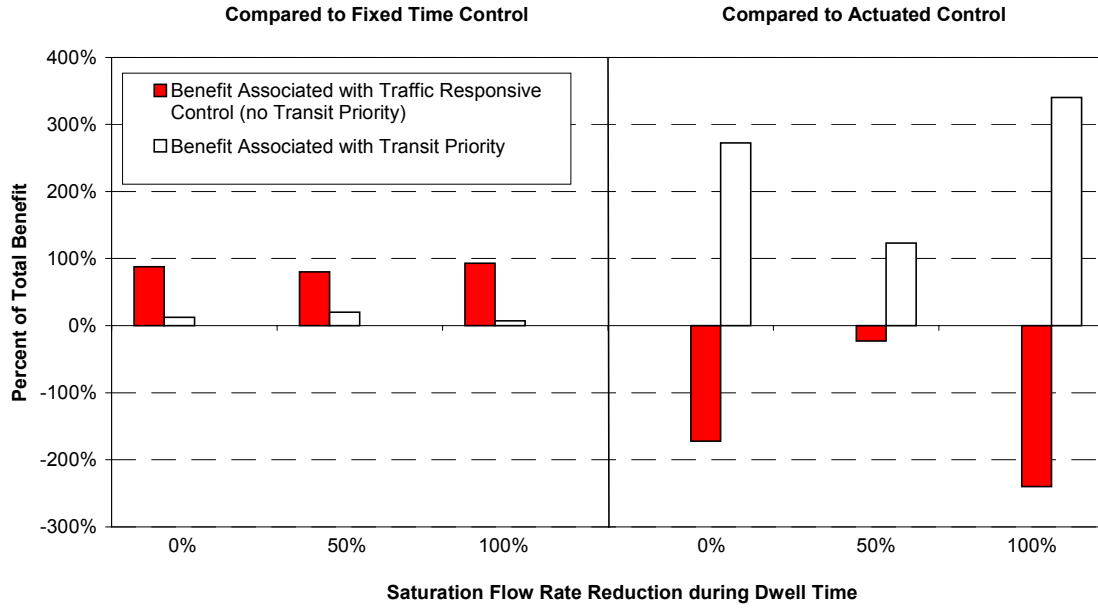

Figure 13 - SPPORT Performance Without and With Provision of Transit Priority

Figure 14: Proportion of Benefits Associated with the Provision of only Traffic Responsive Control and the Inclusion of Transit Priority (Peaking Medium Demand with Transit)