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AN APPROACH TOWARDS THE INTEGRATION OF BUS PRIORITY, TRAFFIC ADAPTIVE SIGNAL CONTROL, AND BUS INFORMATION/SCHEDULING SYSTEM

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ABSTRACT

This paper addresses the integration of adaptive traffic signal control and bus priority and real-time bus scheduling. When one refers to bus priority, several possible approaches are used for giving more "weight" to the buses: (1) passive priority, when signal timings are set, ahead of time, so that buses incur less delays, (2) active priority, where buses are detected at approaches to the intersection and phases are extended, started early, added or omitted to accommodate the bus, and (3) "optimization-based" priority where the current state of the system is estimated and the signals are changed as per active priority schemes. The work reported here is related to last approach where the signals are set based on real-time optimization of the phasing that considers all the vehicles on the network, as well as the buses, the passenger counts in the buses, and the schedule status (is the bus late, on time, early, etc.) of the buses.

The architecture for phase optimization is based on the RHODES© traffic adaptive signal control system developed at the University of Arizona. RHODES© (Real-time, Hierarchical, Optimized, Distributed, and Effective System) takes second-by-second data from loop-detectors at the intersections as input, and outputs the durations of the phases (including the duration of zero if phase skipping is allowed). Objectives for optimizing phase durations include "minimize average delay per vehicle", "minimize average queues at the intersections", " minimize number of stops" as well as others. In the computation of the objective function, each vehicle is given a weight; this weight increases when the vehicle waits too long in queue - if queue delays are considered in the objective function.

When bus priority is introduced into RHODES©, it is assumed that's exact location of busses is available in the network, (e.g., via GPS), as well as passenger counts through an advanced communication/information system. If the passenger counts are not available then RHODES© can include an estimation algorithm that estimates passenger counts. In this way, the bus is given a weight that increases (1) with the number of passenger, and/or (2) when the bus is behind schedule. Likewise, when the bus is early and/or has very few passengers then its weight is decreased. We refer to this priority as "BUSBAND" since it attempts to provide an effective green band through the network for buses that are on time and utilized as expected.

The RHODES©/BUSBAND scheme was analyzed using a micro-simulation modeling package known as CORSIM. RHODES©, with and without bus priority, significantly increases average travel speeds and decreases the total traffic delays. In addition, average and variance of bus delays are decreased. With RHODES© bus priority logic, BUSBAND, there is an additional decrease in bus delays and passenger travel times with little effect on the rest of the traffic.

On-time performance of the buses will depend on how well the route travel times and ridership are estimated when the bus schedules are developed. Future efforts are planned on developing the bus schedules with consideration of ridership and traffic adaptive control.

1. INTRODUCTION

Traffic congestion and traffic signals cause significant delay and increase operating costs for bus service. Signal priority has been a promising method to improve bus, or, in general, bus operations and service quality, but it has not seen widespread deployment in North America. The resistance to implementation has often been based on a concern that overall traffic performance may be unduly compromised when signal timing intended to optimize traffic flow is traded off with the desire to provide a travel advantage to buses.

Traditional traffic signal systems have had limited capabilities, resulting in simplistic bus priority strategies, such as extending the green phase. Recent advancements in the field of Intelligent Transportation Systems (ITS) have created new capabilities to support transit priority in traffic signal systems. These advancements cover a wide range of features including smart buses, detection, communications, control hardware, optimization algorithms, and simulation modeling.

Traffic signal priority for transit must contribute to the objectives set for operation of the transportation system. Some of these objectives (e.g., reducing emissions) will be attractive to both the transit agency and the agency responsible for the signal system. Other objectives (e.g., reducing bus-operating costs) will be principally attractive to the transit agency. Some objectives may be partially conflicting (e.g., reducing average delay of all vehicles, transit and passenger vehicles, and reducing total person delay). In designing transit priority for a traffic signal system, operating objectives must be determined and, if needed, a balance found between conflicting objectives.

Strategies for signal priority can be classified into two general categories [Sunkari et al., 1995], (1) Passive Priority and (2) Active Priority. Real-time, or traffic adaptive priority is a third type strategy that has received some attention [Yager, 1993; Chang et al, 1995]. Table 1 presents a summary of these strategies.

Table 1: Summary of Strategies for Transit Priority

Passive Priority Strategies
- Adjustment of Cycle Length
- Phase Splitting
- Area-wide Timing Plans
- Metering Priority

Active Priority Strategies
- Phase Extension
- Early Phase Activation
- Special Transit Phase (e.g., queue jump)
- Phase Suppression (lift strategy)
- Unconditional Priority
- Conditional Priority

Real-Time Priority Strategies
- Delay Optimizing
- Intersection Control
- Network Control

Passive priority strategies attempt to accommodate bus operations by considering factors such as bus link travel times in headway computations, reducing the cycle length to reduce delay, providing phase sequences designed to more frequently serve a phase that has high bus demand, or by providing bus by-pass at metering locations.

Active priority strategies require the ability to detect or identify buses at the signalized intersections. The most basic active strategies provide bus priority by either extending the current phase or activating a phase early (from a vehicle based control point of view). Other active strategies include the inclusion of special phases, such as a short bus passage phase, that are actuated by the detection of a bus, or phase suppression of non-main street phases with little or no demand.

Depending on the location and capability of the bus sensors, active priority may be either conditional or unconditional. Unconditional strategies provide priority regardless of the status of the transit vehicle. Generally, the conditional decisions are made based on the schedule or headway adherence of the arriving vehicle. This assumes that the system, either a “smart vehicle” or a “smart controller”, knows the operating status of the arriving transit vehicle.

Real-time strategies attempt to provide transit priority based on optimizing some performance criterion, primarily delay. Delay measures may include passenger delay, vehicle delay, weighted vehicle delay or some combination of these measures. Real-time priority strategies use actual observed vehicle (both passenger and bus) arrivals as inputs to a traffic model that either evaluates several alternative timing plans to select a most favorable option, or optimizes the actual timing in terms of phase durations and phase sequences.

Other than a few applications of *SCOOT* [Hunt et al., 1981; Bretherton, 1996] and *SCATS* [Luk, 1984; Cornwell et al., 1986], no real-time traffic-adaptive signal control systems with bus priority are reported in the literature and only a few cities have bus priority capability. The *SCOOT* system is essentially an on-line version of the *TRANSYT* [Robertson, 1969] signal optimization algorithm. *SCOOT* considers either active strategies (phase extension and early phase activation) or, implicitly, passive strategies. Reported results indicate a 22% reduction in bus delay per intersection with as much as 70% reduction in light volumes. *SCATS* accomplishes traffic adaptive control by first dividing a large network into small zones, where definition of each zone is based on contiguous intersections having similar “degrees of saturation”, and then choosing a common cycle time for each zone. Bus priority is accomplished through application of active priority strategies. Reported results state a 6-10% improvement in bus travel times with little significant effect on travel times of other vehicles.

The focus of our work is to consider bus priority within *RHODES©,*a traffic adaptive signal control system developed at the University of Arizona. *RHODES©* (Real-time, Hierarchical, Optimized, Distributed, Effective System) takes as input second-by-second data from loop-detectors at the intersections, and outputs the durations of the phases (including the duration of zero if phase skipping is allowed). Basically, there are two main processes within *RHODES©*: (1) *estimation and prediction* which takes the detector data and estimates the actual flow profiles in the network and the subsequent propagation of these flows, and (2) *optimal control* where the phase durations are selected to optimize a given objective function, the optimization being based on dynamic programming and decision trees. Objectives that can be used are “minimize average delay per vehicle”, “minimize average queues at the intersections”, “ minimize number of stops” and so on. In the computation of the objective function, each vehicle is given a weight, which increases when the vehicle is too long in queue if delays and queue lengths are considered in the objective function.

When bus priority is introduced into *RHODES©*, it is assumed that’s exact location of busses is available in the network, (e.g., via GPS), as well as passenger counts through an advanced communication/information system. If the passenger counts are not available then *RHODES©* can include an estimation algorithm that estimates passenger counts. In this way, the bus is given a weight that increases (1) with the number of passenger, and/or (2) when the bus is behind schedule. Likewise, when the bus is early and/or has very few passengers then its weight is decreased. We refer to this priority as “*BUSBAND*” since it attempts to provide an effective green band through the network for buses that are on time and utilized as expected.

In the next section we provide a brief background on *RHODES©*. In Section 3 we discuss the integration of bus priority within *RHODES©*. Evaluation of *RHODES©/BUSBAND* using simulation modeling is discussed in Section 4. In the concluding Section 5 we summarize our findings and discuss areas of future research.

2.0 *RHODES©* BACKGROUND

The current approaches to control traffic signals on arterials are (1) *fixed time*, perhaps based on time-of-day traffic conditions, and (2) *actuated* (or *semi-actuated*) where sensors on the road (e.g., loop detectors) detect traffic on specific lanes and/or movements and based on some programmed logic provide pre-specified phases, phase skips, phase extensions, force-offs and gap-outs to allow for the movement of the detected traffic. The major deficiency for such types of strategies is that there is no way for the control system to tradeoff or optimize signal settings to respond to anticipated arrival volumes - by varying phase durations and/or using more appropriate cycle times and phase sequencing - even though detectors may have identified unusual traffic conditions (either unusually large volumes or very small volumes, due to, for example, events and incidents). *RHODES©* traffic-adaptive signal control system [Head, Mirchandani and Sheppard, 1992] attempts to address this deficiency by processing the detector data in real-time and then setting phase durations to optimize a given measure of performance.

The *RHODES©* architecture for surface streets is depicted in Figure 1 [from Head et al, 1992]. At the highest level of *RHODES©* is a "*dynamic network loading"* model that captures the slow-varying characteristics of traffic. These characteristics pertain to the network geometry (available routes including road closures, construction, etc.) and the typical route selection of travelers. Based on the slow-varying characteristics of the network traffic loads, estimates of the load on each particular link, in terms of vehicles per hour, can be calculated. The load estimates then allow *RHODES©* to allocate "green time" for each different demand pattern and each phase (North-South through movement, North-South left turn, East-West left turn, and so on). These decisions are made at the middle level of the hierarchy, referred to as *"network flow control"*. Traffic flow characteristics at this level are measured in terms of platoons of vehicles and their speeds. Given the approximate green times, the *"intersection control"* at the third level selects the appropriate phase change epochs based on observed and predicted arrivals of individual vehicles at each intersection. Essentially, at each level of the hierarchy there is an estimation/prediction component and a control component.

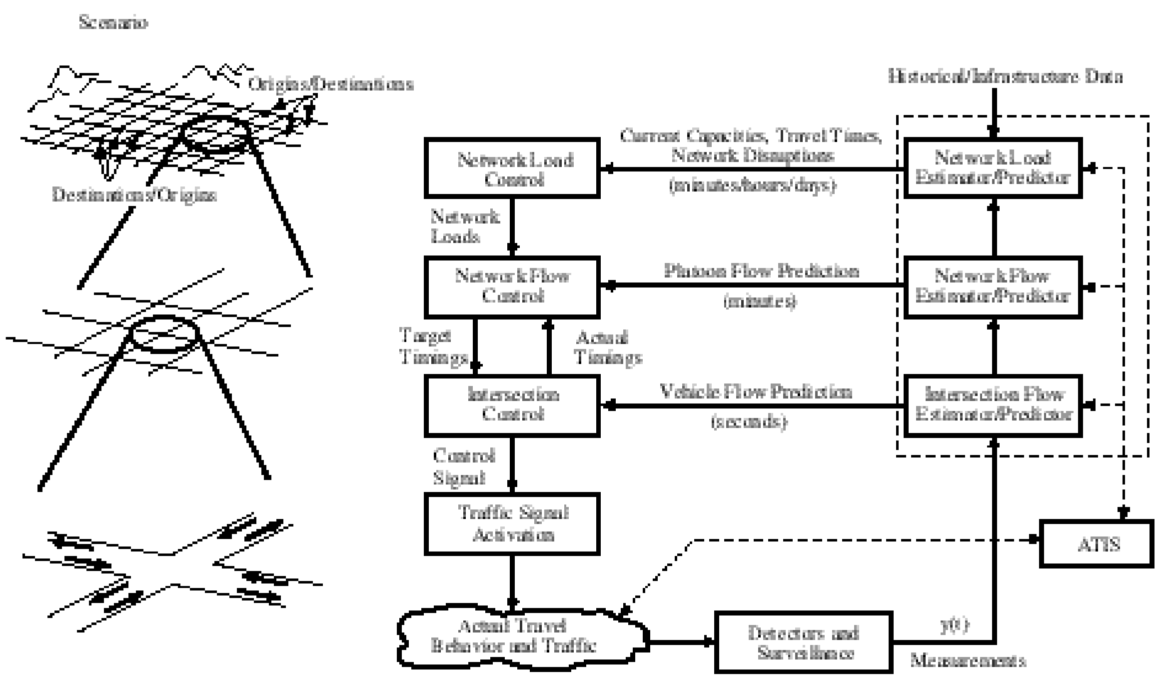

Figure 1. The *RHODES©* Hierarchical Architecture.

There are three aspects of the *RHODES©* philosophy that make it a viable and effective systems to adaptively control traffic signals. First, it recognizes that recent technological advances in communication, control, and computation (a) make it possible to move data quickly from the street to the computing processors (even now most current systems have communication capabilities that are not utilized to their potential), (b) make processing of this data to algorithmically select optimal signal timings fast, and (c) allow the flexibility to implement through modern controllers a wide-variety of control strategies. Second, *RHODES©* recognizes that there are natural stochastic variations in the traffic flow and therefore one must expect the data to stochastically vary (by simply smoothing the data and working with mean values does not make the actual traffic that the system sees smooth and average as assumed by some real-time traffic control schemes). And third, *RHODES©* proactively responds to these variations by explicitly predicting individual vehicle arrivals, platoon arrivals and traffic flow rates, for the three corresponding levels of hierarchies described above.

The *BUSBAND* approach applies to the second and third levels. Basically, the developed *RHODES©/BUSBAND* system predicts arrivals and queues of individual vehicles at the arterial approaches, and tracks and predicts the movement of buses; and based on these predictions and a given criterion of performance determines the optimal phasing of the signals at the intersections.

2.1 Prediction Methods in *RHODES©*

For proactive traffic control, it is important to predict vehicle arrivals, turning probabilities and queues at intersections, in order to compute phase timings that optimize a given measure of effectiveness (e.g., average delay). To emphasize this importance, consider an intersection with several approaches. Associated with each approach are several possible traffic movements: left turn, right turn and a through movement. Any non-conflicting combination of movements that can share the intersection at any one time can be assigned a signal phase that allows those movements protected use of the intersection. Now consider the signal-timing problem given two possible perfect predictions of arrivals during the planning horizon as depicted in Figure 2. Each arrival pattern represents the number of vehicles to arrive at the intersection in fixed time intervals. Both arrival patterns are identical until time t_0 when the signal control has to decide whether to serve this approach or to serve another approach. In the top case, the demand occurs immediately following t_0, whereas in the bottom case there is little demand immediately following t_0 and greater demand in the future. In each case the total number of vehicle arrivals are equal. However, the optimal signal timings could be significantly different. It is of fundamental importance to know the temporal arrival distribution to build a truly real-time traffic-adaptive signal control logic.

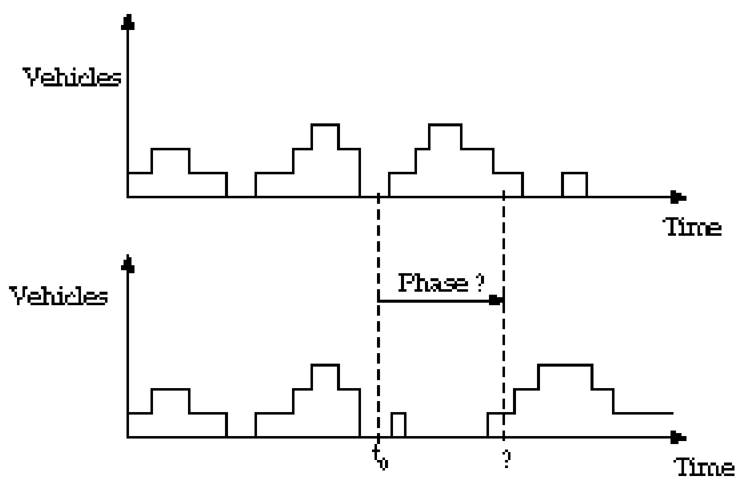

Figure 2. Graphical depiction of the effect of future arrivals on scheduling phase sequences and durations.

The *PREDICT* algorithm [Head, 1995] uses the output of the detectors on the approach of each upstream intersection, together with information on the traffic state and planned phase timings for the upstream signals, to predict future arrivals at the intersection under *RHODES©* control. This approach allows a longer prediction time horizon since the travel distance to the intersection is longer and the delays at the upstream signal are considered. A benefit of this approach is that it includes the effects of the upstream traffic signals in the intersection control optimization problem.

To understand how this approach works consider the scenario shown in Figure 3. It is desired to predict the flow approaching intersection A at detector d_A. Making the prediction for the point d_A is important because it is a point on link AB where the actual flow can be measured, hence the quality of the prediction can be assessed in real-time.

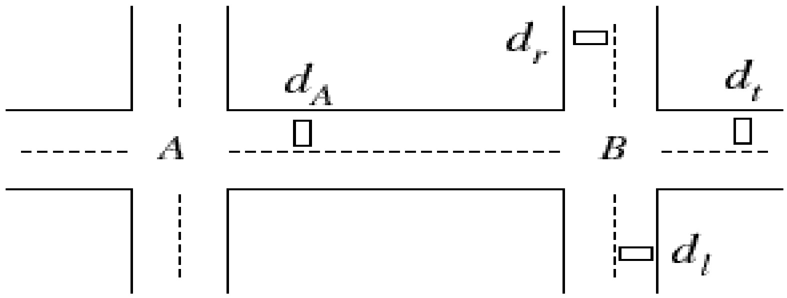

Figure 3. Prediction scenario based on detectors on the approaches to the upstream intersection (B).

Traffic contributing to the flow at d_A originates from the approaches to intersection B and can be measured at detectors d_l, d_t and d_r representing the flows that will turn left, pass through and turn right, respectively, onto link AB. It is possible to have other traffic that originates at sources between intersections A and B, but this can be considered as unmeasurable "noise". Also, it is possible that vehicles passing over d_l, d_t, and d_r will terminate their trip before arriving at d_A. This can also be considered as "noise" in the prediction.

When a vehicle passes a detection point, say d_i where $i \in \{l, t, r\}$, several factors affect when it will arrive at d_A including (1) the travel time from d_i to the stop bar at intersection B, (2) the delay due to an existing queue at B, (3) the delay due to the traffic signal at B, and (4) the travel time between B and d_A.

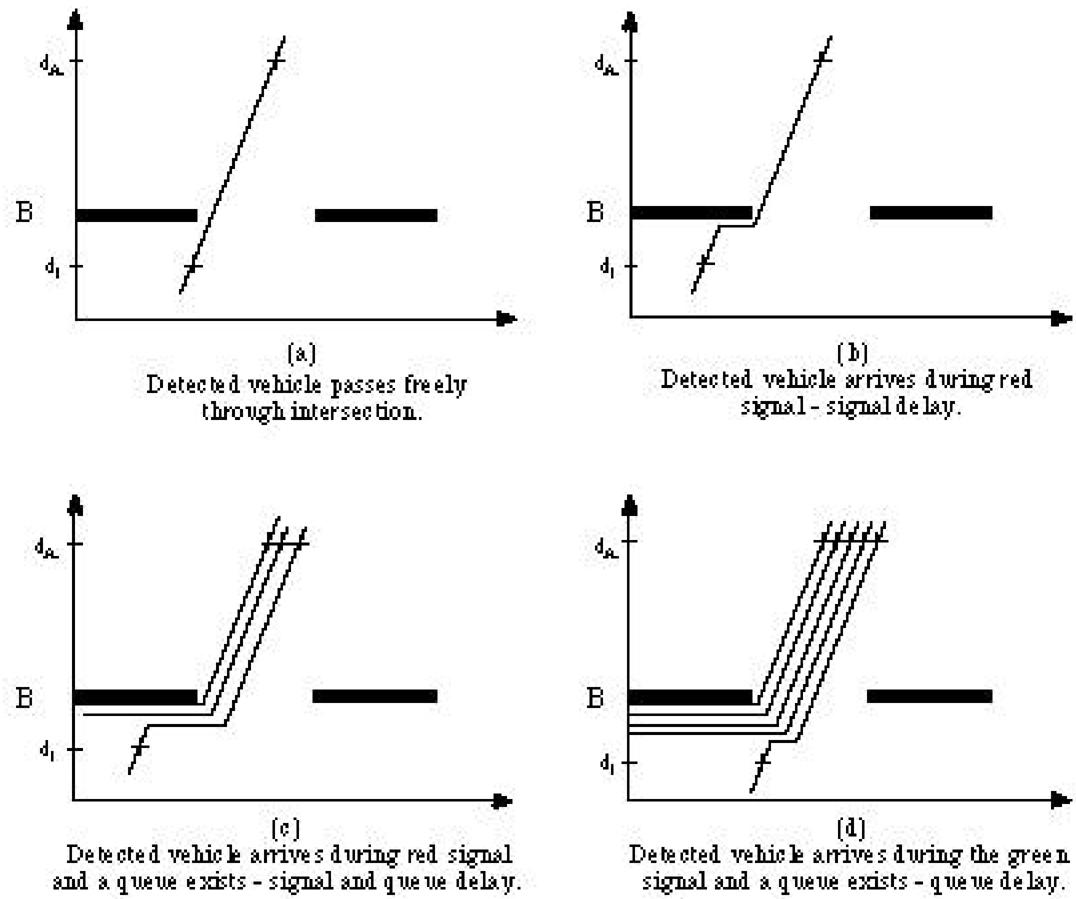

Figure 4. Delays associated with the prediction of arrivals at the detector d_A.

Figure 4 (a)-(d) depicts the delay associated with each of these factors. In Figure 4(a) the vehicle arrives at detector d_i and passes freely to detector d_A. In Figure 4(b) the vehicle arrives at detector d_i and is delayed by the signal at intersection B. Hence the travel time from d_i to d_A must account for the travel time from d_i to the stop bar, the delay due to the signal and the travel time from the stop bar to d_A. In Figure 4(c) the arrival at d_i encounters delay for the signal as well as a standing queue, and has to travel from d_i to the stop bar at B, and from the stop bar to d_A. Figure 4(d) depicts the case when the arrival at d_i occurs after the signal has begun serving the desired phase, but a standing queue is present. This case is similar to the above, except that the delay due to the standing queue must be adjusted based on the amount of time that has elapsed between the onset of the signal and the arrival of the vehicle at d_i and the travel time to the back of the queue.

Once the arrival time at d_A is predicted, the *PREDICT* model adds a fraction to the current estimate of the expected number of arrivals at that time. For example, if 15% of the vehicles that pass over d_i continue on to d_A, then for each actuation of d_i, 0.15 is added to the current estimate of the expected number of arrivals at the predicted arrival time.

2.2 Estimation of Parameters

Observe that to use the *PREDICT* model, several parameters (given in bold) need to be provided: (1) travel times on links (detector to detector) which depends on the **link free-flow speed** and current traffic volumes, (2) **queue discharge rates** which also depends on volumes (as well as on queue spillbacks and opposing- and cross-traffic volumes), and (3) **turning probabilities**. In addition to these parameters, to estimate arrivals and demand for various phases we also need to have **estimates of queues** at the intersections. Included in the *RHODES*© system are algorithms to estimate these parameters [Mirchandani and Head, 1998]

It is important to note that the *PREDICT* model is based on processing arrival data as it becomes available. At any point in time the predicted arrival flow pattern at d_A accounts for vehicles that have already passed the detectors d_l, d_t and d_r. The benefit of this vehicle-additive process of the predictor is that it constantly provides, for a given prediction horizon, (1) nearly complete information of anticipated vehicle arrivals in the very near future (of those vehicles that have already passed the upstream intersections) and (2) partial information of anticipated vehicles in remaining part of the prediction time horizon (of those vehicles that have not passed the upstream intersections, since some new vehicles may still arrive that will effect the delays in the prediction time horizon). Results of an evaluation study of the *PREDICT* algorithm for arrivals at an intersection have been reported by Head [1995].

2.3. The Control Algorithms in *RHODES*©

Fixed control strategies are based on a signal-timing plan defined in terms of operating parameters for traditional signal control, namely *cycle time, splits*, and *offsets*. These parameters are generally developed based on traffic studies and standard procedures, such as the Highway Capacity Manual, or signal timing software such as *TRANSYT* and *PASSER*. The traffic studies result in estimates of traffic conditions, link volumes and turning percentages, for specified time periods. Signal timing parameters are developed for each of these time periods and, typically, implemented on a time-of-day basis with no consideration of current actual traffic conditions. In many cases, even the use of standard procedures for the development of signal timing plans is abandoned and traffic engineers operate in a judgment-based fashion with moderate levels of success. None of these approaches is truly traffic-adaptive or even attempt to actually minimize some measure of traffic performance such as average vehicle-delay.

Currently available traffic responsive systems attempt to address the problem of responding to actual traffic conditions by switching these parametric signal timing plans based on current wide-area traffic conditions rather than time of day. This requires that signal-timing parameters be developed for a variety of possible traffic conditions. Nevertheless, implicit in the usage of parametric timing plans is the assumption that for the next several minutes, or even hours, the traffic in the network can be well characterized by the measured average flows and parameters. No account is taken of the fact that the second-by-second and minute-by-minute variabilities of

traffic are significant and plans based on averages produce unnecessary delays for some traffic movements when the traffic on conflicting movements is absent, or very small, during some periods.
The *RHODES©* approach is to predict both the short-term and the medium term fluctuations of the traffic (in terms of individual vehicle arrivals and platoon movements respectively), and explicitly set phases that maximize a given traffic performance measure. Note that we do not set timing plans in terms of cycle times, splits and offsets, but rather in terms of phase durations for any given phase sequence. (*RHODES©* does not necessarily require a pre-specified phase sequence, but since many traffic engineers prefer a pre-specified sequence, *RHODES©* has been developed to allow the traffic engineer to specify a desired sequence.) In other word, in the *RHODES©* control strategy, the emphasis shifts from changing timing parameters in <u>reacting</u> to traffic conditions just observed to <u>proactively</u> setting phase durations for predicted traffic conditions.

In this project, only the lowest level of the *RHODES©* hierarchy, that is, the intersection control level, was used in the simulation experiment. *RHODES©* uses a dynamic-programming based algorithm *COP*, [Sen and Head, 1997]for this level; for description of traffic control at other levels see Mirchandani and Head [1998] There are other signal timing schemes which have been experimented that do not provide parametric timing plans but instead provide phase durations, notably *OPAC* [Gartner, 1983; Gartner et al., 1991] and *PRODYN* [Khoudour et al., 1991] and *UTOPIA* [Mauro and DiTaranto, 1990]. In some ways these too use dynamic programming or related optimization schemes, but, in their current implementations, the underlying models are more approximate and the methods are not as efficient. Also, there are no results available in the literature on their application to transit priority.

3.0 IMPLEMENTATION OF BUS PRIORITY IN *RHODES©*

As we mentioned earlier, in the computation of the objective function value for the *RHODES©* dynamic program, each vehicle is treated alike. That is, they all have a "weight" of unity. Hence, *RHODES©* gives green phase to the movement which has more "delay" associated with it, where this delay could depend on the number of vehicles needing this movement and the time in queue for these vehicles. In the standard *RHODES©* algorithms, a bus is also given a unity weight regardless of the number of passengers in it and whether or not it is late.

On the other hand, since the *RHODES©* algorithms give individual weights to vehicles, it is not hard to give each bus a variable weight that depends on the number of passengers it has and on how late is the bus, if it is behind schedule. In fact, this is exactly the manner in which we assigned weights to buses and modified *RHODES©* to develop the *RHODES©/BUSBAND* strategy. Let n_i be the number of passengers on bus i, and its "lateness" be denoted by d_i, which is negative when the bus is early, and positive when it is late. Then weight w_i for bus i given to *RHODES©/BUSBAND* was defined by the function

$$w_i = n_i (1 + f_i)$$

$$\text{where delay factor, } f_i \begin{cases} = 0 & \text{if lateness } d_i \leq 0, \\ = Kd_i & \text{if lateness, } d_i > 0, \text{ where K is some constant.} \end{cases}$$

Notice that when the bus is early or "on time" then we count only the number of passengers. This implicitly assumes that each car has a single passenger and that a bus with n passengers has n times the weight of a car. Clearly we could divide the n_i number in the weight function by the average occupancy of a car if it is greater than one. Also, the above weight function becomes zero when there are no passengers on the bus. This implies that only current passengers on the bus are being considered in the objective function. Again, this weight function could be modified easily to account for expected delays of anticipated users. These anticipated users could be forecasted given historical ridership data, or better estimated if real-time passenger information is being obtained from downstream bus stops.

With the inclusion of the bus passengers and the bus lateness in the computation of the objective function value, the *RHODES©* strategy will tend to give higher priority for late buses with many passengers. Hence, in the evaluation of the *RHODES©/BUSBAND* strategy, one would expect that (a) the average delay of the buses would decrease, and (b) the average delay of all passengers (in buses and cars) in the network would also decrease, with, perhaps, car passengers incurring some additional delays. Given the real-time interactions between the signal phasing decisions and vehicle movements, the diversity of the traffic scenario, and the rich variety of driver behavior, we chose to evaluate *RHODES©/BUSBAND* with a micro-simulation model, using different control strategies, including standard actuated control, *RHODES©* without bus priority, and *RHODES©/BUSBAND*.

4.0 EVALUATION USING A SIMULATION PLATFORM

It is clear that any type of real-time traffic control algorithm needs to be tested in the "laboratory" before it is implemented and evaluated in the field. The most appropriate method to do this "laboratory" testing is to (1) have a realistic simulation model of traffic flow at an intersection, (2) emulate the (loop) detection of the traffic flow, and (3) observe the resulting changes that would come about if the algorithm was implemented in place of the current control system.

The ability to represent dynamic recurrent and non-recurrent congestion, as well as other non-congested traffic conditions, is needed for measuring the algorithm's capability to respond to real-time traffic conditions. Also, simulation models used for testing must provide the same surveillance and detection information as that available in the field. The frequency of surveillance and detector system output and the frequency of the signal control input dictate the minimal resolution, and hence the responsiveness, of the signal control logic. The simulation model must be able to represent rates that will be achievable when the control logic is implemented for field-testing.

The simulation model requirements from a development and testing perspective differ from the requirements for performance evaluation. Clearly, the most important requirement of a simulation model is that it accurately represents the dynamics of traffic flow and its response to dynamic signal control. This requirement dictates that the simulation model chosen for development and testing not be based on a macroscopic flow model that assumes constant cycle length and deterministic traffic flow characteristics. Rather, the model should include microscopic flow characteristics, such as car following and overtaking, and include an ability to simulate real-time traffic controls (not necessarily constant cycle lengths) and attendant vehicle response to actual traffic signals.

During the development and testing phase it is essential to have access to both traffic and signal control variables so that detailed behavior can be studied. One may distinguish between traffic simulation information/data that is needed for validation and testing and that information/data which is available as traffic surveillance/detection data for the signal control algorithms. For example, for the purpose of testing a traffic model used in an optimization routine, it may be desirable to compare the traffic model's state-of-the-traffic measures, such as queue length, to the corresponding measures in the simulation model. This form of testing requires that the traffic simulation model provide accurate measurements of queue lengths despite the fact the existing traffic surveillance technology may not provide this information.

Another important consideration is the frequency at which required testing data is available. For example, the average queue length for a simulation period is insufficient for testing a routine that estimates real-time queue lengths. This information must be available as frequently as possible, at least as frequent as queue estimated are generated.

Another major consideration in the selection and/or development of a simulation model is from the realization that we need to code the *BUSBAND* algorithms and test it via a simulation model. That is, we need to represent, identify and monitor buses in the simulation, and either track them throughout the region or detect them at specific points (e.g., at bus stops) to measure bus movement performance.

Based on the requirements and considerations discussed above, we developed a *CORSIM*-based[1] simulation model to implement and test our *RHODES©/BUSBAND* approach. Fixed-time, semi-actuated and actuated signal control strategies (internal to *CORSIM*) were implemented and animations were observed to confirm if the traffic was indeed moving appropriately. Having fine-tuned the actuated timing parameters within the simulation model so that traffic performance was as good as can be expected, *RHODES©/BUSBAND* was interfaced with the simulation model and evaluated.

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[1] *CORSIM* is a software package for modeling and simulating traffic on a network. It has been developed by FHWA.

An essential element of external real-time signal control logic is the traffic surveillance system. In our simulation experiments, we utilized the internal surveillance detector logic of *CORSIM* for the placement and processing of detector events, but we utilized an external *RHODES©/BUSBAND* control logic for processing this detector data. Methods internal to *CORSIM* allowed us to estimate any necessary traffic parameters such as travel times, delays, and queue lengths, in addition to the standard count and occupancy values that were used by the external control logic.

We simulated two networks to test our algorithms. In the preliminary set of tests, we used a simple version of *BUSBAND* logic on a subnetwork within the City of Tucson, which has an arterial with several intersections. The *BUSBAND* logic was based on the network flow control logic of *RHODES©* where phase constraints are provided to the lower intersection level control [Mirchandani and Head, 1998]. Effectively, this implies that the weight of each bus is set high so that *RHODES©* tries and gives it a green phase when it approaches the intersection and the lateness and the number of passengers on the bus does not change priorities. See Knyazyan [1998] for details of the simulations. In these tests we generated buses at given times and, using the performance measures internally generated by *CORSIM*, we compared the following measures for the three scenarios (1) SAC: semi-actuated control within *CORSIM*, (2) RwoB: *RHODES©* without bus priority, and (3) RB: *RHODES©/BUSBAND*:

- Bus travel times and car travel times,
- Bus delays at intersections and car delays at intersections,
- Total person delays.

In these tests it was observed that *RHODES©* with or without bus priority significantly reduced travel times and delays at intersections for all vehicles over semi actuated control (see Table 2).

Table 2: Summary of results from preliminary simulation experiment (seconds/vehicle per link)

	Avg. total travel time RB[1]	**Avg. total travel time SAC[2]**	**% of reduction**	**Avg. delay time RB**	**Avg. delay time SAC**	**% of reduction**
Main Street	55.79	60.95	8.47%	21.83	26.99	19.13%
Side Street	63.11	80.11	21.22%	30.43	47.42	35.82%

	Avg. total travel time RwoB[3]	**Avg. total travel time SAC**	**% of reduction**	**Avg. delay time RwoB**	**Avg. delay time SAC**	**% of reduction**
Main Street	56.11	60.95	7.94%	22.15	26.99	17.94%
Side Street	60.62	80.11	24.33%	27.95	47.42	41.06%

[1]RB *RHODES©/BUSBAND*

[2]SAC semi-actuated control in *CORSIM*

[3]RwoB *RHODES©* (without bus priority)

To compare person delays that included passengers on buses as well as cars, we obtained the following from *CORSIM* simulation results:

Average main street delays (in person minutes)	1259 (SAC)	1030 (RwoB)	1026 (RB)
Average side street delays (in person minutes)	698 (SAC)	444 (RwoB)	500 (RB).

Again, note the significant reductions with *RHODES©* (with and without bus priority) as would be expected with real-time traffic-adaptive control. Comparing the two *RHODES©* scenarios, the person delays were not changed much with bus priority on the main street. On the other hand, person delay was somewhat increased on the side streets when bus priority was used on the main street. This is to be expected because *RHODES©/BUSBAND* provides bus priority to main street at the expense of some delays for the side street vehicles.

Of course, one now needs to compare *RHODES©*' bus delays and travel times, with and without bus priority, to see the effect of bus priority:

Average bus travel time on routes (in minutes)	12.69 (SAC)	12.05 (RwoB)	11.75 (RB)
Total bus delay time per link (in bus-minutes)	30.75 (SAC)	28.29(RwoB)	25.29 (RB).

Observe again, that *RHODES©* improved these measures, but that *RHODES©/BUSBAND* with bus priority shows a further improvement.

In the second set of tests, we used a simulation model that is being developed for an FHWA-sponsored field-test of the *RHODES©* traffic control strategy on an arterial with some cross streets in a Seattle suburb. The model is being developed by a contractor for FHWA and is based on real data. In our simulation experiments the scenario consisted of a single *RHODES©* controlled intersection and for all practical purposes can be thought of as an isolated intersection being fed by streams of realistic car and bus streams.

For baseline conditions against which to evaluate *RHODES©/BUSBAND* we generated several buses at a bus stop upstream of the intersection, say Stop A. For each bus, we generated a "lateness" which was positive if the bus was late and negative if it was early; the distribution we used was from a uniform distribution with range [-30s, +30s]. We also generated a passenger count, from a uniform distribution with range [0, 30]. The baseline case was standard actuated control. At a bus stop downstream from the intersection, say Stop B, we measured arrival times. Assuming that on the average, in the baseline situation, some buses arrive early, some arrive on time and some late, we assumed the average of these arrival times corresponds to was zero delay. Hence we added a fixed travel time component to the average arrival time at upstream bus stop so that this holds. This same travel time component was used for the corresponding case with *RHODES©* traffic control. Two side street traffic volumes were used for the baseline case (SAC), while the main street volume was kept constant at 1074 vehicles per hour. Buses were generated at approximately 36 per hour. We compared *RHODES©* with no bus priority (RwoB) and *RHODES©/BUSBAND* (RB) with these baseline conditions. Tables 3(a) – 3 (b) summarize the results.

For low side street traffic volumes, totaling 550 vehicles per hour in both directions, *RHODES©* reduced average travel times and intersection delays over semi-actuated control, as expected (see Table 3a). *RHODES©/BUSBAND* slightly reduced average bus delays over *RHODES©* (without bus priority), but not significantly.

For high side street volumes, with demand of 1100 vehicles/hour, *RHODES©*, with and without bus priority, significantly increased travel speeds and reduced delays for side street traffic, while decreasing bus delays on the main street (Table 3b). *RHODES©/BUSBAND* slightly reduced average bus delays over *RHODES©* (without bus priority), from –3.59s to –5.54s.

An impressive result in these experiments is the significant reduction in the variance of the bus delays at the downstream bus stop when *RHODES©* is implemented. For example, the standard deviation for the delay decreased from 23.17s (SAC) to 17.4 (RB) and 17.04s (RwoB) at high side street volumes.

When passenger count is included, *RHODES©/BUSBAND* decreased average passenger travel time. For example, at high side street volume, average bus passenger travel time decreased from 80.3 seconds to 75.5 seconds, while the passenger car speeds for both the main street and the side street either were unaffected or slightly decreased.

Table 3: Results from Second Set of Simulation Experiments

(a) Low traffic volume

Control method	Average bus delay at Stop A	Std dev. of bus delay at A	Average bus travel time from A-B	Std dev. travel time from A-B	Average bus delay at stop B	Std dev. of bus delay at B	Average bus passenger travel time from A-B	Side street Average speed	Side street average delay per vehicle
Std actuated control (SAC) (# buses)	-1.19(s) (55)	17.51(s)	73.69(s)	9.4(s)	-1.1069(s)	21.55(s)	NA	11.1mph	29.75(s)
RHODES© without bus priority	-0.9(s) (56)	16.91(s)	73.89(s)	8.1(s)	-0.96(s)	19.41(s)	73.4(s)	14.6mph	18.25(s)
RHODES© with bus priority	-0.27(s) (55)	17.17(s)	71.79(s)	7.7(s)	-0.95(s)	18.5(s)	70.3(s)	14.2 mph	19.5(s)

(b) High traffic volume

Control method	Average bus delay at Stop A	Std dev. of bus delay at A	Average bus travel time from A-B	Std dev. travel time from A-B	Average bus delay at stop B	Std dev. of bus delay at B	Average bus passenger travel time from A-B	Side street Average speed	Side street average delay per vehicle
Std actuated control (SAC) (# buses)	-0.109(s) (57)	18.63(s)	80.649(s)	13.19(s)	-0.15(s)	23.17(s)	NA	9.9mph	33.8(s)
RHODES© without bus priority	-2.96(s) (48)	15.91(s)	80.30(s)	10.32(s)	-3.59(s)	17.4(s)	80.3(s)	15mph	16.5(s)
RHODES© with bus priority	-0.36(s) (57)	16.27(s)	76.46(s)	9.5(s)	-5.54(s)	17.04(s)	75.5(s)	14.9mph	16.7(s)

5. CONCLUSIONS

This paper introduced a new approach to bus priority using the *RHODES©* traffic adaptive logic. Simulation results showed that *RHODES©* significantly increases average travel speeds and decreases the total traffic delays. In addition, average and variance of bus delays are decreased with *RHODES©*. If *RHODES©* bus priority logic, *BUSBAND*, is also implemented then there is a small additional decrease in bus delays and passenger travel times with little effect on the rest of the traffic.

One can assume that if *RHODES©* has been implemented in the city, the overall travel times have been reduced. Then the corresponding travel times used in the baseline case are no longer valid in the bus schedule. In that case, we need to examine the effects of decreased travel times on the schedule and the utilization of buses. Now the

(*RHODES©*) baseline delay at downstream bus stop will average to zero since the bus schedule will include the consideration lower travel times. However, it may be argued that the reduction in standard deviation will make the schedule more reliable and hence increase the bus ridership. Furthermore, if arrival times at bus stops are available using *RHODES©* processed data (*RHODES©* includes bus travel time predictions in its algorithmic logic) through an advanced traveler information systems, then this will also increase the desirability to use the transit system and hence also increase ridership.

Finally, given lower travel times, it can be argued that a fewer buses will now be used in the development of the bus schedule for the given level of service. This will allow the transit system to be profitable and/or economical.

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