Integrated Adaptive-Signal Dynamic-Speed Control of Signalized Arterials

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Abstract: This paper demonstrates the feasibility of an advanced concept of traffic control for congested urban arterials in an intelligent transportation system (ITS) setting. The core idea of the new concept is to integrate the capability of dynamic adaptive signals with dynamically optimized time-dependent variable speed. Under such control, speeds would be automatically optimized and set by a central computer in parallel with the other signal control parameters. Speed and signal control parameters would change between links and over time, in response to changing traffic conditions. Drivers would follow the optimized speed as they enter a link. Once an optimal speed has been set for a link, it remains constant until the control cycle ends. Link speeds would be updated only at the end of every control cycle. The control cycle may change in length as system conditions evolve. The new control concept was tested on a congested arterial with multiple links. The arterial system was modeled as a discrete event time varying dynamic system with a control period spanning several cycles. System throughput was maximized subject to such critical operational measures as intersection blockage, queue spillbacks, and other relevant traffic operation measures. Genetic algorithms were used as an optimization tool. Results show that the proposed control concept will significantly improve traffic flow. The new control concept is suitable for on-line implementation in an ITS setting.

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Introduction

Urban traffic congestion is becoming a fact of life in many urban and suburban areas in the United States and elsewhere in the world. More than 70% of the U.S. urban peak-hour traffic is congested (Turner 1999). Travel demand continues to far outpace provision of roadway capacity. For example, in the D.C. area, vehicle miles of travel are expected to increase by 75% between 1990 and 2020, whereas lane miles of capacity are expected to increase by only 22%. Consequently, vehicle hours of delay are projected to increase by 480%, and 85% of regional travel is expected to occur on congested roadways (Dey 1998). There is little reason to believe that congestion problems will go away simply by building new capacity. New and more advanced techniques within the overall framework of intelligent transportation systems (ITS) are needed to better manage and utilize existing transportation systems. In urban areas, traffic signal control plays a major role in the quality of traffic operations. As part of that, more advanced traffic signal hardware and control procedures are needed. Furthermore, traffic jams contribute substantially to air pollution.

This paper presents an advanced concept of signal control for implementation in an intelligent transportation system environment. The capabilities of adaptive dynamic signals are integrated with dynamic time-dependent speed. Functionally, speed is introduced as a control parameter as opposed to a soft constraint. Speed is optimized and allowed to vary over time (cycles, or time windows) and space (system links). The optimized speeds are then integrated into a dynamic signal control algorithm. The control algorithm assumes functioning intelligent signal hardware and communication systems.

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Background

Traditionally, traffic signal operations are optimized using the control variables of splits, offsets, and phasing. These parameters are usually designed to respond to traffic conditions, including desired speed, so that traffic progression is attained or the delay is minimized. Either way, speed is used as an input on the assumption that it is fixed and that its value is ''optimal.'' But a little examination of how speeds are normally set reveals that an optimal speed value should be a function of traffic conditions, which in turn is time-dependent. In the past, technical difficulties in reliably detecting traffic conditions may have been a serious hindrance in devising time-dependent changeable speeds based on real-time traffic information. Times have changed and a host of new technologies within ITS are changing the way we do business, including traffic sensing and design of traffic signal operations. It is becoming increasingly possible to reliably, but not perfectly, detect traffic conditions in real time. This in turn makes it feasible to vary speed based on field traffic information.

The concept of variable speed in traffic control is not new. It has been successfully used on freeways for quite some time, particularly in Europe (Hardbord 1998; Rumar 1999; Tignor et al. 1999). It is time to start exploring the feasibility of applying a similar concept on signalized arterials—that is, to vary speed dynamically on arterials and use it as an additional control parameter. This is what this paper sets out to explore.

The paper presents a conceptual formulation of an algorithm that dynamically optimizes individual speeds on arterial links and

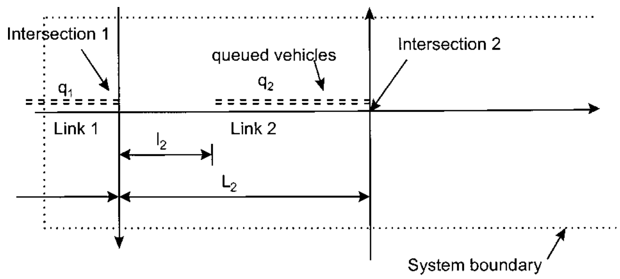

Fig. 1. Notation for two-intersection system

uses them as control parameters along with the other traditionally optimized signal control parameters. The optimized speeds are integrated into a dynamic signal control algorithm (Abu-Lebdeh and Benekohal 1997). Genetic algorithms (GAs) were used to solve the optimization problem. Genetic algorithms' adaptive, robust, directed search and flexible form of the objective function make them an ideal solution technique for dynamic control problems similar to the problem formulated in this paper.

Formulation of New Control Scheme

The key feature of the control scheme of this paper is to dynamically vary speed and use it as a control variable. Speed is optimized in parallel with the other control variables based on evolving traffic conditions. The role of speed in this control scheme is in adapting the values of offsets to traffic conditions on downstream links so that output is maximized and intersection blockage is prevented. Specifically, offsets between neighboring arterial approaches are set based on queue length and the available space on a link. Speed determines the time needed to travel the available space on the link (i.e., the distance between the upstream intersection and the downstream queue). This time element is a component of the offset-determining algorithm. Hence, different speeds would result in different offsets for the same queue length and the same available space on a given link. In this framework, speed is optimized to produce system-optimal (as opposed to link-optimal) performance. In the context of this paper, the term *system* signifies the collection of all arterial links. Vehicle acceleration and deceleration rates were assumed constant. First, we show how speed interacts with control parameters to influence traffic flow, then we present a conceptual formulation of the new control scheme where speed is dynamically optimized along with other signal control parameters. Note that dynamically optimizing and using the ''other'' signal control parameters is normally called adaptive signal control. The paper then continues with a presentation of experimental results.

Offsets

The offset used in the control algorithm of this paper assumes that all signals are ''intelligent'' in that they are able to receive traffic information perfectly. It uses speed as an active decision variable (as opposed to responding to drivers' desired speeds, i.e., treating speed as a passive decision variable). The role of speed is best demonstrated by first presenting the formulation of offsets. Based on the two intersection system shown in Fig. 1, the control uses an offset (between Intersections 1 and 2) of the form

$$\mathrm{off}_{(k)1,2} = td_{(k)1,2} - t_{(k)2}$$

td is the time by which to delay the release of the first vehicle of the upstream queue relative to the time the tail of the downstream queue starts moving. It is determined based on traffic acceleration rate (*acc*), desired speed (*ds*), and the separation between traffic at the beginning of the green interval. This time can be determined using Newton's laws of motion. $t_{(k)2}$ is the time it takes for the tail end of q_2 to start moving. $t_{(k)2}$ is determined using shock wave concepts. For cycle *k*, when the signal for Approach 2 turns green, an acceleration wave ensues and reaches the tail end of the queue in $t_{(k)2}$ seconds, where

$$t_{(k)2} = q_{(k)2} LV/\nu$$

and $q_{(k)2}$=number of vehicles queued at Approach 2 at the beginning of cycle *k*. *LV*=average effective vehicle length; and ν=speed of a starting shock wave.

There are four cases to consider for the determination of the value of *td*. Three cases are for the condition when there are queues upstream at the time the signal turns green. For these cases, the value of *td* is dictated by two factors: (1) the length of space available on the downstream link when the upstream signal turns green; and (2) whether or not the space is sufficient for the vehicle to accelerate, reach the speed limit, and then cruise. The fourth case is for conditions when there are no queues upstream as the signal turns green. Note that in Case 4, it is assumed that the arriving vehicle has attained its desired speed before arriving in Link 2. The four cases are shown in Table 1.

Note that l_2 starts decreasing with time once the upstream signal turns green (and vehicles start moving into Link 2). If we know l_2 at the beginning of g_1, the time when the upstream signal turns green, and the time when the last vehicle in the queue on Link 2 (call it v_2) starts moving, then we can determine the value of *td* that ensures that the first vehicle from Link 1 (call it v_1) and v_2 are traveling at the speed limit as they join. Note that when v_1 joins the tail end of q_2, the value of l_2 is zero. This condition will not always occur when both v_2 and v_1 are on Link 2. In relation to Case 4, the design of the algorithm (specifically, the offset) was such that, if the upstream vehicle is not starting from a stop position (i.e., Case 4), it will enter the subject link at the assigned speed (i.e., the speed that the algorithm decides it is optimal). Furthermore, this is accomplished such that the vehicle

Table 1. Cases for Determining *td*

Case	Movement of vehicle before it enters Link 2	l, distance on receiving link when upstream signal turns green (l_2 in Fig. 1)
1	Stopped (i.e., $q_1 > 0$)	Sufficient to reach speed limit and then cruise, but less than L
2	Stopped (i.e., $q_1 > 0$)	Not sufficient to reach speed limit
3	Stopped (i.e., $q_1 > 0$)	Equal to L (i.e., downstream link is empty)
4	Moving (i.e., $q_1 = 0$)	Sufficient/not sufficient to reach speed limit and then cruise

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Table 2. General Expressions for *td*

Case	Movement of vehicle before it enters Link 2	*td*
1	Stopped (i.e., $q_1>0$)	$1/ds$; *ds*=desired speed or speed limit
2	Stopped (i.e., $q_1>0$)	$\{-spdl+[(spdl)^2+4\cdot l\cdot acc/2]^{0.5}\}/(acc)$, where $spdl=acc\cdot[(2\cdot l/acc)^{0.5}]$; *acc*=assumed vehicle acceleration
3	Stopped (i.e., $q_1>0$)	$(L+dtds)/ds$; *dtds*=distance to reach desired speed or speed limit
4	Moving (i.e., $q_1=0$)	$1+[\min(L-1,dtds)]/ds$

will not be slowed down by traffic ahead except when the vehicle has to stop at the downstream approach because of a red signal. The general expressions for *td* are shown in Table 2.

From Table 2, one can see how speed (*ds*) influences offsets. It is obvious now that changing speed will change offsets. In other words, speed is now a decision variable that can be optimized to produce more favorable flow conditions.

Control Function

The adaptive signal dynamic speed control optimization problem is structured as a discrete event time-varying dynamical system. The optimal arterial control formulation is as follows.

Find the trajectory of control variables:

- $g_{(k)i}$ (green splits),
- $\text{Speed}_{(k)i}$ (speeds), and
- $\text{Offsets}_{(k)i}$ (offsets)

that maximizes the objective function

$$\sum_{\text{all approaches}}\ \sum_{\text{all cycles}} \text{System output(Link}-\text{vehicles)}\times\text{Speed}$$

subject to the constraints on state variables

$$q_{(k+1)i}=q_{(k)i}+AV_{(K)i}-DV_{(k)i}$$

$$(\text{queue formation and dissipation models})$$

and control variables:

- $g_{(k)i\ \min}\leqslant g_{(k)i}\leqslant g_{(k)i\ \max}$ (domain of green splits),
- $\text{Speed}_{(k)i\ \min}\leqslant\text{Speed}_{(k)i}\leqslant\text{Speed}_{(k)i\ \max}$ (domain of speeds), and
- $\text{Offsets}_{(k)i}=f[\text{queue length}_{(k)i},\text{space}_{(k)i},\text{speed}_{(k)i}]$

where q=queue length; *AV*=volume of arriving traffic; *DV* =volume of departing traffic; k=cycle number; and i=link, or approach number. In addition to being in the domain of green splits, the green time has to meet two other important constraints: (1) no de facto red may form; and (2) wasted green or traffic starvation is prevented. De facto red is the condition where traffic cannot discharge because the downstream link is full. These two constraints are satisfied by making the green time an explicit function of the downstream green, downstream queue length, and the offset (Abu-Lebdeh and Benekohal 1997). It should be noted that in a two-way traffic operation, satisfaction of these constraints can be guaranteed for one direction only.

The decision variables in this optimization problem are green splits (hence cycle length), offsets, and speeds. Speeds were allowed to vary between 17 and 45 km/h. Phasing was not optimized. The algorithm was applied to a congested system of seven intersections for a duration of 10 cycles. The cycles could vary between 50 and 120 s (arterial green range is 30-80 s). All links had two through lanes and ranged in length between 250 and 300 m. A saturation flow rate of 1,800 vehicles per hour of green was used. Starting and stopping shock wave speeds were, respectively, 4.9 and 4.3 m/s. The average effective vehicle length was assumed to be 7.6 m.

Microgenetic algorithms (micro-GAs) were used for optimization. Micro-GAs were used because of their ability to overcome combinatorial explosion and the flexibility they allow in formulating the objective function. The results are discussed next.

Evaluation and Discussion of Results

Several measures of effectiveness (MOEs) were used to evaluate system performance with variable speed. The results were contrasted to system performance where a constant speed of 45 km/h is used. All inputs and parameter values were the same for the variable and constant speed schemes. Overall, using the scheme of variable speed appears to improve system performance. Specific results are discussed below. All results are presented on a per lane basis. Changes of speed were assumed to follow a step function.

Selected Speeds

Fig. 2 shows the values of speeds selected along the system for the first and last cycles. Speeds of the early cycles are lower and very close to each other because, at this time, the system is still congested and each link has the same number of vehicles (per initial conditions). Speeds of the last cycles are higher and show more variation—also consistent with the traffic condition of the system where far fewer vehicles are presented on the different links. This outcome shows the ability of the control scheme to select speeds in accordance with prevailing traffic conditions. The control was able to “see ahead” and select speeds based on a system rather than link view. This shows clearly when speed variation is examined for specific cycle and link, as noted in Fig. 3.

Fig. 3 shows the variation of speed for both first and last cycles in relation to the traffic ahead. Speeds of each link are shown in relation to the number of vehicles on the current and the two links ahead. There is a clear and logical association between

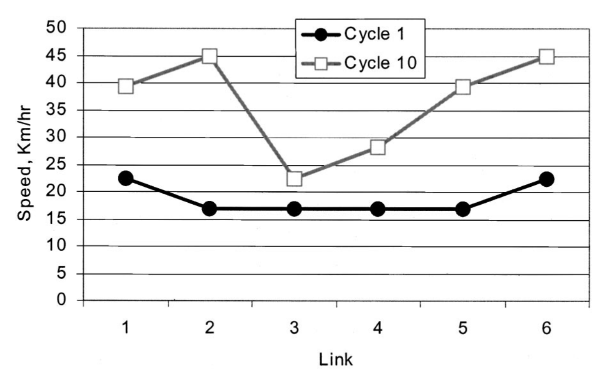
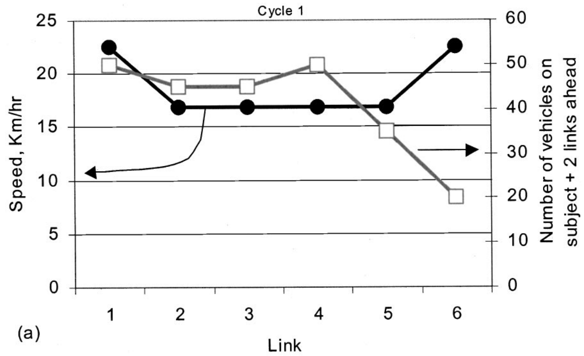


Fig. 2. Selected speeds along system for first and last cycles



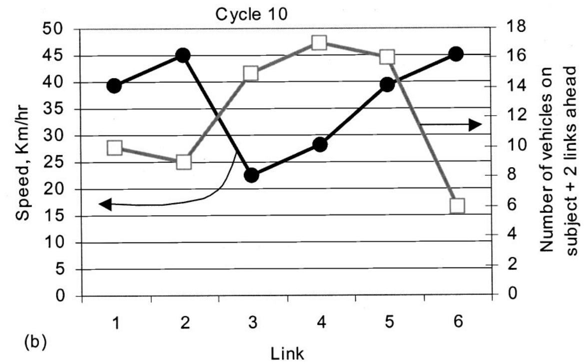


Fig. 3. Association between selected speed and traffic ahead: (a) first cycle; (b) last cycle

the volume of traffic ahead and the selected speed; more traffic ahead dictated selecting a lower speed.

Number of Stops

A vehicle is said to have stopped if it was unable to leave the link during the same cycle it entered in. The number of stops provides a general measure of quality of progression, fuel consumption, and vehicle emissions. Fig. 4 shows the number of stops per unit of output for each link for both variable and constant speed control schemes. The number of stops is lower under the variable speed scheme; for the entire system, there were 25% fewer stops. At the link level, the number of stops was generally lower under the variable speed scheme. The trend between individual links varied; two of the six links experienced more stops under the variable speed scheme. This is not unexpected, since the algorithm does system optimization, not individual intersection or link

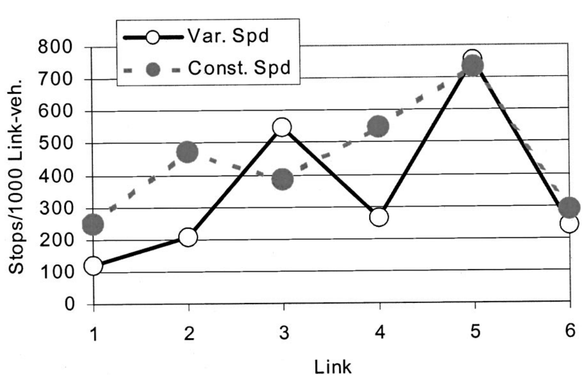


Fig. 4. Variation of number of stops on system links

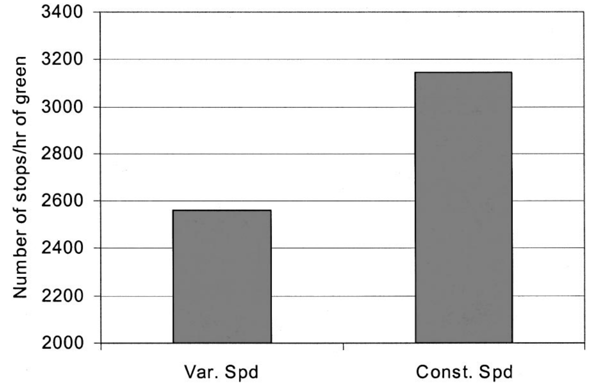


Fig. 5. Comparison of total system number of stops

optimization. It is conceivable that the control for a given intersection during one or more cycles is suboptimal (for that location/time combination) but the overall system control is optimal. The optimality of the system is not determined through a linear combination of the contributions from its individual components. When examined at the system level, the number of stops is significantly lower with variable speed control (Fig. 5).

The lower number of stops with variable speeds is expected. The algorithm has a ''system view'' of traffic conditions, or, in other words, it can ''see'' beyond the immediate downstream link. This makes it possible to employ a speed value that is system-optimal as opposed to ''link-optimal,'' which would be the case if speed selection is left to drivers. In real world conditions, drivers can see only conditions on the link they are driving on. Hence, they select a speed they think is optimal for that link, only to find themselves forced to stop at intersections further downstream. Employing variable speed, in effect, overcomes this condition; that is, it takes the decision of selecting speed from drivers and gives it to the system's ''central controller,'' which in turn assigns speeds to system links so that the overall system performance is optimal. Note that the lower number of stops may have been achieved at the expense of higher speed. It is possible that a lower speed was selected, which then resulted in a lower number of stops. This is consistent with the objective of the control.

System Traffic Content

System content measures the volume of traffic present on system links during a given time window. Higher traffic content means less chance for progression and more chance of stopping. Fig. 6 shows the system content at the beginning of each cycle. Traffic content is lower under the variable speed control scheme than

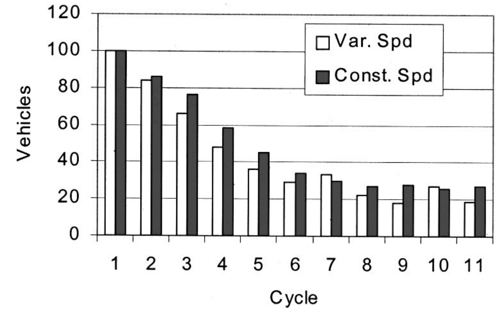


Fig. 6. System content of traffic over time

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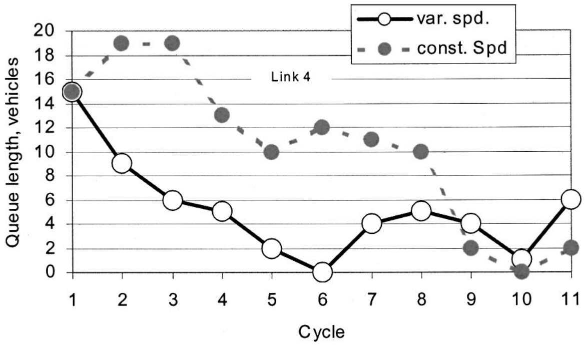

Fig. 7. Change of queue length with time on typical link

under the constant speed scheme. The trend is clearer at the link level (Fig. 7). Here, we see that the variable speed scheme was far more successful at reducing standing queues. This outcome follows from the fact that fewer vehicles are arriving ''prematurely'' at the respective approaches. Flexibility in speed makes this possible.

In the last few cycles, Link 4 and the system traffic content is slightly higher under the variable speed scheme. In part, this is because the system, including Link 4, has little traffic at this point. At this stage the system is operating satisfactorily so that control with variable speed offers no advantage over constant speed.

System Output

System output, measured in link-vehicles and normalized by arterial green time, is shown in Fig. 8. The output is only slightly higher under the variable speed control scheme. The experimental setup could have contributed to this marginal difference; the optimized variable speeds were allowed to vary from 17 to 45 km/h, whereas under the constant speed scheme, speed was set at 45 km/h.

Examination of individual MOEs in isolation from others can be misleading. In some cases, that type of examination may not provide an accurate picture of how the system is operating. Multiple MOEs, or MOEs that are more encompassing, should be used to evaluate control schemes. From the above results, a slightly higher output rate was achieved under the variable speed control scheme, but that was accompanied by a significantly lower number of stops. These two MOEs need to be considered simultaneously to appreciate the value of the variable control scheme.

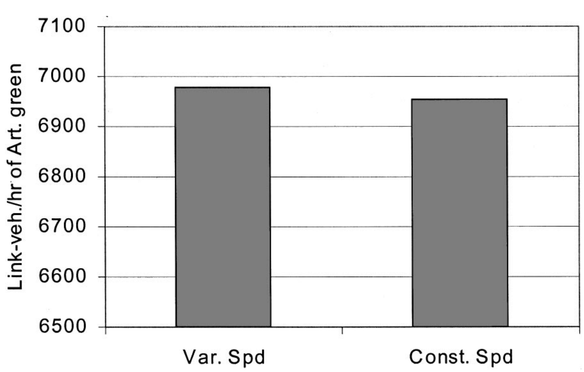

Fig. 8. System output for two control schemes

Conclusions

This paper presents an advanced signal control algorithm wherein speed is used as a decision variable as opposed to a soft constraint—as is traditionally the case. The algorithm treats link speeds as functions of time, dynamically optimizes them, and then uses them as control parameters along with green splits and offsets. Speed is dynamically optimized along with the other conventional control parameters based on evolving traffic conditions. Using speed as another control parameter adds a new dimension to the control problem and hence increases the spectrum of control choices. The algorithm was tested on a congested seven-intersection arterial system. The results were then contrasted to those with constant speed. Variable speed-based control was more efficient in many respects: it resulted in less stops, better conditions for progression, better queue management, and more system output. This implies improved traffic flow. There would be less premature arrivals at intersections and formation of queues (hence shorter time to clear queues), fewer number of stops and ''stop-and-go'' maneuvers, and less interactions and complications resulting from continuous stopping and starting shock waves. Reduced fuel consumption and harmful emissions is another desirable outcome.

The new control concept is intended for on-line implementation in an ITS setting. The value of this procedure is greater when traffic on system links varies considerably due to either geometry or traffic generation factors. In the results presented above, we assumed complete driver compliance with speed—an overly optimistic assumption, given current modes of operation. However, with the advent of automated and advanced control features on vehicles, this will become less of an issue. This and other implementation issues will have to be addressed before variable speed type control can be implemented in real-world conditions. It is recommended that this concept of control be further evaluated and validated in preparation for implementation. The concept's application to networks with closed loops is possible; however, it is not a simple extension of the version presented in this paper.

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