Traffic Signal Control with Connected Vehicles

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ABSTRACT

The operation of traffic signals is currently limited by the data available from traditional point sensors. Point detectors, often in-ground inductive loop sensors, can provide only limited vehicle information at a fixed location. The most advanced adaptive control strategies are often not implemented in the field due to their operational complexity and high-resolution detection requirements. However, a new initiative known as *connected vehicles* would allow for the wireless transmission of vehicles' positions, headings, and speeds to be used by the traffic controller. A new traffic control algorithm, the predictive microscopic simulation algorithm (PMSA), was developed in this research to utilize these new, more robust data. The decentralized, fully adaptive traffic control algorithm uses a rolling horizon strategy, where the phasing is chosen to optimize an objective function over a 15-second period in the future. The objective function uses either delay-only, or a combination of delay, stops, and decelerations. To measure the objective function, the algorithm uses a microscopic simulation driven by present vehicle positions, headings, and speeds. Unlike most adaptive control strategies, the algorithm is relatively simple, does not require point detectors or signal-to-signal communication, and is completely responsive to immediate vehicle demands. To ensure drivers' privacy, the algorithm stores no memory of individual or aggregate vehicle locations. Results from simulation show that the algorithm maintains or improves performance compared to a state-of-practice coordinated-actuated timing plan optimized by Synchro at low- and mid-level volumes, but performance worsens during saturated and oversaturated conditions. Testing also showed improved performance during periods of unexpected high demand and the ability to automatically respond to year-to-year growth without retiming.

INTRODUCTION

Traffic signals, when operated efficiently, can enable safe and efficient movement of vehicles through an intersection and minimize delays in a corridor. However, most signal timing plans in use must ignore or make assumptions about many aspects of traffic conditions. Fixed time control, where a signal system uses a static and repeating sequence of phases and durations designed to serve a certain time period, has no way to detect vehicles and therefore relies on the expected approach volumes from manual traffic counts. Actuated timing plans use point detectors to modify a fixed timing plan, by occasionally skipping a phase if no vehicle is present, or shortening a phase when vehicles are not being served. Some adaptive timing plans attempt to adjust to slow or systematic changes in volumes. Split Cycle Offset Optimisation Technique (SCOOT) *(1)* and Sydney Coordinated Adaptive Traffic System (SCATS) *(2)* are two prominent examples. However, both are restricted in that they only alter a cyclic timing plan.

Other timing plans do allow acyclic operation, but differ in their approach. The most common technique is to use the concept of rolling horizon, where a traffic control algorithm attempts to optimize an objective function such as delay over a short period into the future, generally one or two cycle lengths. The objective function is optimized by estimating the positions of vehicles during the horizon over several possible phasings. Some examples of point detector-based rolling horizon strategies are ALLONS-D *(3)*, UTOPIA *(4)*, PRODYN *(5)*, OPAC *(6)*, and RHODES *(7)*. However, because these strategies are point detector-based, they are forced to make several estimations, including a vehicle's precise positions after passing a detector, queue length, and vehicle speeds. Additionally, these adaptive control strategies are not widely implemented in the United States, due primarily to their operational complexity (engineers typically require 4-6 months to understand the systems) and maintenance demands *(8)*.

Connected Vehicle Wireless Detection Systems

A new initiative to allow wireless communication between vehicles and the transportation infrastructure, referred to here as "connected vehicles," may have broad implications for how traffic signal control will operate in the future. Instead of relying on point detectors (such as inductive loops or video detection systems) that sense only presence at fixed locations, signal systems would be able to use data from in-vehicle sensors transmitted wirelessly from equipped vehicles to the signal controller. Traffic signal control logic would have access to many measures that were previously estimated or unknown such as vehicle speeds, positions, arrival rates, rates of acceleration and deceleration, queue lengths, and stopped time.

A clear definition of the types of data and communications used by connected vehicles is found in the Society of Automotive Engineers (SAE) J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary *(9)*. This standard defines vehicle-to-vehicle and vehicle-to-infrastructure communications using DSRC, the medium-range communications channels dedicated for vehicle use by the Federal Communications Commission (FCC) in 1999. For safety applications, each vehicle transmits a Basic Safety Message (BSM) that transmits its temporary ID, location, speed, heading, lateral and longitudinal acceleration, brake system status, and vehicle size to surrounding vehicles and the infrastructure. By "listening" to these messages, a signal controller could gain a more comprehensive understanding of the movements of nearby vehicles than with loop and video detection.

Traffic Signal Control Using Individual Vehicle Locations

Several traffic signal timing plans have been proposed which utilize some form of wireless communication between vehicles and the signal controller. Premier and Friedrich *(10)* proposed a rolling horizon algorithm using vehicle-to-infrastructure communications based on the IEEE 802.11 standard. The algorithm sought to minimize queue lengths by optimizing phases in five-second intervals over a 20-second horizon using the techniques of dynamic programming and complete enumeration on an acyclic, decentralized system.

Datesh et al. *(11)* proposed an algorithm which uses vehicle clustering to apply a sophisticated form of actuated control. The acyclic timing plan assigns the next phase to the first group of queued vehicles to surpass a predetermined cumulative waiting time threshold. The phase is extended to allow the next platoon to pass, which are identified using k-means clustering based vehicles' speeds and locations.

Lee *(12)* proposed the Cumulative Travel Time Responsive (CTR) Real-Time Intersection Control Algorithm. This algorithm uses connected vehicles to determine the amount of time that a vehicle has spent traveling to the intersection from within 300 meters or the nearest intersection, whichever is closer. The travel time includes the time that the vehicle is in motion, as well as its stopped time at the intersection, if any. The algorithm then sums the travel times for each combination of movements (i.e. NEMA phases 2 & 6, or 4 & 8). The phasing with the highest combined travel time is selected as the next phase, with a minimum green time of five seconds. To supplement the travel time figures obtained at less than 100% market penetration, a Kalman filtering technique was used to estimate actual cumulative travel times based on a prediction of future travel times and the measurement of sampled vehicles.

He et al. *(13)* proposed the platoon-based arterial multi-modal signal control with online data (PAMSCOD) algorithm, which used mixed integer linear programming to determine phasing and timings every 30 seconds for four cycles in the future, based on predicted vehicle platoon sizes and locations. PAMSCOD was able to improve vehicle and bus delay at saturation rates greater than 0.8, but often experienced higher delays at saturation rates less than 0.6. The saturation rate was calculated using Synchro's intersection capacity utilization metric *(14)*.

To date, no research has investigated utilizing microscopic simulation as a tool to estimate future conditions in a rolling horizon algorithm in a connected vehicle environment *without re-identifying vehicles*. Unlike previous connected vehicle signal control algorithms that required at least short-term tracking of vehicle locations (e.g. to measure platoon movements or waiting time), this research proposed the first signal control algorithm to use wireless vehicle locations without re-identification or short-term tracking of vehicles. Furthermore, no other research has investigated multi-objective optimization over the short-term horizon and its affect on delay in the long-term in a connected vehicle environment.

PROPOSED TRAFFIC SIGNAL CONTROL ALGORITHM DESCRIPTION

The traffic signal control algorithm proposed in this paper, called the predictive microscopic simulation algorithm or PMSA, has the following three objectives:

1) to match or significantly improve the performance of a state-of-practice actuated-coordinated system;
2) to respond to real-time demands only, thereby eliminating the need for manual timing plan updates to adjust for traffic growth or fluctuations; and
3) to never re-identify, track, or store any records of individual or aggregate vehicle movements for any length of time, thereby protecting driver privacy.

To accomplish these objectives, the PMSA uses a rolling horizon approach, where the traffic signal controller attempts to minimize an objective function over a short time period in the future. Although many detector-based traffic signal control strategies use rolling horizon, they require complicated algorithms to estimate vehicle arrivals *(15)* and delay *(3)*. They also require reliable and highly accurate detection, generally in the form of loop detectors both at the intersection and upstream of each approach. The failure of one or more detectors could be catastrophic for the rolling horizon approach.

The PMSA, uses microscopic traffic simulation to simulate vehicles over the horizon period, and calculates the objective function delay directly from the vehicle's simulated behavior. For the purposes of this description, an intersection's movement is defined as a single controlled vehicle path, e.g. westbound left, whereas a phase is defined as two non-contradictory movements, e.g. westbound left and eastbound left. When the algorithm recalculates the signal's phase, it first collects a snapshot of the position, heading, and speed of every equipped vehicle within 300 meters of the intersection (at 45 mi/hr, the speed of this corridor, a vehicle travels exactly this distance during the 15-second horizon). This information is then used to populate a model of the intersection, as shown in Figure 1.

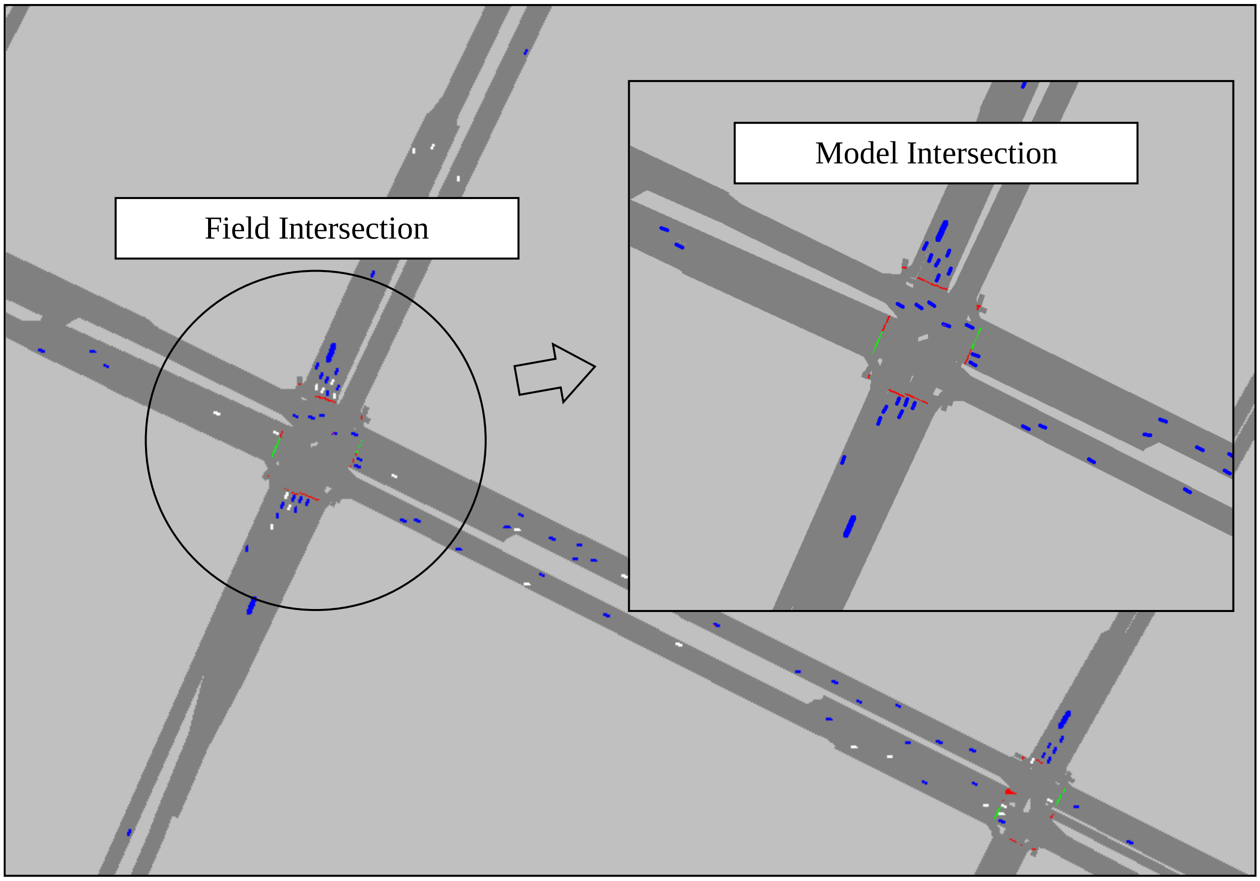

FIGURE 1 The PMSA populating a model of the intersection with the positions and speed of the equipped vehicles from the "real world" field intersection.

Once the model has been populated with the new vehicles, the vehicles are simulated fifteen seconds into the future. Because the turn lanes in the test network were between 75 and 300 meters in length, the turning movement of many vehicles can be assumed based on their current lane. For vehicle's upstream of the turning lane, it was assumed that 50% of those in the lane nearest a turning lane would use the turning lane. This is repeated once for each possible new phase configuration, as well as for the possibility of maintaining the current phasing. Four-second amber phases and two-second red phases are simulated as well. The phase with the optimal objective function over the fifteen second horizon is selected as the next phase.

The new phase's green time is determined from the horizon simulation as the time required to clear all simulated vehicles from a single movement. This time is bound with a minimum of 5 seconds, and a maximum time before recalculation of 15 seconds.

To ensure smooth operation of the signal, several restrictions are put in place. Because the algorithm is acyclic and allows phase skipping, each movement has a maximum red time of 120 seconds. This was considered reasonable, as the Synchro-recommended timing plan for the corridor was 120 seconds. Also, to take advantage of the queue detection capabilities of connected vehicles, the algorithm will not allow queues to block a turning lane or through lane. When a vehicle is detected within 40 feet of blocking a movement, the vehicle's movement is given priority at the next phase recalculation. The PMSA's decision process is shown in Figure 2.

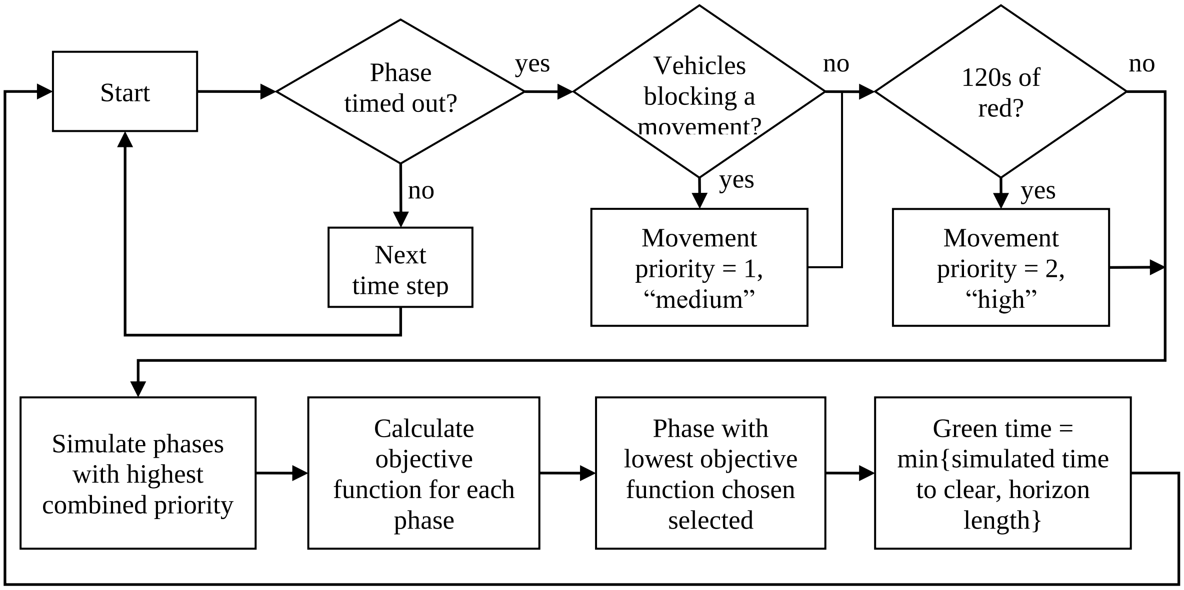

FIGURE 2 Predictive microscopic simulation algorithm's logic flow chart.

The algorithm operates completely without loop or video detection, with no knowledge of expected demand or memory of past demand, and is completely decentralized. There is no communication with any other signal on the corridor, either ad hoc or through synchronized timing. The algorithm was designed to be compatible with the SAE J2735 standard for DSRC communications. It requires only the information required in the Basic Safety Message no more than once per second, whereas the message is sent ten times per second according to the standard. Further, the algorithm is able protect driver privacy by clearing any vehicle data seconds after it is recorded. Specifically, the algorithm does not store any vehicle location data, neither aggregated volumes nor individual vehicle trajectories, once the next phase has been determined.

SIMULATION TESTING AND RESULTS

To simulate the connected vehicle environment, the microscopic simulation software package VISSIM was used, as it allows users to easily access individual vehicle information via a COM interface, and allows a second "future" simulation to run parallel to the primary simulation. For this study, a program was written in the C# programming language using VISSIM's COM interface to extract individual vehicle characteristics such as speed and position no more than once per second.

The test network is a calibrated model of four intersections along Route 50 in Chantilly, Virginia, shown in Figure 3. Vehicle volumes and turning movements were collected in 2003 between 3:00PM and 4:00PM on weekdays *(16)*. Pedestrian movements, which were very low at these intersections, were eliminated for the purpose of this analysis, as the minimum pedestrian crossing time often exceeded 60 seconds, well beyond the algorithm's 15-second horizon.

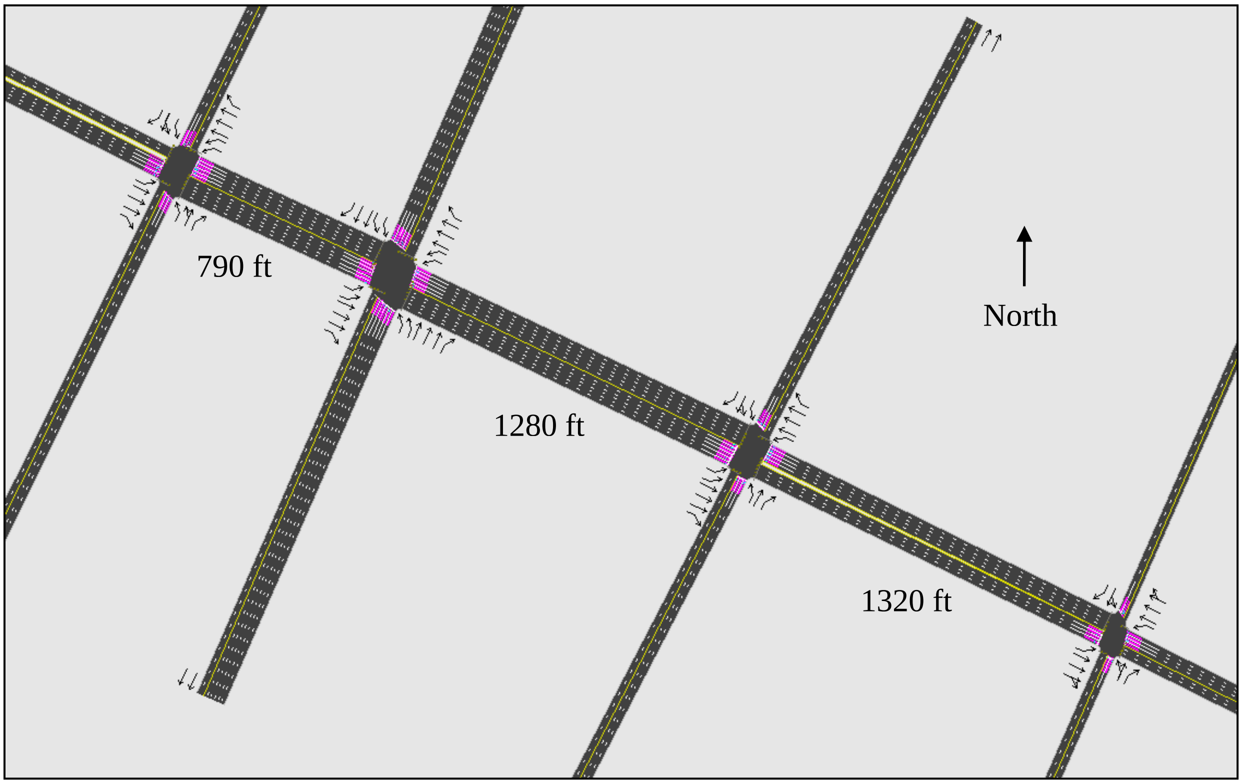

FIGURE 3 Map of the test segment, a 4-signal stretch of US-50 in Chantilly, Virginia.

Vehicle volumes were converted to approximate intersection saturation rates using Synchro's intersection capacity utilization (ICU) metric *(14)*, and measured at an average of 0.75. To test the sensitivity of the algorithm to various equipped vehicle penetration rates, the algorithm was tested at 10%, 25%, 50%, and 100% vehicle participation, using total delay over the horizon as the sole element of the objective function. Each scenario was evaluated for 30 minutes after 400 seconds of simulation initialization *(17)*. Each scenario was tested ten times at different random seeds, and all produced statistically similar results with a 95% confidence level *(18)*.

Off-line signal system optimization tools such as Synchro *(19)* and TRANSYT-7F *(20)* are often used in practice to develop timing plans. In this research, Synchro was used to develop an optimized coordinated-actuated timing plan with a 120 cycle length as a base case for comparison with the PMSA. Synchro's recommended timing plans were programmed into and tested in the VISSIM network.

Single Variable Objective Function

The algorithm attempts to optimize some objective function over a 15 second interval. Initial testing focused on a single variable, the cumulative vehicle delay. Although decentralized, the algorithm produced coordinated flow, as evidenced by the signal timing and vehicle trajectories shown in Figure 4.

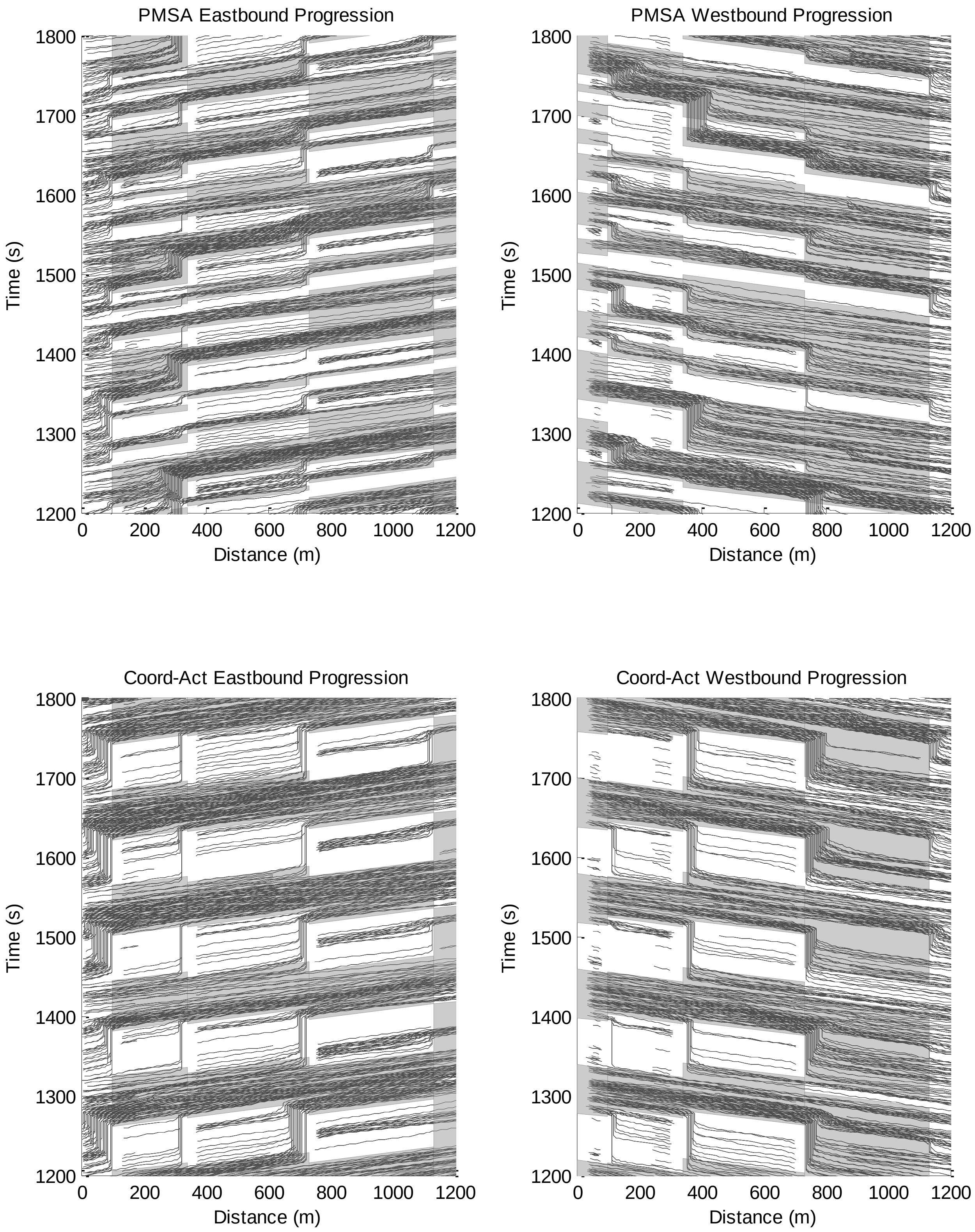

FIGURE 4 Signal system coordination and vehicle trajectories comparison of the PMSA and a coordinated-actuated system.

The results of the testing are shown in Table 1. Improvements in delay and speed are only experienced at penetration rates of 50% and higher. There are fewer stops at higher penetration rates, but always more stops compared to a coordinated-actuated system. Stopped delay improves at 25% penetration and higher, with a 34% improvement experienced with 50% of vehicles participating. It should be noted that these improvements are experience with neither any assumed knowledge of historical demand volumes, nor of any coordination or communication with neighboring signals.

TABLE 1 Performance of PMSA at Various Equipped Vehicle Penetration Rates

Metric	Method	Value	Difference	*P* value*
Delay *(s/veh)*	Coord-Act	49.7		
	10% PMSA	54.1	8.9%	< 0.001
	25% PMSA	47.1	-5.2%	0.001
	50% PMSA	45.2	-8.9%	< 0.001
	100% PMSA	48.3	-2.7%	0.102
Average Speed *(mi/hr)*	Coord-Act	28.7		
	10% PMSA	28.0	-2.6%	< 0.001
	25% PMSA	29.3	1.9%	< 0.001
	50% PMSA	29.7	3.2%	< 0.001
	100% PMSA	29.1	1.1%	0.035
Stopped Delay *(s/veh)*	Coord-Act	28.1		
	10% PMSA	29.6	5.4%	0.024
	25% PMSA	24.5	-12.8%	< 0.001
	50% PMSA	23.9	-14.8%	< 0.001
	100% PMSA	26.4	-6.0%	0.009
Stops	Coord-Act	4755		
	10% PMSA	5707	20.0%	< 0.001
	25% PMSA	4997	5.1%	0.005
	50% PMSA	4680	-1.6%	0.351
	100% PMSA	4843	1.8%	0.308

* n = 10

According to Federal Highway Administration (FHWA) estimates, 25% of congestion is caused by incidents *(21)*. The PMSA, because it requires no knowledge of historical traffic demands, has the advantage of responding to unexpected demands due to incidents with minimal transition time compared to a time-of-day plan. To evaluate the PMSA’s ability to handle large unexpected variations in flow, a simulation was run where volumes entering the mainline heading east increased by 30%. This represents a realistic scenario for vehicles rerouting to avoid an incident on a parallel freeway or arterial. The PMSA, operating with 100% equipped vehicle penetration rate, is able to respond instantly to the increased demand, with no outside input from operators or communication with roadside infrastructure or nearby signals. The results of this analysis are shown in Table 2. With the unexpected volume increase, the PMSA produces greater benefits compared to the PMSA's improvements of a correctly-timed coordinated-actuated system.

TABLE 2 Performance of PMSA During an Unexpected 30% Increase in Volumes from the West

Metric	Method	Value	Difference	*P* value*
Delay *(s/veh)*	Coord-Act	55.2		
	10% PMSA	58.3	5.8%	0.010
	25% PMSA	49.4	-10.5%	< 0.001
	50% PMSA	47.6	-13.7%	< 0.001
	100% PMSA	49.8	-9.7%	0.001
Average Speed *(mi/hr)*	Coord-Act	28.0		
	10% PMSA	27.6	-1.4%	0.093
	25% PMSA	29.1	4.1%	< 0.001
	50% PMSA	29.5	5.4%	< 0.001
	100% PMSA	29.1	3.9%	0.001
Stopped Delay *(s/veh)*	Coord-Act	30.4		
	10% PMSA	31.0	1.8%	0.565
	25% PMSA	24.9	-18.2%	< 0.001
	50% PMSA	23.8	-21.8%	< 0.001
	100% PMSA	24.8	-18.3%	< 0.001
Stops	Coord-Act	5704		
	10% PMSA	6533	14.5%	< 0.001
	25% PMSA	5513	-0.3%	0.137
	50% PMSA	5198	-8.9%	< 0.001
	100% PMSA	5624	-1.4%	0.595

*****n = 10

Another common cause of congestion is poor signal timing, estimated by FHWA to be responsible for 5% of all congestion *(21)*. Many transportation agencies lack the resources to update signal timing plans every three years as recommended *(22)*. Annual traffic growth, if not addressed, can quickly overwhelm a timing plan and lead to poor performance. The PMSA, because it responds only to immediate traffic demand, can accommodate annual volume increases without adjustments. To test the PMSA's ability, the algorithm was tested at 100% market penetration against a coordinated-actuated timing plan that was optimized for the much lower ten-year-old volumes ten years in the past, assuming a 3% annual growth rate for all volumes. This equates to a 34% volume increase in all directions, with no change to the timing plan. The results of this analysis are shown in Table 3. The PMSA showed significant benefits across all metrics.

TABLE 3 Performance of PMSA on a Network with 3% Annual Volume Growth against a 10-year Old Coordinated-Actuated Timing Plan

Metric	Method	Value	Difference	*P* value*
Delay *(s/veh)*	Coord-Act	52.1		
	10% PMSA	54.1	3.8%	0.017
	25% PMSA	47.1	-9.7%	< 0.001
	50% PMSA	45.2	-13.2%	< 0.001
	100% PMSA	48.3	-7.2%	< 0.001
Average Speed *(mi/hr)*	Coord-Act	28.3		
	10% PMSA	28.0	-0.9%	0.067
	25% PMSA	29.3	3.6%	< 0.001
	50% PMSA	29.7	4.9%	< 0.001
	100% PMSA	29.1	2.8%	< 0.001
Stopped Delay *(s/veh)*	Coord-Act	29.6		
	10% PMSA	29.6	2.6%	0.208
	25% PMSA	24.5	-15.1%	< 0.001
	50% PMSA	23.9	-17.1%	< 0.001
	100% PMSA	26.4	-8.5%	< 0.001
Stops	Coord-Act	5097		
	10% PMSA	5707	12.0%	< 0.001
	25% PMSA	4997	-2.0%	0.206
	50% PMSA	4680	-8.2%	< 0.001
	100% PMSA	4843	-5.0%	0.008

* n = 10

The PMSA was additionally tested at uniformly varying volumes. Volumes at all intersection were uniformly multiplied by 0.5, 0.75, 1, and 1.25, which by using Synchro’s intersection capacity utilization metric as a surrogate, translated into approximate average saturation rates of 0.45, 0.60, 0.75, and 0.90 respectively. Different optimized coordinated-actuated timing plans were developed using Synchro for each of the new volume scenarios, while the PMSA was tested unaltered regardless of the volumes, and assuming 100% equipped vehicle penetration rate. The results are shown in Table 4. The PMSA either improves on or has no significant effect on delay, average speed, or stopped delay below 0.90 saturation rate. There are fewer stops at a saturation rate of 0.45, no difference at 0.60, and increased stops at 0.75 and 0.90. These results are similar to Lämmer and Helbing's decentralized adaptive systems, where performance degrades at near-saturated conditions *(23)*.

TABLE 4 Performance of PMSA at Various Saturation Rates

Saturation Rate*	Metric	Coordinated -Actuated	100% PMSA	Difference	*P* value**
0.45	Delay *(s/veh)*	41.4	30.4	-26.6%	< 0.001
	Average Speed *(mi/hr)*	30.5	32.9	8.0%	< 0.001
	Stopped Delay *(s/veh)*	24.0	17.4	-27.3%	< 0.001
	Stops	2381	1827	-23.3%	< 0.001
0.60	Delay *(s/veh)*	43.1	37.9	-12.1%	< 0.001
	Average Speed *(mi/hr)*	30.1	31.3	4.0%	< 0.001
	Stopped Delay *(s/veh)*	25.1	20.9	-16.7%	< 0.001
	Stops	3335	3067	-8.0%	< 0.001
0.75	Delay *(s/veh)*	49.7	48.3	-2.7%	0.102
	Average Speed *(mi/hr)*	28.7	29.1	1.1%	0.035
	Stopped Delay *(s/veh)*	28.1	26.4	-6.0%	0.009
	Stops	4755	4843	1.8%	0.308
0.90	Delay *(s/veh)*	65.7	62.6	-4.6%	0.013
	Average Speed *(mi/hr)*	26.1	26.5	1.4%	< 0.057
	Stopped Delay *(s/veh)*	38.5	33.2	-13.9%	< 0.001
	Stops	6246	7681	23.0%	0.008

* Approximate average saturation rate based on Synchro's ICU metric
** n = 10

Multivariable Objective Function

The previous analysis used vehicle delay as the sole variable in the objective function. Several other variables were tested as well if factors other than delay could improve performance of the algorithm. The objective function is described in Equation 1:

$$f = \alpha d + \beta a + \gamma s \tag{1}$$

where α, β, and γ are factors, *d* is delay per second per vehicle, *a* is negative acceleration per second per vehicle, and *s* is stops per vehicle. Delay and stops are commonly used measures of effectiveness for signal timing. Negative acceleration was selected because of its relationship with emissions; while positive acceleration is correlated with emissions, it is an unrealistic metric in practice as it discourages phase changes under all circumstances. Negative acceleration is a leading indicator of positive acceleration, and is therefore an acceptable surrogate measure. The variables are defined in Equations 2-4:

$$d = \min\left\{1, \frac{\sum_{i=1}^{n}\sum_{j=1}^{t} d_{ij}}{ntd_{\max}}\right\} \tag{2}$$

$$a = \min\left\{1, \frac{\sum_{i=1}^{n}\sum_{j=1}^{t}\max\left\{-a_{ij},0\right\}}{nta_{\max}}\right\} \quad (3)$$

$$s = \min\left\{1, \frac{\sum_{i=1}^{n}\sum_{j=1}^{t}s_{ij}}{ns_{\max}}\right\} \quad (4)$$

where the terms d_{max}, a_{max}, and s_{max} are terms used to cap and normalize the observed values, and are set at 1 s/s/veh, 3 m/s^3/veh, and 2 stops/veh, respectively. The term i represents an individual vehicle and j represent a single time interval, while n and t represent the total number of vehicles and total time respectively. For example, d_{ij} represents the delay of vehicle i over time j.

A range of factors were tested, between 0 and 1 at intervals of 0.1, and ensuring that the sum of α, β, and γ were equivalent to 1. The 30 combinations with the lowest average delay are shown in Table 5, with the delay-only single variable objective function as a baseline. Results that are significantly different from the delay-only results are marked in bold ($p < 0.05$). All scenarios assume an equipped vehicle penetration rate of 100%. Different objective functions were unable to significantly improve on the delay-only function, either in average delay or stops. A high acceleration factor in particular produces poor performance when compared to a delay-only function.

TABLE 5 Results from Using a Multivariable Objective Function

Delay Factor α	Acceleration Factor β	Stops Factor γ	Average Delay *(s/veh)*	Average Deceleration *(m/s^2/veh/sec)*	Average Stops
1	0	0	48.3	0.52	4843
0.8	0.0	0.2	47.9*	0.52	4900
0.9	0.0	0.1	48.1*	0.52	4858
0.6	0.0	0.4	49.0*	0.53	4949
0.9	0.1	0.0	49.1*	**0.50***	**4934***
0.7	0.0	0.3	49.9*	0.52	5008
0.8	0.1	0.1	50.0*	0.51	5044
0.5	0.0	0.5	**50.3***	0.52	5187
0.8	0.2	0.0	**50.3***	**0.51***	**5064***
0.6	0.1	0.3	**51.0***	0.51	4983
0.7	0.1	0.2	**51.1***	0.52	5107
0.3	0.1	0.6	**51.3***	0.52	5109
0.3	0.0	0.7	**51.4***	0.52	5133
0.6	0.2	0.2	**51.4***	**0.50***	**4971***
0.5	0.1	0.4	**51.4***	0.51	5102
0.6	0.3	0.1	**51.8***	**0.50***	**4976***
0.7	0.2	0.1	**52.0***	**0.50***	**4949***

0.4	0.0	0.6	**52.0***	0.52	5115
0.7	0.3	0.0	**52.5***	**0.50***	**5141***
0.5	0.2	0.3	**52.5***	**0.50***	**5139***
0.6	0.4	0.0	**53.1***	**0.50***	**5181***
0.4	0.2	0.4	**53.2***	0.51	5226
0.2	0.0	0.8	**53.2***	0.53	5265
0.5	0.3	0.2	**53.3***	**0.49***	**5201***
0.4	0.1	0.5	**53.4***	0.51	5378
0.2	0.1	0.7	**53.5***	0.52	5333
0.1	0.1	0.8	**53.6***	0.52	5273
0.4	0.4	0.2	**53.8***	**0.49***	**5157***
0.3	0.2	0.5	**53.8***	**0.51***	**5299***
0.1	0.0	0.9	**54.0***	0.52	5479

$^*n = 5$, $p < 0.05$

CONCLUDING REMARKS

A rolling horizon traffic signal control algorithm called PMSA is presented in this paper. The algorithm uses individual vehicle locations, headings, and speeds to predict an objective function over a 15-second future horizon using microscopic simulation. The algorithm does not use any data from point detectors or any historical demands, nor does it require any communication between signals. An important feature of the algorithm is that it only uses instantaneous vehicle data, and does not re-identify or track vehicles in any way to protect privacy.

Microscopic simulation shows that PMSA, using delay as the sole variable in the objective function, is able to significantly improve or have no effect on the performance of coordinated-actuated systems in several scenarios, specifically at low and medium demand saturation, and with greater than 50% penetration rate of equipped vehicles. The algorithm shows much greater improvements during unexpected demands for which the baseline Synchro coordinated actuated timing plan was not optimized, particularly in a simulated incident and with annual traffic volume increases where the timing plan is not updated. Different horizon objective functions using delay, deceleration, and stops as variables were unable to improve the performance of a delay-only function.

Future work will involve improving the performance of the algorithm at low connected vehicle penetration rates. Recent research suggests that the behavior of a few connected vehicles can estimate positions of unequipped vehicles in real-time on freeways *(24)*, *(25)* and delayed on arterials *(26)* These techniques may be adapted for signal control, where they can provide real-time estimates of individual vehicle locations, thereby artificially augmenting the equipped penetration rate. The algorithm will also be compared to existing adaptive control algorithms.

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