IntelliDrive^{SM} Traffic Signal Control Algorithms

Report – Task 2: Development of New Traffic Control Signal Algorithms under IntelliDrive^{SM}

Brian L. Smith, Ramkumar Venkatanarayana, Hyungjun Park, Noah Goodall, Jay Datesh, and Corbin Skerrit
University of Virginia

Prepared for
IntelliDrive^{SM} Pooled Fund Study

August 18, 2010

TABLE OF CONTENTS

OBJECTIVE AND SCOPE OF THE DOCUMENT 2
BACKGROUND OF INTELLIDRIVE^{SM} AND TRAFFIC SIGNAL CONTROL 2
OVERSATURATED CONDITIONS ALGORITHM 2
VEHICLE CLUSTERING ALGORITHM 6
PREDICTIVE MICROSCOPIC SIMULATION ALGORITHM 10
REFERENCES 12

OBJECTIVE AND SCOPE OF THE DOCUMENT

This interim report details the traffic signal algorithms developed by the project team in Task 2 of the project. These algorithms were developed specifically to utilize the new data made available by IntelliDrive^{SM} and to implement strategies that are either impossible or cost prohibitive with detector data alone. The three algorithms developed are as follows:

- Oversaturated conditions algorithm
- Vehicle clustering algorithm
- Predictive microscopic simulation algorithm

BACKGROUND OF INTELLIDRIVE^{SM} AND TRAFFIC SIGNAL CONTROL

IntelliDrive^{SM} combines several emerging technological advances, such as advanced wireless communications, on-board computer processing, advanced vehicle sensors, GPS positioning, smart infrastructure etc. to provide a networked environment. This environment allows for high speed information transactions between the vehicles (V2V), between vehicles and the infrastructure (V2I and I2V), and between vehicles and handheld devices (V2D) (MDOT). Several researchers have recently been conceptualizing and investigating various promising applications of the IntelliDrive^{SM} environment, including the areas of safety (crash prevention, dilemma zone advisory), mobility (lane changing advisory, platoon formation, route guidance), transit, performance measurement, weather information, and pavement condition monitoring.

Many of the new vehicle data available with IntelliDrive^{SM} are particularly useful to traffic signal operations. While traditional video and in-pavement detectors generally provide presence information, IntelliDrive^{SM} allows vehicles to transmit a much broader range of information to controller, such as vehicle locations and speeds (SAE, 2009). These new data provide signals a much more complete picture of vehicle behavior and conditions, allowing more dynamic and responsive signal control strategies and much more accurate ways of measuring signal performance.

Several recent research studies have specifically evaluated the application of IntelliDrive^{SM} to arterial networks and signal systems, towards performance measurement (Li et al, 2008; Song et al, 2010), safety (Dickey et al, 2008; Doerzaph et al, 2010; Saleem et al, 2008), route guidance (Lee and Park, 2008), dynamic gap out (Agbolosu-Amison and Park, 2009), dynamic speed control (Abu-Lebdeh and Chen, 2010), and driver behavior (El-Shawarby et al, 2010). However, no studies have investigated a complete reevaluation of signal control logic to best utilize IntelliDrive^{SM}, but instead have investigated incremental improvements in signal control. The algorithms presented in this report are attempts to determine next-level signal control utilizing the full capabilities of IntelliDrive^{SM}.

OVERSATURATED CONDITIONS ALGORITHM

Oversaturated conditions on arterial systems are common and are expected to increase in the future (Wu et al, 2010). The queues that spill back from an intersection experiencing oversaturated conditions could cause de facto red conditions at an upstream intersection, whereby vehicles are unable to pass, even when the signal displays green. If this effect cascades to further upstream intersections, the signal timing inefficiency spreads spatially across the network. Therefore, quick identification of these queues, as well as the elimination or mitigation of the de facto reds will significantly increase the network efficiency during oversaturated conditions. Further, the speedy return of the network again to manageable levels of traffic is made possible.

This algorithm uses the detailed vehicular data available in an IntelliDrive^{SM} environment to address signal system inefficiencies that result from spillback during oversaturated conditions. The algorithms were developed to: (1) monitor queues in real-time, using the location and speed data from IntelliDrive^{SM}-equipped vehicles; and then (2) modify the offset and splits at the upstream intersection, also in real-time. In short, the green phase for the affected approach is either delayed or cut short, as dictated by the real-time queue length on the downstream link. Further, additional time available from the affected approach is transferred to the opposite approach. The algorithms were evaluated using VISSIM microscopic traffic simulations on a 2-intersection test network with one-way streets.

The core algorithm is based on a study network consisting of 2 intersections of all one-way streets with 2 lanes each, as depicted in Figure 1. The intersection on the right is designated as node 1, and the other as node 2, with a separation of approximately 330ft. The network links are designated as L1-L7. All the traffic flow directions and their NEMA movement numbers are also presented in the Figure. The Main Street, represented by NEMA 2, is coordinated. The links L3, L4 and L7 were all loaded with vehicles at the rate of 4000 per hour, to simulate high traffic conditions. Further, to simulate oversaturation on links L2 and L3, the right lane on link L1 and the right lane connector between links L1 and L2 were made unavailable to all traffic. Further, the left lane on link L1 included a reduced speed zone. As a result, it can be seen that while L2 is full, movement 2 at intersection 2 continues to get Green signal, but is unusable (i.e. faces de facto red).

One goal of the proposed algorithm therefore is to detect this type of situation, and then avoid or mitigate its effects by cutting off the Green on Main earlier than prescribed and allocate it to the side street. Another goal is to delay the start of Green on Main at intersection 2, if the available "space" on Link L2 is below a threshold.

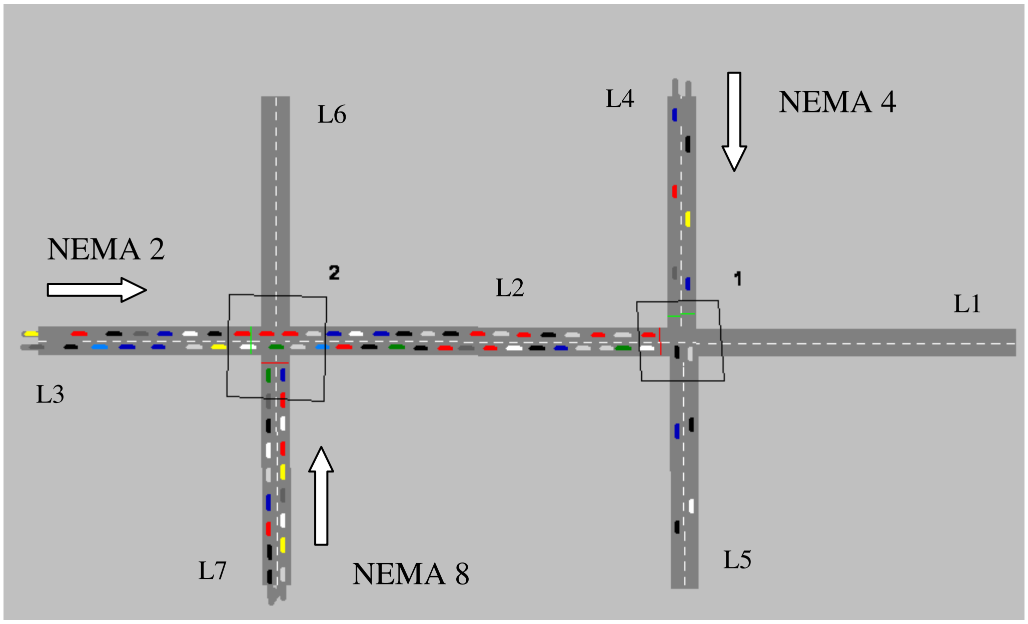

Figure 1: Study Network

In specific, there are 3 main parts of the signal control algorithm developed in this study, as shown by the dashed, red rectangles in Figure 2 below. These parts are:

1. ECG (Early Cut-off of Green on Main): This part is the rectangle on the left. The focus of this part is to monitor the queues on link L2 when the movement 2 at Node 2 has Green, and to cut it off earlier than the original plan, if
    a. The total available "space" across all the lanes on the receiving approach (i.e. L2) is below a certain threshold (shown as 200ft in the flow chart), and
    b. Less than a threshold amount of Green time is left for the movement 2 at Node 2 (shown as 10 seconds in the flow chart).
2. LSG (Late Start of Green on Main): This part is the rectangle in the middle. The focus of this part is to monitor the developing queues on link L2 and delay the start of Green for Node 2, movement 2, if the remaining supply on link L2 is below a certain threshold (shown as 200ft in the flow chart).
3. SSC (Side Street Coordination): This part is the rectangle on the right. The focus of this part is to start the Side Street Green (Node 2, movement 8) no later than the time prescribed by the original plan, so as to not impact coordination on the Side Street (as well as the Main Street). Without SSC, delaying the start of Green on Main through LSG without making adjustments to its Green split will offset the side street Green also. And after a few cycles, the offsets may be so large as to seriously impact the coordination along both streets. Further, if the original plan asks for the start of Side Street Green in the next ***s*** seconds, then, at a minimum, ***s*** must be greater than the amber time. In this study, the amber time is 4 seconds. And the threshold for s is set at ***5*** seconds.

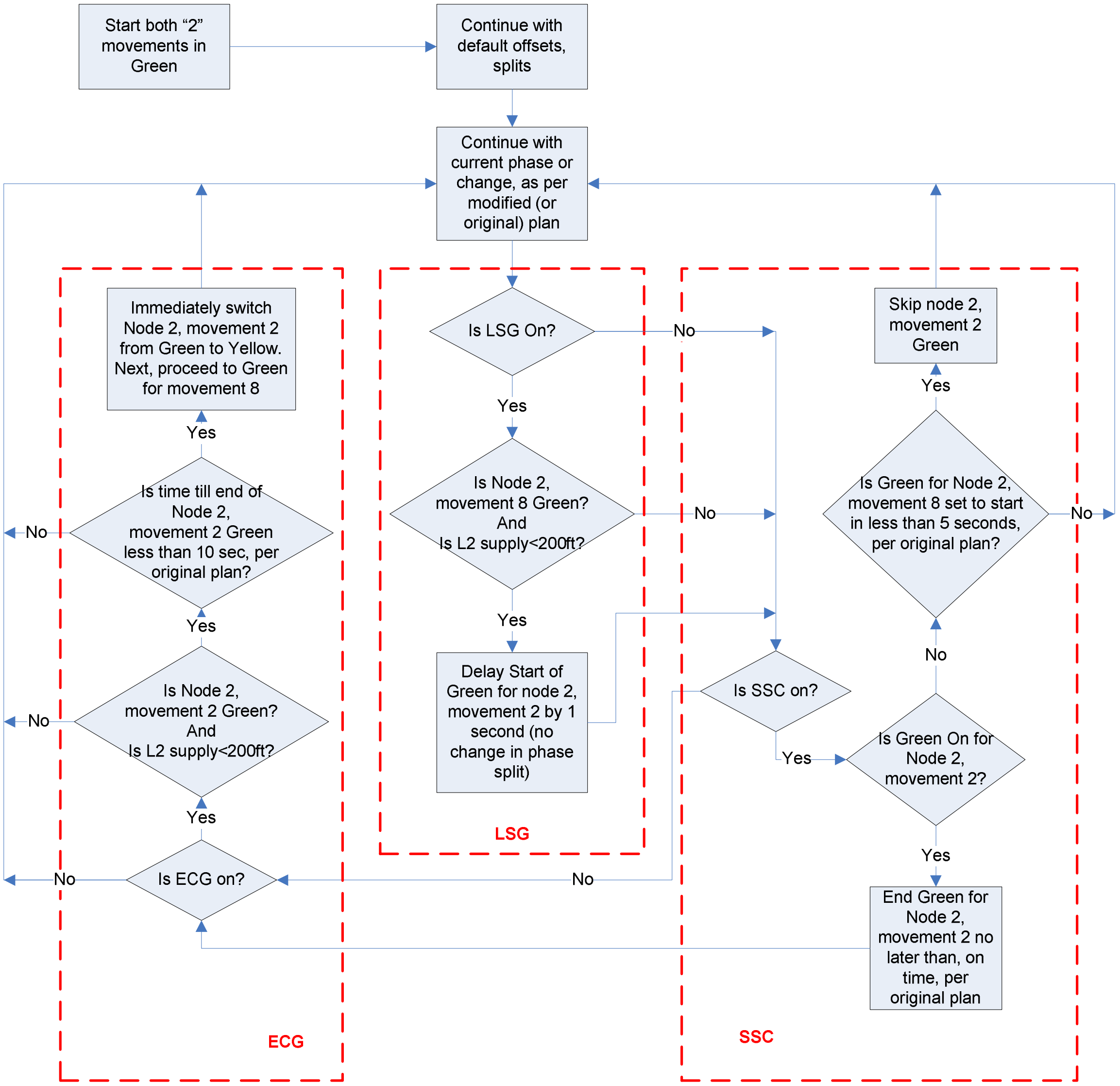

Figure 2: Algorithm Flow Chart

The effect of the combination of the above three parts on the Main Street Greens are presented in Figure 3 below. The arrows indicate the direction in which a particular phase is changed. Bold vertical lines indicate the particular start/end time for that phase remains unchanged. In all the cases, the first Main Street Green phase (first column) is shown as constant, for reference. The effects of the algorithm on the other three phases are noted. For simplicity, only the Main Street phases are shown for cases other than the base case. In all these cases, the Side Street obtains Green phase when the Main Street is Red and vice-versa. Further, for simplicity, the yellow periods are omitted in the Figure.

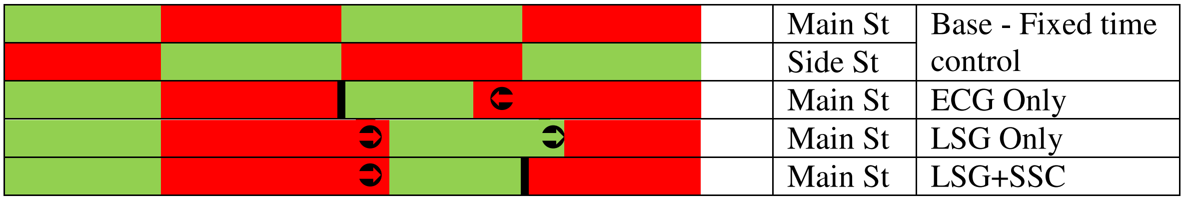

Figure 3: Effects of Algorithm on the Phases

LSG is the only part that delays the start of Green on the Main. ECG and SSC both define when the Green split on Main is ended. Application of SSC is useful only in combination with LSG, since without a delay in the start of Green on Main, the side street Green split is not reduced, or delayed. Further, only LSG and ECG use IntelliDrive^{SM} data. SSC provides an alternative to ECG, in terminating the Main Street Green, and resetting the offset to default. Owing to these reasons, a total of five possible strategies are possible, using these three parts:

1. ECG Only: The offsets are not adjusted in this strategy. The Main Street Green split starts on time, but may be cut short, and additional time reallocated to Side Street Green split.
2. LSG Only: The offsets progressively increase from one cycle to the next, depending on how much oversaturation on link L2 affects traffic flow on L3. No changes are made to any Green splits.
3. LSG+SSC: In this strategy, the offset is increased for only one cycle at a time, and the Main Street Green split is reduced in that cycle to allow for side street coordination. The next cycle will start at the predetermined time, unless LSG comes into force again. Main Street Green split may be skipped, if there is no room on L2 to receive traffic.
4. ECG+LSG: In this strategy, the offsets increase progressively from one cycle to the next. Additionally, the Main Street Green split is reduced, if enough supply is not available on L2 to accommodate more traffic from L3.
5. ECG+LSG+SSC: In this strategy, in addition to the actions in the LSG + SSC strategy above, the Main Street Green may also be cut short, if there is no room on L2 to receive traffic.

The algorithm has been coded in the IntelliDrive^{SM} test bed (described further in the project's Task 3 report). Significant preliminary evaluations have been completed, and the algorithm presented above is the refined, final version that will be evaluated in Task 4.

VEHICLE CLUSTERING ALGORITHM

The Vehicle Clustering Algorithm (VCA) was designed primarily for urban arterials, where there is a high-speed major corridor crossing low-speed, low-volume side streets, and is decentralized, using only information that is local to the intersection that it controls. The VCA utilizes IntelliDrive^{SM} data regarding the location and speed of every vehicle in order to detect the state of the traffic and respond accordingly. It uses a novel gap out approach, ensures that "leftover" queues on roads with green signals are cleared, and prevents the breakup of vehicle platoons using a hierarchical clustering algorithm, hence the algorithm's name. These primary aspects produce a robust algorithm that can respond to different traffic volumes and patterns in real time, attempting to reduce average delay and increase throughput. While the algorithm was initially designed assuming 100% IntelliDrive^{SM} market penetration, it can easily be adapted for lower adoption rates. Before detailing the manner in which the VCA uses the unique information that IntelliDrive^{SM} provides, an overview of the algorithm is presented.

The VCA works in three phases. In Phase Zero, it computes the cars' cumulative waiting time (CWT in Figure 4) for each movement with a red signal, the red-movements, at an intersection. For example, if a vehicle has been waiting at a red signal for twenty seconds before another vehicle arrives and both then wait for ten seconds, the cumulative waiting time for that movement would be forty seconds. If the cumulative waiting time for one of the red-movements exceeds a predetermined threshold value (T in Figure 4), this movement requests the green signal and Phase One of the algorithm begins; otherwise, the simulation time is advanced. The value for the threshold, T, can depend on the type of intersection and/or the vehicle volumes in the red-movements.

The purpose of Phase One is to clear any remaining queue that may exist in a green-movement. Any car traveling in a green-movement with a speed of less than 5 mph is considered to be part of the leftover queue. If no such queue exists, the algorithm moves directly to Phase Two; otherwise, it waits until the car at the end of the queue passes through the green signal before continuing to Phase Two, unless a maximum time is reached in which case it proceeds without clearing the queue to prevent excessively long green times.

In Phase Two, the VCA looks at vehicles farther upstream and uses the single-link clustering algorithm (SLINK) to group them into pseudo-platoons ("pseudo-" is used to distinguish them from platoons as typically defined in the literature). Once these pseudo-platoons have been formed, the algorithm uses the vehicles' distances to the intersection to determine which pseudo-platoon comprises vehicles that are the closest to the intersection, yet farther than a certain threshold distance (D in Figure 5), which depends on the road's speed limit. Currently this distance is the far end of the dilemma zone as defined by Hurwitz (2009). Then, the green-extension time, t_e, is obtained using the following formula:

$$t_e = d_l / v_l \tag{1}$$

where d_l is the distance of the last vehicle in this pseudo-platoon of interest from the intersection and v_l is that vehicle's speed. After the extension time has elapsed, or the maximum time has been reached, the movement with the highest cumulative waiting time and the non-conflicting movement with the highest waiting time are selected as the next phase, and the process repeats.

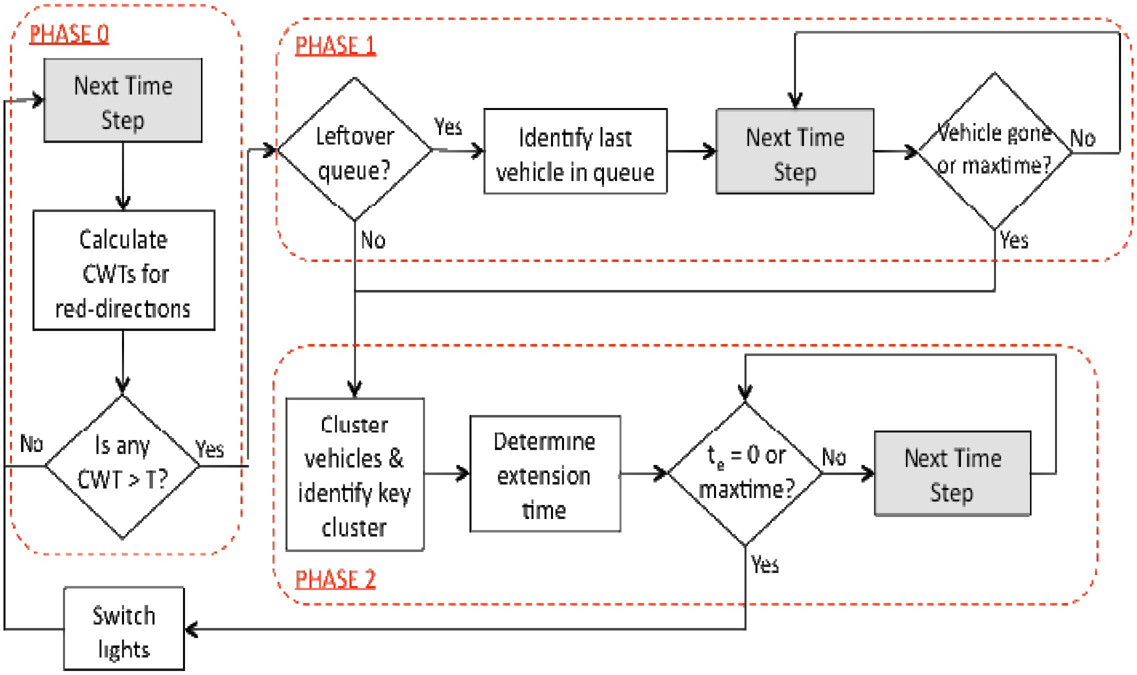

Figure 4: Vehicle Clustering Algorithm Flowchart

In each phase, the Vehicle Clustering Algorithm takes advantage of IntelliDrive^{SM} data, delivering a “smarter” intersection than is currently possible with conventional detectors. In Phase Zero, monitoring the CWT of each red-movement is made possible with V2I communication. To achieve this with loop detectors, each section of road surrounding an intersection would have to contain a detector. The CWT thresholds allow the VCA to switch the traffic signals only when it is necessary – a clear improvement over fixed-time signals – and offers other benefits as well: the threshold values could be different for each movement at an intersection and could be determined using to real-time traffic data or changed in order to account for a traffic incident, such as an accident. This allows for increased adaptability.

Phase One of the algorithm was designed to exploit the unique information that IntelliDrive^{SM} affords. With current detectors, the clearance time of a queue at a green signal needs to be estimated. The intersection cannot know with certainty whether or not the last vehicle in the queue has passed through without several seconds of unused green time passing (i.e. the gap out time). This diminishes throughput and increases delays at side streets. The VCA again utilizes V2I communications to ensure that queues at green signals are cleared, and that no green time is wasted during gap out.

Phase Two is intended to provide two interrelated benefits to the VCA. The first is that it limits the breakup of vehicle platoons. Platoons have been traditionally defined by a critical vehicle headway, which depends on a roadway’s speeds and traffic volumes. Determining the value for the critical headway is not always straightforward; see Jiang, et al. (2003) for a discussion. After obtaining the distances of all vehicles in the green-movement(s), the VCA clusters the vehicles using SLINK and, from these clusters, infers the distribution of the vehicles upstream in a green-movement to automatically form pseudo-platoons. Once these pseudo-platoons have been formed, the VCA can use instantaneous vehicle speeds, which are not available with traditional detectors, to compute the appropriate green-extension times. This allows the pseudo-platoon to pass through the intersection unimpeded, reducing average delays.

The second potential benefit of Phase Two comes from careful selection of the threshold distance, D (Figure 5). Setting D equal to the far limit of the dilemma zone could eliminate potential conflicts regarding yellow signals by detecting whether vehicles will be present in the dilemma zone at the time that switching will occur. With 100% IntelliDrive^{SM} market penetration, a scheme has been proposed that would allow variable yellow clearance times, and could even skip all-reds in certain situations (Raavi, 2010). The traffic signal controller would be able to send an early indication to vehicles that should not proceed through the intersection, well in advance of a yellow signal (Figure 5). Extending this concept further, the need for traditional traffic signals could be eliminated all together, as the V2I infrastructure would communicate the (legally binding) signals directly to vehicles. Although possible in theory, the VCA currently does not employ this. The VCA instead sets yellow times and all-reds according to traditional standards, but may attempt variable yellow and red signals in future versions.

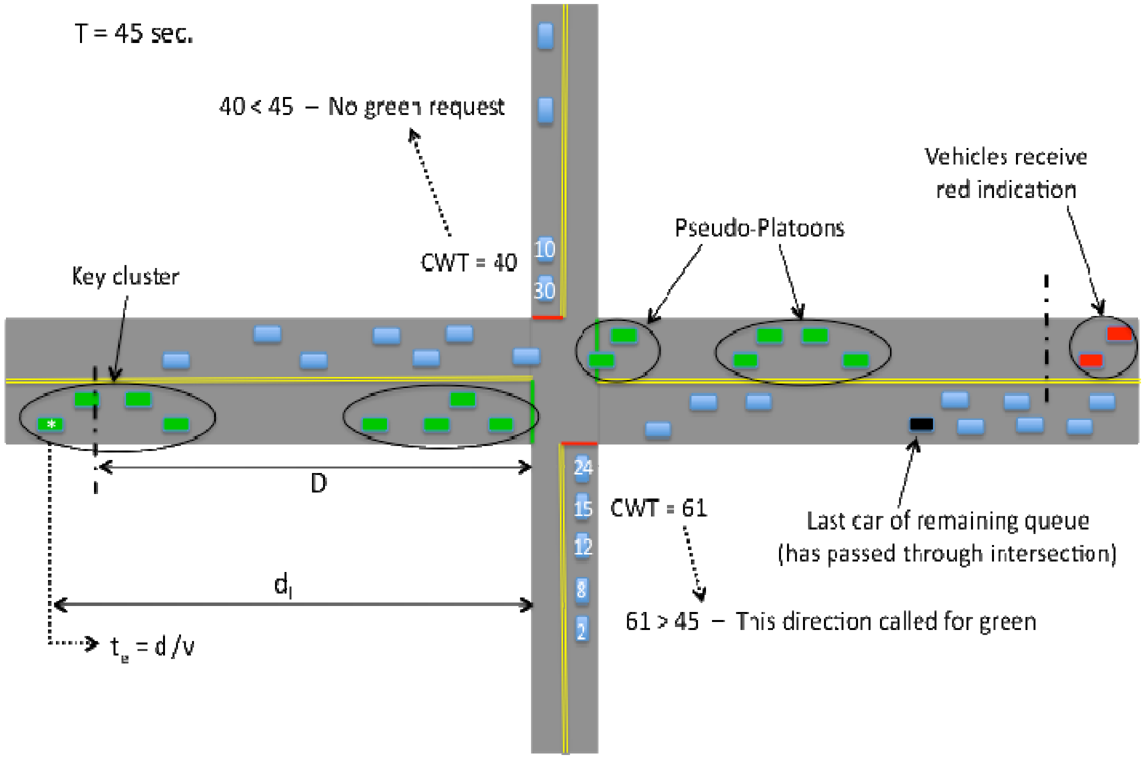

Figure 5: Key features of the Vehicle Clustering Algorithm.

In Figure 5, the white numbers on the vehicles in the red-movements represent the time each vehicle has spent waiting at the red signal. These values are used to calculate the cumulative waiting time (CWT) for each movement. The bottom red-movement's CWT has surpassed the threshold, T, and it has called for a green signal. Demonstrated by the black vehicle being downstream of the intersection, the algorithm has passed through Phase One and has clustered the vehicles into pseudo-platoons. The last car in the key cluster has been indentified (marked with a white asterisk); its speed and distance to the intersection have been used to determine the green-extension time. The green signal will end when this time elapses. Additionally, the intersection has transmitted the signal indications. The green vehicles will be able to pass through the intersection, while the red vehicles will not. The main street then gets the red signal and the green switches to the side street and the process repeats.

The Vehicle Clustering Algorithm incorporates the valuable information that would be available with IntelliDrive^{SM}, and should achieve significant improvements over conventional signal timing plans. Future work on the algorithm include: 1) testing the algorithm on several traffic networks and comparing its performance to more traditional signal timing schemes and 2) improvements that provide coordination between intersections in an arterial. An example would be to account for vehicles that have just received a green upstream and are approaching a red signal at an intersection. The effects of market penetration levels on the algorithm's performance will also be investigated.

PREDICTIVE MICROSCOPIC SIMULATION ALGORITHM

The Predictive Microscopic Simulation Algorithm (PMSA) is based on the rolling horizon traffic control scheme, first introduced by Alan Miller (Miller, 1963). In rolling horizon traffic control, the signal is optimized to reduce delay over a very short fixed period of time in the future, called the horizon. As time moves forward, the horizon "rolls" forward as well. A similar strategy was proposed by Roy Sumner, using predicted vehicle locations to determine the next phase and its length (Sumner, 2008). The PMSA uses a similar concept, employing vehicle position and speed data available with IntelliDrive^{SM} to populate a model of the signalized intersection. The algorithm then uses microscopic simulation to continuously predict future vehicle delays over the horizon at a variety of signal phasings.

With the PMSA, in order to determine the next phase, the signal controller determines the speed, heading, and location of all IntelliDrive^{SM}-equipped vehicles. This information, along with the current signal phasing, is recreated in a microscopic simulation of the intersection. Vehicles are simulated 20 seconds into the future, including the necessary yellow and red time for a signal change. This simulation is repeated for every potential possible phase that the current signal timing plan allows, including the current phase. The delay is measured every second and is calculated by subtracting the vehicle's actual speed from the speed limit of the vehicle's road. The phase with the lowest total cumulative delay after 20 seconds is selected as the next phase.

By only looking at delay over such a short interval, occasionally some movements can be skipped indefinitely and never served. For example, a busy three-lane mainline will often take precedence over a low-volume single left turn lane as the delay penalty for the mainline is much higher over 20 seconds. Vehicles that are stopped for an unusually long period of time may worry that the traffic signal hasn't detected them, and may be tempted to ignore a red signal. To ensure that all vehicles are served in a timely manner, any movement with vehicles waiting over a certain threshold, tentatively 150 seconds, are given highest priority and must be served at the next phase.

Also, to ensure that turn lanes do not fill with vehicles and block the through lanes, any movement with a vehicle with a speed of less than three miles per hour and located within 40 feet of the beginning of a turn lane, that movement will be given medium priority as the next phase, and will be served next unless there are competing movements with highest priority.

After determining the next phase, that phase is left in place for either the length of the horizon (20 seconds) or until the real-time delay in both movements is zero, whichever situation occurs first. At the end of the phase, the next phase determination process is repeated.

Figure 6 shows an overview of the logic of the Predictive Microscopic Simulation Algorithm.

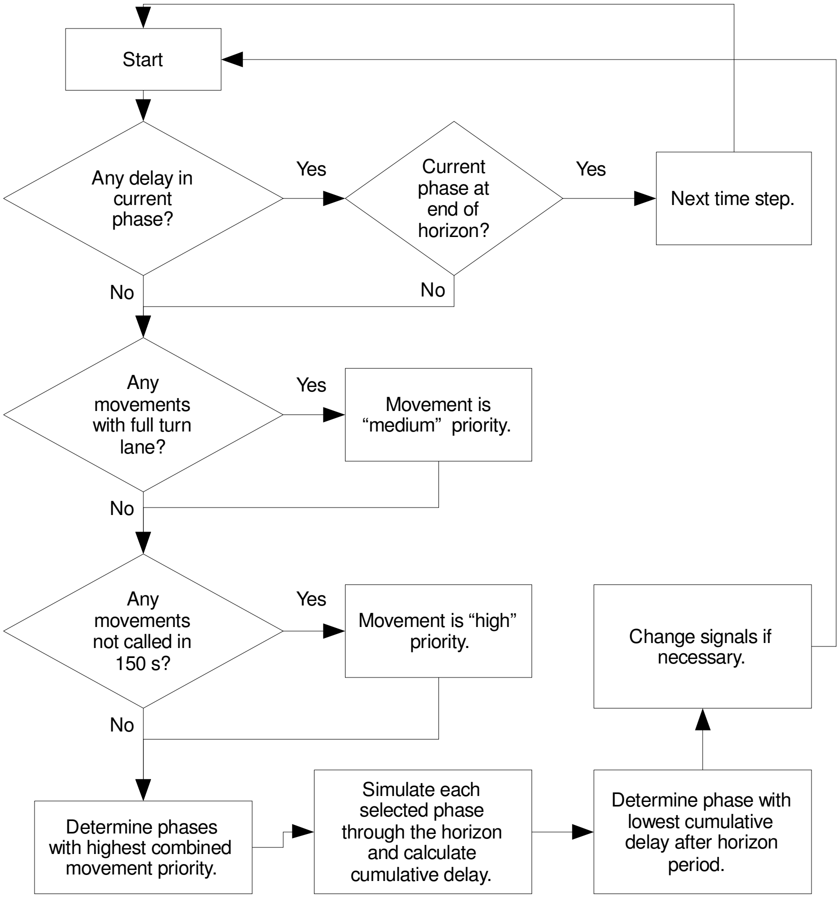

Figure 6: Predictive Microscopic Simulation Algorithm Flow Chart

The PMSA makes effective use of IntelliDrive^{SM} data, including specific vehicle locations and speeds. The PMSA is designed to optimize the signal based on current vehicles present, instead of estimates from past turning movement studies. Because it is based on real-time vehicle counts, the algorithm can easily and quickly adjust to unusual traffic conditions such as special events and lane closures. The PMSA are that it can effectively measure the penalties of the lost time experienced in changing signals, by simulating not only potential new signal phases, but also the signal change process.

The PMSA as designed operates for a single intersection, with no communication with other signal controllers. Some signal-to-signal communication will likely be required when two intersection are spaced so closely together that a vehicle can travel through both intersections during the horizon time. In this situation, the status at one signal will affect another during the horizon. Some possible solutions include broadcasting a signal's status and likely next status, or using the same PMSA future simulations on both intersections simultaneously.

REFERENCES

Abu-Lebdeh, G., and Chen, H., Exploring the Potential Benefits of IntelliDrive-Enabled Dynamic Speed Control in Signalized Networks, Paper: 10-3031, TRB Annual Meeting CD-ROM, 2010.

Agbolosu-Amison, S.J., Investigating Mobility Benefits from Applying Probe Vehicle Technology Information to Traffic Signal Control, Dissertation, University of Virginia, 2009.

Dickey, S.R., Bougler, B., Kretz, P., and Nelson, D., Intersection Signal Controllers and Vehicle-Infrastructure Integration: Putting Safe Intersections to Practice, Paper: 08-2627, TRB Annual Meeting CD-ROM, 2008.

Doerzaph, Z.R., Neale, V.L., and Kiefer, R.J., Cooperative Intersection Collision Avoidance for Violations (CICAS-V) Threat Assessment Algorithm Development and Evaluation Method, Paper: 10-2748, TRB Annual Meeting CD-ROM, 2010.

El-Shawarby, I., Rakha, H., Amer, A., and McGhee, C., Characterization of Driver Perception Reaction Time at the Onset of a Yellow Indication, Paper: 10-0520, TRB Annual Meeting CD-ROM, 2010.

Hurwitz, David. Application of Driver Behavior and Comprehension to Dilemma Zone Definition and Evaluation. PhD Dissertation, University of Massachusetts Amherst, 2009.

Jiang, Yi, et al. Development of Vehicle Platoon Distribution Models and Simulation of Platoon Movements on Indiana Rural Corridors. Federal Highway Administration Final Report, Publication Number: FHWA/IN/JTRP-2002/23, 2003.

Li, M., Zou, Z., Bu, F., and Zhang, W., Application of Vehicle-Infrastructure Integration (VII) Data on Real-Time Arterial Performance Measurements, Paper: 08-2835, TRB Annual Meeting CD-ROM, 2008.

MDOT, VII is now IntelliDrive, http://www.michigan.gov/mdot/0,1607,7-151-9621_11041_38217-218864--,00.html, Last Accessed: July 2010.

Miller, Alan J. A Computer Control System for Traffic Networks. Proceedings of the 2nd International Symposium on the Theory of Road Traffic Flow. London, pp. 200-220, 1963.

Raavi, Venkata S. A Novel Approach To Dilemma Zone Problem for High Speed Signalized Intersections. Masters Thesis, University of Akron, 2010.

Saleem, F., Nodes, S., and Head, L., E-VII Arizona's Emergency VII Program, T3 Webinar, October 2008, www.pcb.its.dot.gov/t3/s081023/presentation_saleem.ppt, Last Accessed: July 2010.

Society of Automotive Engineers (SAE), J2735, Dedicated Short Range Communications (DSRC) Message Set Dictionary, November 2009

Song, M.K., Li, M., and Nakamura, H., Real-Time Arterial Performance Measurement using Signal Timing Data and Bus Rapid Transit (BRT) as Probes, Paper: 10-3292, TRB Annual Meeting CD-ROM, 2010.

Sumner, Roy. Adaptive Signal Control with VII. Proceedings of the 15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting, New York, 2008.

Wu, X., Liu, H.X., and Gettman, D., Identification of oversaturated intersections using high-resolution traffic signal data, Transportation Research Part C, 2010.