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Survey: Traffic Signal Control with Wireless Sensors

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ABSTRACT

This paper is the survey of SURTRAC (Scalable Urban Traffic Control) and Traffic Signal Control With Connected vehicles (TSCWCV). Both the approaches operates totally in decentralized manner and these are fully adaptive traffic control algorithms uses a rolling-horizon strategy in which the phasing is chosen to optimize an objective function over a 15-s period in the future. In TSCWCV, 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**.** 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 does not store individual or aggregate vehicle locations. SURTRAC aims at managing urban (grid-like) road networks with multiple (competing) traffic flows. SURTRAC truly operates in real-time; each intersection recomputes its allocation plan and re-communicates projected outflows as frequently as once per second in rolling horizon fashion, enabling both effective operation in tightly spaced signal networks and responsiveness to sudden changes in traffic conditions. SURTRAC is seen to achieve major reductions in travel times and vehicle emissions over pre-existing signal control. Results from a simulation showed that the algorithm maintained or improved performance compared with that of a state of the practice coordinated actuated timing plan optimized by Synchro at low and midlevel volumes, but that performance worsened under saturated and oversaturated conditions.

INTRODUCTION

Traffic congestion in urban road networks is a substantial problem, resulting in significant costs for drivers through wasted time and fuel, detrimental impact to the environment due to increased vehicle emissions, and increased needs for infrastructure upgrades. (1). One of the largest recurring sources of traffic congestion are poorly timed traffic signals (2). Even when signals have been recently retimed, the inability to respond to current traffic patterns can cause pockets of congestion that lead to larger traffic jams Inefficiencies in traffic signal timing stem from poor allocation of green time, inability to respond to real-time conditions, and poor coordination between adjacent intersections. Traffic signals, when operated efficiently, can enable the 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, in which 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.

This paper investigates the potential of a recently developed approach to real-time adaptive traffic signal control (5, 6) in an actual traffic control setting. The approaches which are realized in a system called SURTRAC (Scalable Urban Traffic Control) and TSCWCV (Traffic Signal Control With Connected Vehicle).

A distinguishing characteristic of the SURTRAC and TSCWCV design is their emphasis on real-time responsiveness to changing traffic conditions. Many adaptive traffic control systems (e.g., BALANCE, ACS-Lite and ACDSS (13)) are designed to effect changes to traffic signal timings on the order of minutes based on average flow predictions, which limits how quickly and effectively a system can respond to locally changing traffc patterns. SURTRAC alternatively adopts the real-time perspective of prior model-based intersection control methods (e.g., ALLONS-D (14), PRODYN (15), OPAC (16), RHODES (17), CRONOS (18), and others (19, 20)) which attempt to compute intersection control plans that optimize actual traffic inflows. By using a novel reformulation of the optimization problem as a single machine scheduling problem, SURTRAC is able to compute near-optimal intersection control plans over an extended horizon on a second-by-second basis.

In addition, decision making in SURTRAC proceeds in a totally decentralized manner. Although more centralized approaches to adaptive traffic signal control have been effectively applied in many settings (e.g., SCOOT (9), BALANCE (10), ACS-lite (11), and SCATS (12)), they nonetheless require tradeoffs that can be limiting. Decentralized control of individual intersections enables maximum responsiveness to real-time traffic conditions. It promotes scalability by allowing incremental addition of intersections over time with minimal change to the existing adaptive network. There is also no centralized computational bottleneck and no single point of failure.

Finally, SURTRAC is designed to aim generally at managing urban (grid-like) road networks, where there are multiple (typically competing) dominant flows that shift dynamically through the day, and where specific dominant flows cannot be pre-specified (as in arterial or major cross-road applications). Urban networks also often have tightly spaced intersections requiring tight coordination. The combination of competing dominant flows and densely spaced intersections presents a challenge for all adaptive systems. SURTRAC determines dominant flows dynamically by continually communicating projected outflows to downstream neighbours (in similar fashion to the earlier PRODYN system (15)). This information gives each intersection a more informed basis for locally balancing competing inflows while simultaneously promoting establishment of larger "green corridors" when traffic flow circumstances warrant.

To demonstrate the potential of the SURTRAC approach, a pilot implementation was installed at a nine-intersection road network in the East Liberty neighbourhood of Pittsburgh, Pennsylvania, and a performance comparison was carried out with the existing traffic signal control scheme at this pilot site.

In addition, in TSCWCV Actuated timing plans use point detectors to modify a fixed timing plan by the occasional skipping of a phase if no vehicle is present or shortening of a phase when vehicles are not being served. Some adaptive timing plans attempt to adjust to slow or systematic changes in volumes. The split cycle offset optimization technique (1) and the Sydney coordinated adaptive traffic system (2) are two prominent examples. However, both are restricted, in that they alter only a cyclic timing plan.

The remainder of the paper is organized as follows. First, the decentralized, schedule driven approach to real-time, adaptive signal control that underlies the SURTRAC system is summarized. Then the approaches used in the traffic signal control with connected vehicle are described. Then the architecture and configuration of the pilot SURTRAC implementation are described. The pilot study design is presented next, followed by a discussion of the results obtained. Finally, some conclusions are drawn.

SCHEDULE-DRIVEN TRAFFIC CONTROL

As indicated above, the traffic signal control problem is formulated in SURTRAC as a decentralized, schedule-driven process (5, 6). At the lowest level, each intersection is controlled independently by a local scheduler, which maintains a phase schedule that minimizes the total delay for vehicles travelling through the intersection and continually makes decisions to update the schedule according to a rolling horizon. The intersection scheduler communicates outflow information implied by its current schedule to its immediate neighbours, to extend visibility of incoming traffic and achieve network level coordination.

Effective consideration of the significance of short-term (second-by-second) variability of traffic flows at the individual intersection level is made tractable by a novel formulation of online planning as a single machine scheduling problem (5). Key to this formulation is an aggregate representation of traffic flows as sequences of clusters (corresponding specifically to anticipated queues (21) and platoons) in a limited prediction horizon. These cluster sequences preserve the non-uniform nature of real-time flows while providing a more efficient scheduling search space. Interpreting each cluster as an input job, the scheduling problem is to construct an optimal sequence of all jobs that preserves the ordering of jobs along each inflow and treats all jobs as non-preemptable. A given sequence dictates the order in which jobs will pass through the intersection and can be associated with an expected phase schedule that fully clears the ordered jobs in the shortest possible time, subject to basic timing and safety constraints. The optimal sequence (schedule) is the one that incurs minimal delay for all vehicles. A forward recursion, dynamic programming process is used to solve this scheduling problem. From a constructive view, the state space can be organized as a decision tree: each schedule is built from the root node, and a new job is added to the end of the (partial) sequence at each stage. At the same depth in the tree, states are grouped if they designate the same jobs (with different orders) and the same last job (referring to the same last phase). A greedy state elimination strategy is then applied to each group, where only the state reached with the minimum delay is kept while all other states are eliminated. Thus, most branches are pruned during early stages. The total process has at most $|I|^2 \cdot \Pi^{J}$i=1 (Ji +1) state updates (where Ji ≥ 0 is the number of jobs in the ith inflow and jIj is the number of phases), and each state update can be executed in constant time. The time complexity is polynomial in the prediction horizon HP, since jIj is limited for each intersection in the real world. A nice property is that Ji is insensitive to the granularity of time resolution in HP (5). In practice, Ji<<HP. For minor inflows (e.g., protected left turns) that are only subject to queue clearance Ji ϵ{0,1}.

This approach to intersection control can be contrasted with previous research in model based optimization methods (3, 14, 15, 16, 17, 18, 19, 20). Under the standard model-based optimization formulation, the primary state space is defined differently - it contains all possible signal sequences over a discretized optimization horizon (HO), where HO is sufficiently long for clearing all vehicles in the prediction horizon (HP), as in ALLONS-D, and time resolution is sufficiently fine to avoid any significant rounding errors for temporal values in timing constraints and model parameters (e.g., start-up lost time). However, the size of this search space is exponential in the number of time steps in HO. To be real-time tractable, all methods are approximated through space reduction and state elimination. There are some simple space reduction settings used in other existing methods such as a coarser time resolution (14), a short optimization horizon (e.g., using HP as HO (15, 17)), or a smaller number of phase switches (16). The use of variable time steps has also been attempted (19). In our approach, the scheduling search space provides the approximation- it is a subspace that is tailored to the intersection control problem. For further state elimination, existing methods, e.g., RHODES and PRODYN, group "equivalent" states when they are in the same time step; our approach introduces a new state variable, called schedule status, to analogously identify states with the same remaining jobs (and hence vehicles). If an intersection has a sufficiently long look-ahead horizon, our intersection scheduling approach can efficiently find near optimal solutions. In (5), it has been shown to reduce delay in comparison to other state-of-the-art intersection control strategies (e.g., COP (22)) with 2-4 orders of magnitude speedup. In the pilot test described later in the paper, HP had a value of 120 seconds with 0.1-second time precision (note that HO would be much longer).

When operating within an urban road network, any local intersection control strategy might be susceptible to myopic decisions that look good locally but not globally. To reduce this possibility, network level coordination mechanisms are layered over SURTRAC's basic schedule-driven intersection control strategy. As a basic protocol, referred to as optimistic, non-local observation, each intersection sends its projected outflows to its direct neighbors (6). Given an intersection schedule, projected outflows to all exit roads are derived from models of current inflows and recent turning proportions at the intersection (6). Intuitively, the outflows of an intersection's upstream neighbors become its predicted non-local inflows. The joint local and non-local inflows essentially increase the look-ahead horizon of an intersection, and due to a chaining effect, a sufficiently long horizon extension can incorporate non-local impacts from indirect upstream neighbors. The optimistic assumption that is made is that direct and indirect neighbors are trying to follow their schedules.

Normally, the optimization capability of the base intersection control approach results in schedules that are quite stable, given enough jobs in the local observation and large jobs (platoons) in the local and nonlocal observation. It is also the case that minor changes in the schedules of neighbours can often be absorbed, if there is sufficient slack time between successive jobs. As mentioned earlier, this basic protocol is essentially the same coordination mechanism previously utilized in PRODYN (15, 19). One difference is that we assume asynchronous coordination, so that temporary communication failures can be mostly ignored.
However, circumstances can and do cause schedules to change, in which case mis-coordination can occur, especially for intersections that are very close together. To this end, additional coordination mechanisms are incorporated into SURTRAC for handling specific nontrivial miscoordination situations. One common inefficiency is caused by spillback which, due to insufficient capacity on a road segment, can block the progress of traffic flow from an upstream intersection if the segment is short and/or the traffic demand is high. The basic coordination protocol is augmented with a spillback prevention mechanism that acts to detect and prevent unnecessary spillback in advance of its occurrence by accelerating phase changes. If spillback occurs, the basic protocol enables estimation of queue length across intersections and facilitates efficient clearance of highly congested links if downstream intersections allow. Another source of mis-coordination is "nervousness", the tendency for the schedules of coordinating neighbors to oscillate due to small inconsistencies, which is handled by a second mechanism. Futher description of these coordination mechanisms can be found in (6).

THE SURTRAC SYSTEM

SURTRAC (Scalable Urban Traffic Control) implements schedule-driven traffic control as part of a flexible signal control system that is designed to be easily integrated with controller and sensor hardware from any vendor. True to the schedule-driven traffic control model, SURTRAC is organized as a completely decentralized multi-agent system. Each intersection is controlled by an agent running on an embedded computer located in the traffic cabinet for the intersection. The agent for each intersection manages the control of the traffic signal and all of the vehicle detectors located at that intersection.
The agent for each intersection is modeled as a multi-threaded service-oriented architecture, shown in Figure 1. The Communicator service handles the routing of all information between different services as well as information sharing between intersections. The Detector service interfaces with all vehicle sensors, processing real-time data into messages that can be used by local and remote services. The Executor service manages the interface with the traffic signal controller, reading status information about the state of the traffic signals and controlling the duration and sequence of phases. The Scheduler service uses data from the other services to create schedules that allocate green time at the intersection.
SURTRAC is designed to be integrated with any type of traffic signal controller or vehicle sensor. All information sharing is routed through the Communicator service, so different Executor and Detector service modules may be loaded depending on the hardware configuration at the intersection. Since information is passed using standard message types, service modules that integrate hardware from different vendors can provide the same information to the rest of the system. This design allows SURTRAC to work with many types of hardware as well as microscopic road traffic simulators for testing.

Communicator

The communication infrastructure of SURTRAC is designed to be flexible and general, allowing communication of many types of information. SURTRAC deployments must be networked, but it is only necessary for an intersection to be able to communicate with direct neighbors. By keeping communication strictly between neighbors, the SURTRAC system can scale to very large signal networks. All communication is asynchronous and robust to temporary network failure.

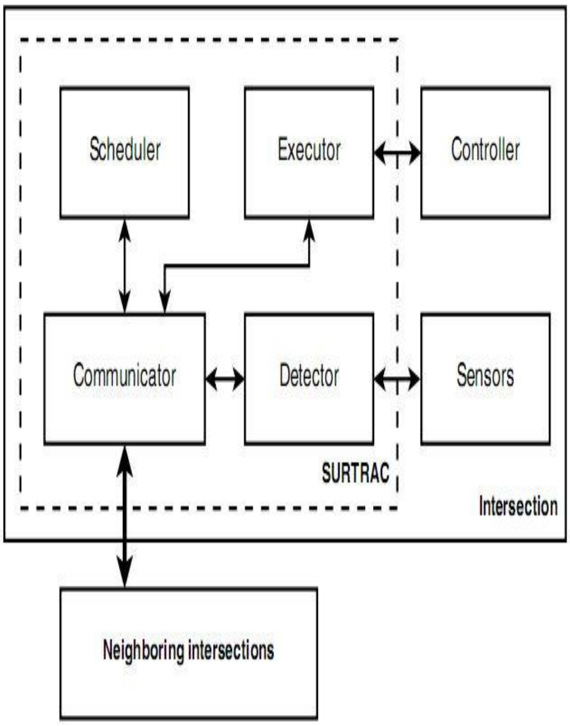

FIGURE 1 SURTRAC system diagram.

Detector

The Detector service manages the interfaces with all sensors located at an intersection. For each sensor, real-time data must be retrieved, encoded into message, and then sent to the local Scheduler service. If the sensor functions as an advance detector for a neighboring intersection, the message must also be sent to the remote Scheduler.

Executor

In order to control the traffic signals at an intersection, SURTRAC interfaces with the traffic signal controller. The controller continues to enforce maximum and minimum phase durations, transitions between phases, and other safety constraints, while SURTRAC adaptively allocates the green time for the intersection. SURTRAC is designed to work with any controller. For the pilot test, an interface was developed for 170 controllers running the Wapiti firmware.

When the Executor is active, it communicates frequently with the controller, polling for state and setting vehicle calls multiple times per second. Transitions in the controller state—e.g. the beginning or end of a phase—are relayed to the Scheduler. The Executor follows the schedule provided by the Scheduler, sending vehicle calls to continue in the current phase until the scheduled phase end time, at which time the Executor sets vehicle calls for the next desired phase. When the Scheduler updates the schedule, it may extend the current phase by any amount _ the minimum extension (a system parameter). The minimum extension time for the pilot was set to one second, so that the schedule could be adjusted as frequently as once per second. Although this setting was the same for all intersections, it isn't necessary since coordination is asynchronous. When the current phase is extended, the Executor notifies the Scheduler of the upcoming decision point in the schedule—the point by which a subsequent update to extend the phase must be received. For small minimum extension times, the time for the Scheduler to make a decision may be extremely short (less than half a second), such that schedules may arrive too late to extend the current phase. To protect against such "dropped" schedules, the Executor uses default phase durations calculated by the Scheduler. The Executor will only end a phase earlier than the default duration if the Scheduler chooses to terminate the phase. The Executor may also fall back to these phase durations in the case of prolonged sensor or network failure.

Scheduler

The Scheduler service implements the schedule-driven traffic control approach described earlier. It continuously receives real-time phase and detection data and scheduled upstream outflows, and builds a model of the traffic approaching the intersection. It then constructs a schedule for allocating the green time at an intersection between phases. The leading portion of this schedule is then sent to the Executor for controlling the traffic signals, and the scheduled outflows are sent out to downstream intersections. Some basic failure mitigation mechanisms are included to enhance reliability in the real world. These mechanisms only need to work locally due to the decentralized nature of the system.

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 reliance on point detectors (such as inductive loops or video detection systems) that sense only the presence of vehicles at fixed locations, signal systems would be able to use data transmitted wirelessly from in-vehicle sensors in 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 SAE J2735 dedicated short-range communications message set dictionary. This standard defines vehicle-to-vehicle and vehicle-to-infrastructure communications through the use of dedicated short-range communications, the medium-range communications channels dedicated for vehicle use by the Federal Communications Commission in 1999. For safety applications, each vehicle transmits a basic safety message that transmits its temporary identifier, 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 can gain a more comprehensive understanding of the movements of nearby vehicles than it can with loop and video detection.

TRAFFIC SIGNAL CONTROL USING INDIVIDUAL VEHICLE LOCATIONS

Several traffic signal timing plans that use some form of wireless communication between vehicles and the signal controller have been proposed. Priemer and Friedrich proposed a rolling-horizon algorithm that uses vehicle-to-infrastructure communications and that is based on the IEEE 802.11 standard (9). The algorithm sought to minimize queue lengths by optimization of phases in 5-s intervals over a 20-s horizon by use of the techniques of dynamic programming and complete enumeration on an acyclic, decentralized system.

Datesh et al. proposed an algorithm that uses vehicle clustering to apply a sophisticated form of actuated control (10). 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. The platoon is identified by the use of K-means clustering on the basis of the vehicles’ speeds and locations. Lee proposed the cumulative travel time-responsive real-time intersection control algorithm (11). This algorithm uses connected vehicles to determine the amount of time that a vehicle has spent travelling to the intersection from within 300 m 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., Phases 2 and 6 or Phases 4 and 8 of the National Electrical Manufacturers Association). The phasing with the highest combined travel time is selected as the next phase, which has a minimum green time of 5 s. 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 on the basis of a prediction of future travel times and the measurement of sampled vehicles. He et al. proposed an algorithm with platoon-based arterial multimodal signal control with online data. The algorithm uses mixed-integer linear programming to determine phasing and timings every 30 s for four cycles in the future on the basis of predicted vehicle platoon sizes and locations (12). PAMSCOD was able to improve vehicle and bus delay at saturation rates greater than 0.8 but often experienced higher delays at saturation rates of less than 0.6. The saturation rate was calculated by the use of Synchro’s intersection capacity

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utilization metric. To date, no research has investigated the use of microscopic simulation as a tool to estimate future conditions in a rolling horizon algorithm in a connected vehicle environment without vehicle re identification. 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 times), this research proposes 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 time horizon and its effect on delay in the long term in a connected vehicle environment.

DESCRIPTION OF PROPOSED TRAFFIC SIGNAL CONTROL ALGORITHM

The traffic signal control algorithm proposed in this paper, called the predictive microscopic simulation algorithm (PMSA), was developed to achieve the following three objectives:
1. To match or significantly improve the performance of a state 90of- the-practice actuated coordinated system;
2. To respond to real-time demands only, and thereby to eliminate the need for manual timing plan updates to adjust for traffic growth or fluctuations; and
3. Never to reidentify, 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, in which the traffic signal controller attempts to minimize an objective function over a short period of time in the future. Although many detector-based traffic signal control strategies use the rolling-horizon approach, they require complicated algorithms to estimate vehicle arrivals 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 the path of a single controlled vehicle, for example, westbound left, and a phase is defined as two non contradictory movements, for example, 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 m of the intersection (at 45 mph, the speed of this corridor, a vehicle travels exactly this distance during the 15-s horizon). This information is then used to populate a model of the intersection, as shown in Figure 2.

Once the model has been populated with the new vehicles, the vehicles are simulated 15 s into the future. Because the turn lanes in the test network were between 75 and 300 m in length, the turning movement of many vehicles can be assumed on the basis of their current lane. For vehicles 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 possible maintenance of the current phasing. Four second amber phases and 2-s red phases are simulated as well. The phase with the optimal objective function over the 15-s 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 s and a maximum time before recalculation of 15 s. To ensure smooth operation of the signal, several restrictions are put into place. Because the algorithm is acyclic and allows phase skipping, each movement has a maximum red time of 120 s. This was considered reasonable, as the Synchro-recommended timing plan for the corridor was 120 s. Also, to take advantage of the queue detection capabilities of connected vehicles, the algorithm does not allow queues to block a turning lane or through lane. When a vehicle is detected to be within 40 ft 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 3. The algorithm operates completely without loop or video detection and with no knowledge of expected demand or memory of past demand and is completely decentralized. The algorithm has 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 dedicated short-range communications. It requires only the information required in the basic safety message no more than once per second, even though the message is sent 10 times per second according to the standard. Furthermore, the algorithm is able to protect driver privacy by clearing any vehicle data seconds after it is recorded. That is, the algorithm does not store any vehicle location data, either aggregated volumes or individual vehicle trajectories, once the next phase has been determined.

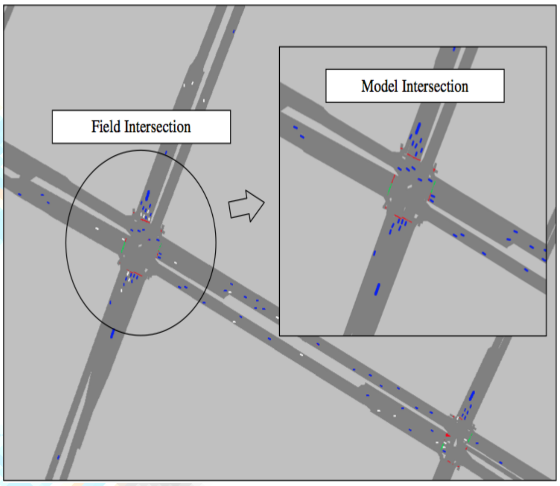

FIGURE 2 PMSA populations of model of intersection with positions and speeds of equipped vehicles from actual field intersection.

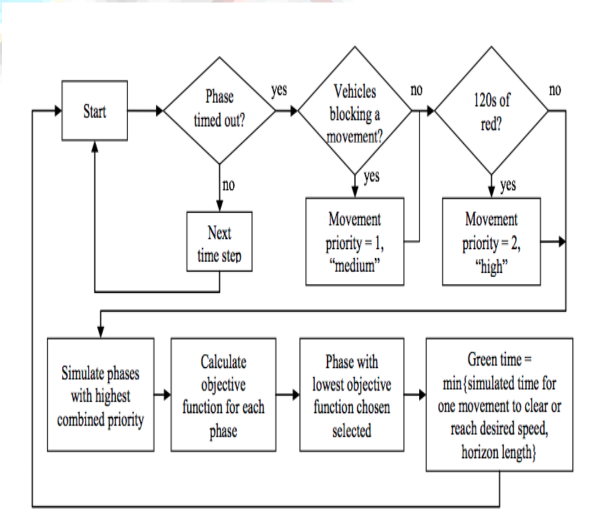

FIGURE 3 Algorithm logic flowcharts to calculate Green time.

CONCLUSION

Many current approaches are used for adaptive traffic signal control they both need aggregate sensed traffic flow data and coordinate network control centrally (which limits real-time responsiveness) or drive local intersection control with static, pre-computed global coordination plans. This paper also presents an algorithm called PSMA for rolling-horizon traffic signal control. These approaches have proven most effective in arterial settings. The SURTRAC system design, in contrast, aims specifically at urban road networks, where there are multiple, competing traffic flows that dynamically shift through the day. By controlling each intersection locally, responsiveness to real-time traffic conditions is maximized, and by communicating planned outflows to neighboring intersections larger corridor flows can be established on demand to match actual traffic flow volumes. Since the system operates in a totally decentralized manner, it is easily extended to incorporate additional intersections and inherently scalable to road networks of arbitrary size. The algorithm uses individual vehicle locations, headings, and speeds to predict an objective function over a 15-s future horizon through the use of microscopic simulation.

The algorithm does not use any data from point detectors or any historical demands, nor does it require any communication between signals. Algorithm is that it uses only instantaneous vehicle data and does not re identify or track vehicles in any way, to protect privacy.

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