SIMULATING ADAPTIVE CONTROL STRATEGIES IN LARGE URBAN NETWORKS

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Submission Date: August 1, 2015
Word count: 4,333 + (7 x 250) = 6,083

ABSTRACT
This paper describes a scalable approach to simulation of decentralized adaptive signal control systems, motivated by our interest to provide a basis for assessing the benefit of the Surtrac adaptive signal control system at a potential deployment site in advance of installation. The approach centers around a simulation controller interface called VISCO, which links the VISSIM microscopic traffic simulator to a set of externally hosted local intersection control processes. Local control processes are free to communicate with each other and exchange control information in the same manner that they would in a field implementation. VISCO coordinates all interaction with the simulator process to create a distributed software-in-the-loop simulation architecture. To illustrate and analyze the efficacy of the approach, we summarize a simulation analysis that was conducted of the downtown triangle area of Pittsburgh PA. A 63-intersection VISSIM model of this site is described and analyses are presented to characterize both the efficiency of the distributed architecture and the potential utility of Surtrac adaptive control. With respect to the former, the distributed simulation of local Surtrac control processes is found to run in roughly 4.4 times faster than real-time, in comparison to the 14.4 times faster than real-time speed that a conventional VISSIM simulation of this model with fixed timing plans performed. Experiments also show that the VISCO distributed architecture is effective in significantly reducing the cost associated with VISSIM's external COM interface. With respect expected improvement of adaptive signal control in the downtown triangle area of Pittsburgh, the simulation analysis shows strong benefit of Surtrac over both the existing timing plans in use in this area and Synchro optimized plans that were generated with perfect knowledge of traffic volumes and turning counts.

1. INTRODUCTION

Adaptive traffic signal control systems are being deployed with increasing frequency in recent years [Stevanovic 2010], based on their promise of achieving more efficient, flexible, environmentally friendly and safer traffic flows. However, the deployment of an adaptive signal system typically requires significant upfront investment (for detection, communication, etc., in addition to the control system itself), and as such, adoption remains a difficult decision for municipalities. Existing adaptive signal technologies operate on different principles and assumptions, which can make them more or less effective in different settings. Decision-makers currently lack tools for reliably projecting the benefit of an adaptive system in advance of actual deployment. In urban environments, the principal focus of our research, the introduction of adaptive signal technology can be particularly challenging, where there is often misconception regarding its potential, and there often does not seem to be the "low hanging fruit" that simpler arterial settings might offer.

Microscopic traffic simulation tools (e.g., VISSIM, AIMSUN, SUMO) provide a general basis for analyzing the effectiveness of traffic signal control alternatives in advance of implementation. However, other than providing embedded support for simple actuated control, these tools are generally aimed at modeling the performance of pre-programmed signal timing plans. To incorporate an adaptive signal control scheme, the modeler typically must interface the simulator with an external (independently developed) controller process. Depending on the API provided, the modeler is often forced to alter the behavior of the adaptive signal control system from the manner that it operates in the field, which lessens the predictive credibility of the simulation results that are subsequently obtained. Ideally, it should be possible to interface the simulator directly to the actual system that is installed in the field.

In this paper, we describe a simulation-based framework for estimating the performance of an adaptive signal system on a target road network prior to deployment. We focus specifically on infrastructure for simulating adaptive signal control systems that operate in a decentralized manner (e.g., (Mirchandani and Head 2001, Rhythm 2010, Smith et.al 2013). To mimic the inherent scalability of decentralized adaptive signal control systems in the field and enable consideration of large-scale road networks, our approach exploits a distributed computing environment where each intersection in the target network is controlled by a separate local process and local processes execute concurrently as the simulation advances. These local control processes can in fact be the same processes that would be running at each intersection in the field application, and they are expected to communicate with each other exactly as they would in the field. Our current implementation uses VISSIM as the underlying traffic simulation platform, but we believe the same approach could be taken with other simulators.

Our basic motivation for developing this infrastructure has been to analyze potential future deployments of the Surtrac (Scalable URban TRAffic Control) system (Xie et. al 2012a, Xie et. al 2012b, Smith et.al 2013), a decentralized real-time adaptive signal system. In Surtrac, intersections dynamically compute timing plans to optimize local throughput of observed traffic, and then asynchronously communicate expected outflows to downstream neighbors to enable local planning over a longer horizon and achieve coordinated behavior at the network level. To illustrate use of the proposed distributed simulation infrastructure, we describe a 63-intersection simulation model of the Downtown Pittsburgh PA that was constructed to quantify the expected benefit of a downtown Surtrac deployment. To our understanding, simulation analysis of adaptively controlled signal systems of this scale at the microscopic level is unprecedented, and we see this capability as an important catalyst to broader application of adaptive signal technology. More generally, such tools also provide the opportunity for direct comparative analysis of alternative approaches.

The remainder of this paper is organized as follows. In Section 2, we review related work in this area. In Section 3, we introduce our framework for managing multiple local signal control processes and describe our Vissim Simulation Controller (VISCO) interface. In Section 4, we summarize the downtown Pittsburgh simulation model we have constructed with our framework, and present performance results. Finally, In Section 5, we draw some conclusions and discuss further work.

2. RELATED RESEARCH

It is common practice to use simulation to evaluate the performance of urban arterials. Transyt 7F, and Passer have been used extensively in this regard and they are useful for quickly evaluating benefits and designing fixed-time signal plans (Balk et al. 2000, Bonneson et al. 2002). In addition, software packages like Synchro can optimize most actuated and coordinated controller systems (Bullock & Catarella 1998). However, one weakness of most of these macroscopic traffic simulation models is their inability to represent complex control strategies, especially those dependent on sophisticated detector placements. Microscopic simulation packages such as VISSIM and AIMSUN provide richer modeling capabilities that can overcome this weakness, but they tend to emphasize analysis of conventional fixed signal control plans. Since various adaptive traffic control systems have unique control logic algorithms (potentially implemented on unique computing platforms), the best way to evaluate complex traffic control systems is frequently to replace the controller in the simulation model with the actual control logic itself. Previous research efforts have achieved this objective in two ways: 1) Hardware-in-the-Loop (HIL) simulation, and 2) Software-in-the-Loop (SIL) simulation.

2.1. Hardware-in-the-Loop Simulation

A hardware-in-the-Loop (HIL) architecture provides a hardware-based framework for evaluating the performance of a particular controller/control strategy in conjunction with traffic simulation (Bullock et al. 1999; Burns & Wellings, 1990; Engelbrecht et al. 1999; Haenel and Messer 1974). There are four main components of an HIL system:

1) A microscopic simulation model (engine) that moves vehicles through a defined network and tabulates measures of effectiveness (MOEs).

2) A Controller Interface Device (CID): The purpose of this device is to provide the interface between the computer running a traffic simulation model and the traffic controller. The interface is based upon discrete controller inputs and outputs. These discrete states are exchanged via the voltage levels used to monitor the load switches;

3) A software interface module: This component provides the interface between the CID and microscopic simulation model

4) The controller and possibly other types of hardware.

In HIL simulation, at each time step, detector calls generated by the simulation model are transferred to the external controller through the software interface module and controller interface device. The traffic controller in turn analyzes the detector input data, makes control decisions, and sends the signal indications data to the simulation model through CID. To run distributed control strategies using HIL architecture, networking between hardware is carried out just like as it is done in the field, i.e., one physically networks the controller units by connecting them together with switches. Several research efforts [Zhang et al], [Kwon et al] have evaluated adaptive and distributed control strategies using HILS architecture.

While a HIL approach provides the basis for confirming the behavior of a complex control strategy, it has several limitations from the standpoint of modeling the behavior of decentralized traffic control schemes at the network level. First, HIL simulation requires one CID and one external controller for every intersection being simulated. Therefore it is not a cost-effective approach for simulating large networks. Second, the simulation must run in wall-clock time in order to ensure synchronization between the microscopic simulation model and the traffic controller. Thus, analysis of performance across a range of circumstances can be quite time consuming. Third, software and hardware latencies in HIL system could make the simulation process challenging [Li et al].

2.2. Software-in-the-Loop Simulation

Software-in-the-Loop principles have been developed to address some of the above limitations. The basic idea of SIL simulation is to replace the signal controller logic in the simulation model with the software that runs on physical traffic signal controllers. Therefore, one need not worry about the cost and complexity of physical controllers and controller interface devices. Furthermore, a SIL simulation also offers the possibility to run simulations in faster than wall-clock time, which further enhances model scalability. The principal example of a SIL simulation framework incorporates the ASC/3 SIL controller, developed by PTV America and Econolite Control Products in conjunction with the University of Idaho, for use within VISSIM [T. Urbanik II]. The ASC/3 SIL controller is compliant with National Transportation Communications for Intelligent Transportation Systems (NTCIP) protocol and operates from the same code base as the ASC/3 hardware controllers. Prior research has used the ASC/3 SIL controller to test the implementation of Transit Signal Priority (e.g., [Zlatkovic et al] among others).

The ASC/3 SIL controller offers one approach to modeling decentralized signal control processes. In this case, the information that must be communicated between intersections can be exchanged via NCTIP protocol, and this framework works very efficiently for simulating small traffic networks. However, since the ASC/3 SIL controller does not support distributed (parallel) computation (at least in its current form), the ability to keep pace with the simulation clock can quickly become an issue as the number of intersections is increased.

In the next section, we propose an alternative SIL architecture that overcomes this limitation by enabling adaptive traffic signal decisions to be made in parallel by different local intersection control procedures (as they would in the field).

3. VISCO DISTRIBUTED SOFTWARE ARCHITECTURE

The design of a framework for microscopic simulation of decentralized adaptive signal control systems raises three broad requirements. First, to achieve the scalability of such systems in the field, it must be possible to make signal control decisions at different intersections in parallel. Second, to achieve coordination at the network level for peer-to-peer systems such as Surtrac, it must be possible for these local intersection control processes to communicate with each other and share information, again as they would in the field. Third, if local intersection control processes permit, it should be possible to run simulations of the adaptive control system in faster than wall-clock time. These three requirements have driven the development of VISCO (VISSIM Simulation Controller).

VISCO is a software package that provides an interface between the VISSIM microscopic traffic simulator and a set of externally hosted intersection control processes (one for each intersection). At every tick of the VISSIM simulation clock, VISCO collects current detector information from VISSIM and distributes it to respective intersection control processes along with internally maintained intersection state information. Each intersection control process will assimilate this information and may or may not choose to make a control decision. As control decisions are made, they are communicated back to VISSIM and the cycle repeats. To ensure synchronization between VISSIM and the set of external control processes under the assumption that the simulation is running in faster than real (wall clock) time, VISCO takes control of the simulation clock on each cycle and requires an acknowledgement from each external control process before advancing the tick and relinquishing control of the clock. This ties the simulation speed to the actual time required for local control decisions to be made, where it is assumed that decision time is generally much less than the available decision window (which is the case, for example, in Surtrac).

The VISCO architecture is illustrated in more detail in Figure 1. An Executive process provides the VISCO interface between VISSIM and local intersection control processes. As can be seen, stop-bar detector occupancy and advance detector impulse data are retrieved from VISSIM at the beginning of each decision cycle (Step 1 in Figure 1). For efficiency reasons, this data is obtained from two global COM (Component Object Model) calls, a first call to pull occupancy data for all stop-bar detectors in the network and a second call to pull impulse data associated with all advance detectors).[1] For similar efficiency reasons, VISCO internally maintains the current signal state of each intersection rather than retrieving it from VISSIM at each decision cycle.

When a local adaptive control process receives new detector and signal state information for the intersection it is controlling (Step 2 in Figure 1), its logic is invoked to determine if a control decision needs to be made and if so, what decision should be taken. In the case of Surtrac, a new schedule of vehicle movements (equivalent to a new local timing plan) will be

[1] Obviously, one could obtain this data by making separate COM calls for each intersection and this would be more convenient approach for passing information to local control processes. However, our preliminary explorations indicated that the time overhead associated with COM calls is substantial; with a given COM call taking ~ 300 milliseconds. To avoid this cost, we instead extract all detector data at once and then unpack it for communication to local control processes. This optimization reduced the average time taken for COM calls (both read and write) to ~ 16 milliseconds.

computed based on the current detector state and the latest outflow information received from its upstream neighbors if the intersection control process's internal parameters indicate that it is time to re-compute. If a new schedule/timing plan is computed, then a control decision will be taken to start executing the new plan, and the outflows implied by this plan will be communicated to the control processes of downstream neighbors.

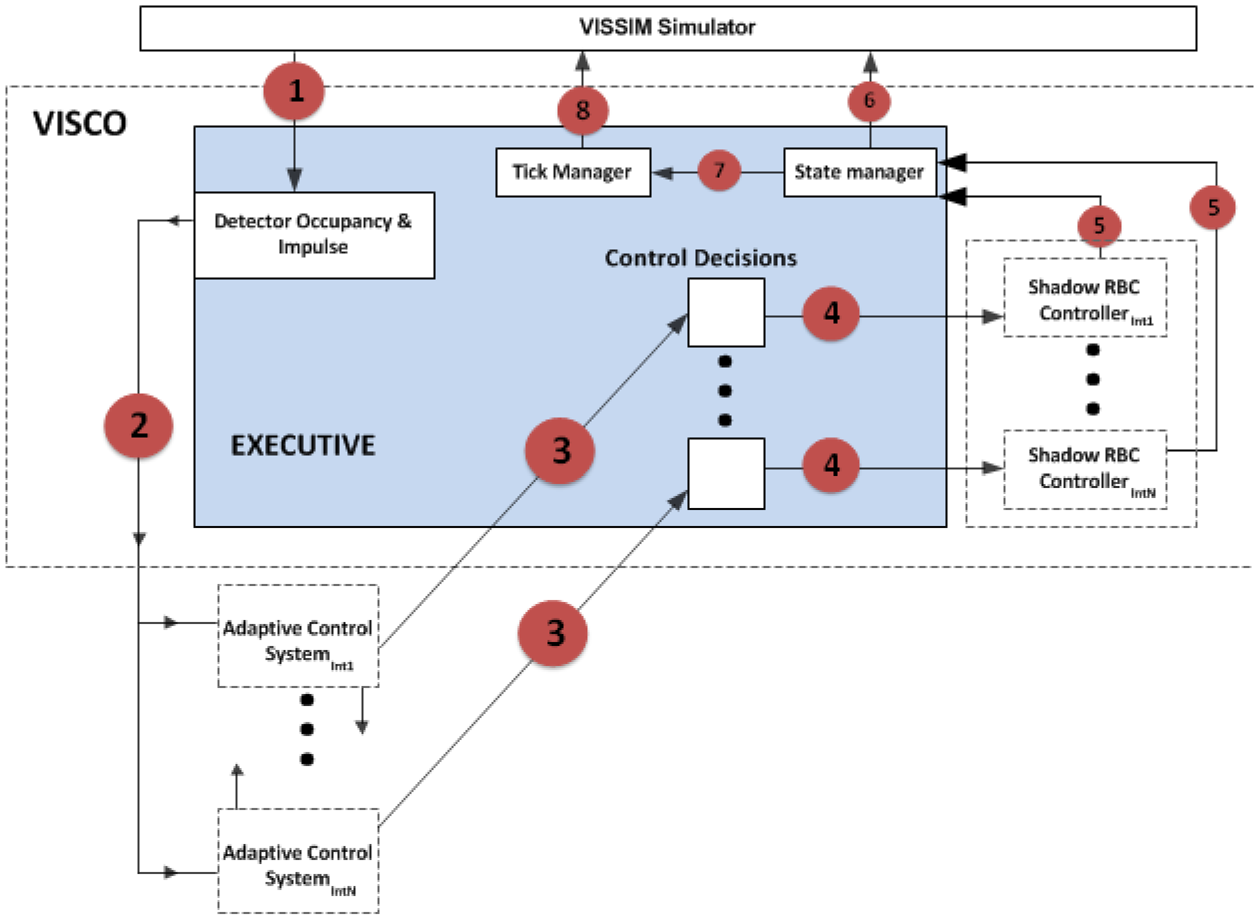

Figure 1: Overview of VISCO architecture

As control decisions are made by local control processes and communicated back to VISCO, they are entered into a queue for processing within VISCO (Step 3 in Figure 1). In the case of Surtrac these control decisions will either 1) extend the current phase by some number of seconds or 2) switch to a new phase. Given that the default Ring Barrier Controller (RBC) in VISSIM is not capable of accepting commands to extend an existing green phase, nor can it be given back control after its logic has been over-ridden, VISCO implements an instance of its own shadow RBC controller for each intersection that is being adaptively controlled. This controller follows standard dual-ring eight phase actuated control logic. It also provides the capability to service actuated minor movements (left turns) on either side of the barrier before servicing through movements, if adaptive control decisions are only being made for through movements. Each shadow RBC controller maintains information relating to its current controller state (e.g., current phase, time to max, gap out, etc.) and when invoked executes the control decision that has been designated by the local control process (Step 4 in Figure 1). If the control decision for a given intersection is to remain in the same phase then local state is simply updated (Step 5); if the decision is to switch to a new state, then the state change is communicated back to the VISSIM simulator (Step 6) through a standard COM call. When all local control decisions have been implemented, the simulation clock is advanced (again through a COM call) and control is passed back to VISSIM.

4. APPLICATION OF THE FRAMEWORK

As mentioned at the outset, our basic motivation for developing VISCO has been to analyze potential future deployments of the Surtrac system. Following the successful deployment of Surtrac in the East Liberty neighborhood of Pittsburgh [Smith et al. 2013, Barlow et al, 2014], a study was commissioned by local foundations to investigate the broader impact of Surtrac adaptive signal control in other areas of Pittsburgh. Of particular interest was the potential for traffic flow improvement in the downtown triangle area of Pittsburgh, the main business district of the city that occupies the land between the Allegheny and Monongahela Rivers as they converge to form the Ohio River. The extended downtown triangle area is a densely connected urban road network consisting of about 88 signalized intersections. VISCO was conceived specifically to allow use of a microscopic traffic simulation analysis to address this question, and we illustrate its use by considering the Surtrac simulation model of the downtown triangle area that we have constructed and analyzed. After summarizing the VISSIM model that was developed, we first characterize scalability properties of the approach, and then summarize results obtained with the model showing the expected benefit of Surtrac adaptive control over current fixed timing plans.

4.1. The downtown triangle model

For purposes of our analysis, attention was restricted to the core downtown triangle area. This area consists of 63 signalized intersections, and is bounded (approximately) by Penn Avenue, Boulevard of the Allies, Stanwix Street, 11th Street and Chatham Square. Figure 2 presents a schematic view of this road network (with intersections in green). The model constructed captures the AM Rush period, using the City of Pittsburgh’s most recently collected volume and turning count data (in this case vintage 2004). This data was then adjusted slightly to incorporate the Port Authority’s current bus schedules through this area.

Three control variants of this basic model were then defined for comparative analysis:

- *Existing timing plans* – A first control variant encodes the fixed timing plans that are currently used to control this signal network.
- *Synchro optimized plans* – At the time when volume and turning count data was last collected by the City, the Synchro analysis tool was applied to this data to generate new timing plans. These new timing plans were never subsequently installed and used (for unrelated technical reasons). Since our simulation analysis is assuming the same traffic count data that these plans were optimized for, a second model that uses these timing plans is also defined as a “best case” fixed timing plan.
- *Surtrac adaptive control* – Finally a third, distributed simulation variant is configured using VISCO to implement Surtrac adaptive signal control. In this third version of the model vehicle detectors are of course also added to the model.

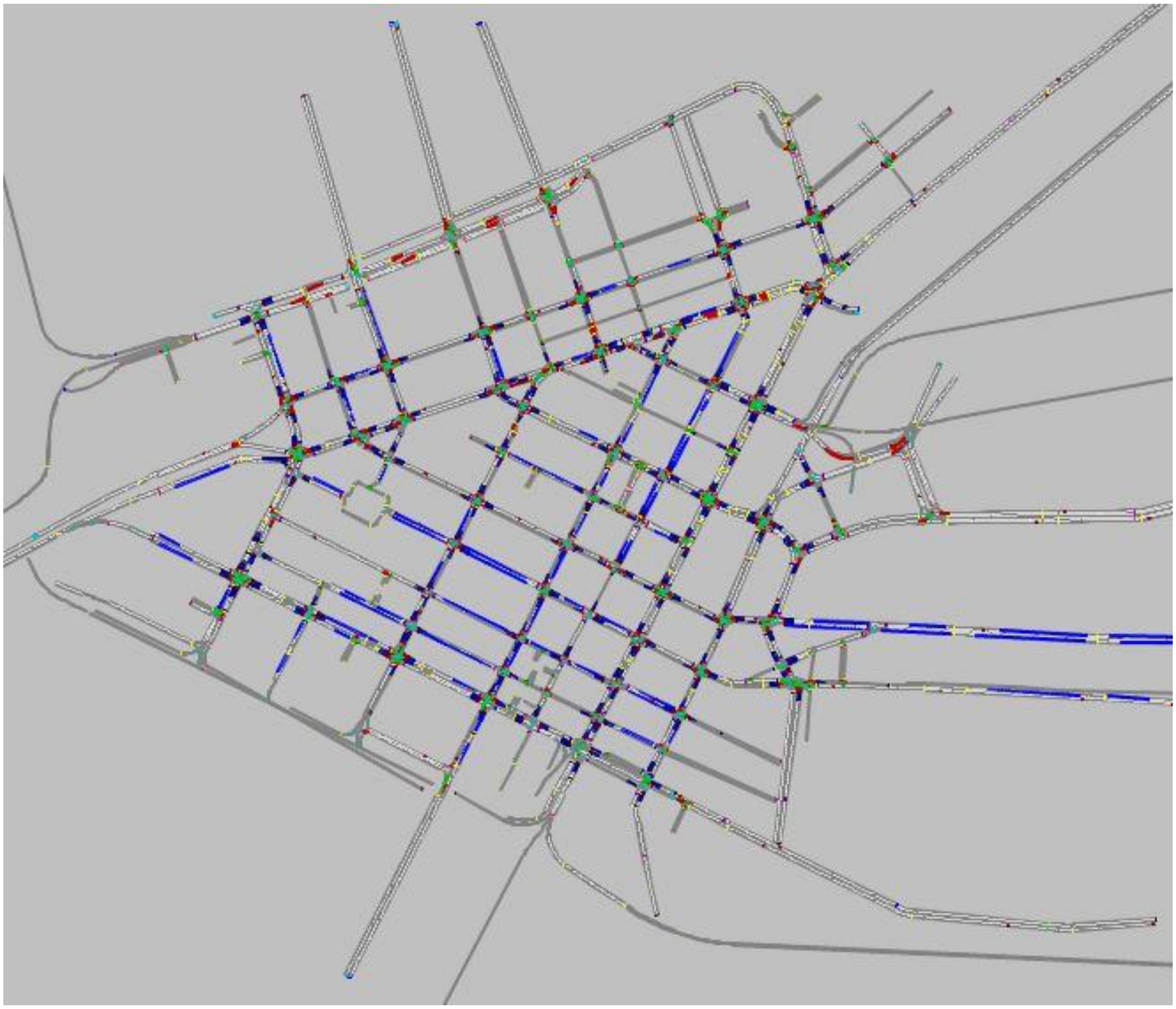

Figure 2: VISSIM Simulation Model of downtown Pittsburgh network

4.2. Performance analysis of the VISCO architecture

To characterize the scalability of our distributed simulation approach, we compare the computational performance of different configurations of the VISSIM simulation model. As indicated earlier in Section 3, VISSIM requires VISCO to communicate with the simulator process via COM calls and there is a non-trivial cost associated with every COM call (that is independent of the time required by Surtrac processes to make control decisions). Furthermore, it was noted that VISCO architecture minimizes number of COM related calls. Three simulation configurations were considered. First, a version of the VISSIM simulation of the downtown model that incorporates the *Existing timing plans* control variant but uses explicit COM calls to advance (or step) the simulation clock is included (to provide a baseline for integration with any external traffic control decision procedure); Second, a simulation variant that utilizes VISCO and its shadow RBC controllers to make the same control decisions as *Existing timing plans* is considered (to quantify the additional cost of communicating signal phase changes via COM calls). This configuration implies that both stop-bar detector occupancy and advance detector impulse data are retrieved from VISSIM for each intersection every time step. Third, a VISSIM simulation variant that utilizes VISCO to integrate a set of local Surtrac intersection control processes is included.

We will refer to these three scenarios below as *COM-Stepping, VISCO–Fixed, and VISCO–Surtrac respectively.*

Using simulation time as a basic performance indicator, *COM-Stepping* provides a lower bound baseline; *VISCO-Fixed* is designed to isolate the overhead associated with integrating an external controller with VISSIM; *VISCO-Surtrac* provides an indication of the additional time required to run the VISCO architecture with Surtrac adaptive control strategy on the downtown traffic network.

To evaluate these three VISSIM simulation configurations, we performed 5 simulation runs of each, using the same 5 random seeds, and report the average results. Each simulation run covered a span of 12,600 seconds (to ramp up and cover the entire AM Rush period). To configure the *VISCO-Surtrac* simulation, it was necessary to make some assumptions about how to distribute Surtrac intersection control processes across machines. In the field, each Surtrac process runs on its own machine (which is situated at the intersection in the traffic cabinet). However, given the greater computing power of the multi-core machines in our lab, it is possible to run multiple Surtrac processes on a single machine while maintaining the compute times that are observed in the field. For the experiments reported below, the 63 Surtrac processes required to control the downtown network were spread across 12 machines, where 5 instances were run on each of 11 machines and 8 were run on the remaining (higher performance) machine.

The results of these simulation runs are given in Table 1. We list two metrics for comparison, the average run time incurred by each simulation configuration and the average speed at which each configuration ran when compared to wall-clock time. The *COM-Stepping* simulation model, which indicates the maximal efficiency possible with use of VISSIM's COM interface, is shown to run 14.4 times faster than wall-clock time. The *VISCO–Fixed* configuration is observed to run 11.7 times faster than wall-clock time, indicating that the VISCO distributed architecture has effectively minimized the cost of COM read/write calls that are required for each intersection. Finally, the *VISCO-Surtrac* configuration is observed to add significant computational overhead, due principally to the cost of asynchronous communication with distributed local control processes. At the same time, the distributed *VISCO-Surtrac* configuration still runs 4.4 times faster than real-time on the 63-intersection downtown model, and this overhead has been observed to be independent of the size of the network[2].

[2] In the final version of the paper we will also include results obtained a 17-interesection model of a subset of the downtown network to substantiate this claim, and further enhance our claims of scalability.

Network	Run time (seconds)			Comparison to wall-clock time		
	COM-Stepping	VISCO-Fixed	VISCO-Surtac	COM-Stepping	VISCO-Fixed	VISCO-Surtac
Downtown-63	876	1076	2845	14.4	11.7	4.4

Table 1: Run Time Performance

4.3. Performance analysis of Surtrac adaptive control

To address the question of original interest and assess the potential benefit of Surtrac adaptive signal control in the downtown triangle area, the traffic behavior produced by the (VISCO-Distributed) *Surtrac* control variant of the downtown model was compared with that produced by both the *Existing timing plans* and the *Synchro timing plans* control variants. To support this comparison, a VISSIM event record for every vehicle in the network was written every 2 seconds of each run performed using *Existing Timing Plans* and *VISCO-Surtrac* in the scalability analysis above, and 5 additional runs were performed to capture the behavior generated by *Synchro timing plans*. Based on this information, three performance metrics were computed for each scenario: 1) average travel time through the network, 2) average delay (over the time that would be required if traveling at free flow speed with no stops) 3) and average number of stops. These metrics were averaged for all vehicles across five simulation runs for each scenario.

Table 2 summarizes the results produced by this simulation analysis. Each row of the table indicates the percentage improvement of Surtrac over a competing alternative, for each of the metrics just discussed. As can be seen, Surtrac significantly reduces travel time, delay, and number of stops over both the timing plans that currently in use downtown and the “ideal” Synchro optimized timing plans. It is interesting to note that Surtrac achieves an 8% reduction in travel time and a 14% improvement in delay over use of the Synchro plans, even though they are being evaluated on exactly the same traffic volumes for which that we designed (i.e., as if they were designed with perfect knowledge of traffic volumes). This shows the basic advantage of basing traffic control decisions on actual traffic flows rather than expected traffic flows.

% Improvement over	**Travel Time**	**Delay**	**# of Stops**
Existing Timing Plans	20	30	22
Synchro Timing Plans	8	14	9

Table 2: Summary of results

5. CONCLUSIONS

In this paper we describe a scalable approach to simulation of decentralized adaptive signal control systems. The approach centers around a simulation controller interface called VISCO, which links the VISSIM microscopic traffic simulator to a set of externally hosted local intersection control processes. Local control processes are free to communicate with each other and exchange control information in the same manner that they would in a field implementation. VISCO coordinates all interaction with the simulator process to create a distributed software-in-the-loop simulation architecture.

The development of VISCO aims generally at providing a mechanism for assessing the potential of decentralized adaptive signal control systems at a given site in advance of actual deployment, and was motivated specifically by prospective opportunities to more broadly deploy the Surtrac adaptive control system. To illustrate and analyze the efficacy of the approach, we described a simulation analysis of one such Surtrac deployment opportunity: the downtown triangle area of Pittsburgh PA. A 63-intersection VISSIM model of this site was constructed and analyses were presented to characterize both the efficiency of the distributed architecture and the potential utility of Surtrac adaptive control. With respect to the former, the distributed simulation of Surtrac control processes was found to run in roughly 4.4 times faster than real-time, in comparison to the 14.4 times faster than real-time speed that was observed using a VISSIM simulation of this model with fixed timing plans developed to represent a lower bound on any externally configured control process. Finally, a fixed-timing plan alternative that uses the VISCO interface as a complete two-way interface to VISSIM is tested and observed to run at 11.7 times faster than wall-clock time, indicating that VISCO is quite effective in reducing the inherent cost of VISSIM's COM interface. With respect to adaptive signal system improvement in the downtown triangle area of Pittsburgh, the simulation analysis showed strong benefit over both the existing timing plans in use in this area and a set of Synchro optimized plans that were generated with perfect knowledge of traffic volumes and turning counts.

We are currently applying the VISCO framework to analyze a number of additional potential deployment sites, including the Route 51 corridor into Pittsburgh from the south, and a 27-intersection network in Burlington Vermont. Our broader interest is in methodologies that enable comparisons of alternative systems and the development of tools capable of categorizing differential strengths and weaknesses.

ACKNOWLEDGEMENTS

This research was funded in part by the Hillman Foundation, the Heinz Endowments, and the CMU Robotics Institute.

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