A New Hardware-in-the-Loop Traffic Signal Simulation Framework to Bridge Traffic Signal Research and Practice

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***Abstract*—In this paper, we present a new hardware-in-the-loop traffic signal simulation framework, which is referred to as HILS-NG. With this proposed framework, pioneering traffic signal control strategies proposed by researchers can be separated from traffic simulation engine while interacting with simulations as independent applications via standard traffic control communication. The advantages of this new framework include the following. First, pioneering traffic signal logic only needs to be programmed once for simulation, and the same code can be deployed to the field with minimal porting efforts. Second, control algorithms are hosted in supplemental hardened single-board computers (SBCs) do not require replacing traffic signal controllers in the field; therefore, the proposed framework will not compromise the existing signal safety protections in signal cabinets, such as phase conflict monitor. We expect that this new framework will greatly facilitate the prototyping and field tests of new traffic signal control strategies for scholars and practitioners. To further demonstrate the potential of this new framework, in the second part of this paper, we utilize an industrial communication standard for traffic signal controllers in North America, i.e., the National Transportation Communications for ITS Protocol (NTCIP), to set up real-time communications with a full-scale traffic signal emulator in simulation and then develop and evaluate a set of innovative e signal control strategies. A set of new signal control strategies is also presented to demonstrate how to design control functions and the corresponding NTCIP communication stacks.**

***Index Terms*—Traffic simulation, optimization, traffic signal control, adaptive signal control, signal optimization, NTCIP.**

I. Introduction

THE advancement of traffic signal simulation enables researchers to develop and evaluate innovative signal control strategies in traffic simulation. In the meantime, many innovative signal control strategies involve unconventional control logic and must be retrofitted into the control equipment in the field test. This task requires not only the expertise in transportation but also in information technology. As a result, only a small portion of conceptual signal systems were tested

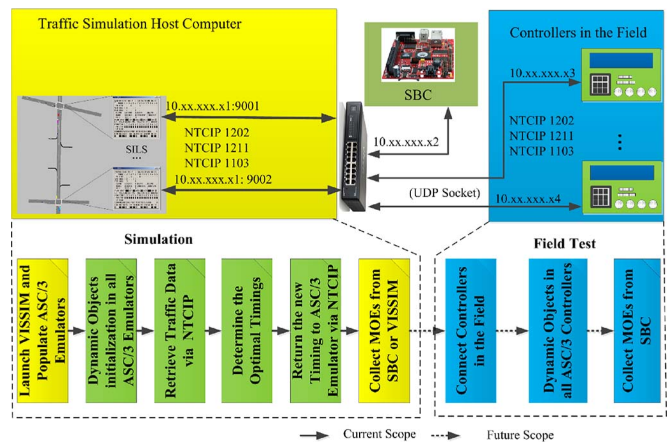

Fig. 1. System architecture of the "HILS-NG" signal simulation platform.

and eventually deployed in the field in the past. To address this issue, we propose a new hardware-in-the-loop traffic signal simulation framework to fill the gap between traffic signal research and signal operations (referred to as HILS-NG hereafter). In the last two decades, numerous efforts have been dedicated to improving interoperability among various traffic equipment manufactures. As a direct result, communication between different brands of traffic signal controllers and traffic central systems have been standardized. For instance, in North America, such communication standard is the National Transportation Communications for ITS Protocol or NTCIP [1]. With this industrial standard, it is possible to manipulate standard-compliant traffic signal controllers with an external program. In the meantime, some mainstream traffic simulation packages have also evolved to include advanced traffic signal emulators. For instance, PTV VISSIM has embedded a fully functional traffic signal emulator into its latest release which not only emulates functions the hardware traffic signal controllers but also provides a full-scale NTCIP-compliant communication module [2]. Based on these new technical developments in traffic simulation, any new control strategies are programmed into an independent program residing in supplemental hardened signal board computers (SBC) aside existing control equipment. Then SBCs can communicate with traffic signal emulator in VISSIM through NTCIP. In general, the control program is composed of two modules, *control logic module* and *communication module*. As in Fig. 1, while VISSIM is running, the control program in SBC reads the detector and phase statuses from the ASC/3

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SILS as well as updates of signal timings. The SBC also writes back new signal timings to the ASC/3 SILS via NTCIP. Since the control logic is completely separated from VISSIM and the communication between the SBC and ASC/3 SILS is purely based on NTCIP, the control strategies in the same SBC can be evaluated both with the signal emulators in simulation and with the hardware NTCIP-compliant signal controllers in the field. Therefore, it is expected that the HILS-NG simulation framework will facilitate the deployment of innovative signal systems in the future.

The rest of this paper is organized as: first, literature on traffic signal simulation technology is reviewed. Then the HILS-NG architecture and related technologies are elaborated. Thirdly, as a demonstration of how to apply the HILS-NG framework to non-conventional traffic signal control logic designs, we present a set of non-conventional traffic signal control strategies and show what control functions could be provided and their corresponding communication objects in the HILS-NG framework. In the end, the proposed traffic signal control strategies are extensively evaluated with the new signal simulation framework through a case study.

II. Literature Review

There are two concerns in traffic signal simulation including: the mechanism of data exchange between traffic simulation engine and signal emulators; and the form in which the signal control strategies are realized. As characterized by Stevanovic *et al.* [3] and Day *et al.* [4], the progression of traffic signal simulation technologies can be divided into four generations:

A. Emulator-in-the-Loop System (EILS)

Most fine-grained traffic simulation packages include signal emulators containing basic control functions. Examples include the signal emulators in CORSIM [5], VISSIM [6], AIMSUN [7] and TransModeler [8]. Compared to fully functional signal controllers, these signal emulators can meet the basic control needs while they cannot realize many advanced functions. In addition to the provided signal emulators, some traffic simulation packages also provide flexible application program interfaces, or APIs, for users to build customized control emulators. Since the signal emulators are an integral part of traffic simulation, users do not need tackle the mechanism of data exchange or synchronization between signal emulators and traffic simulation.

B. Hardware-in-the-Loop System (HILS)

The objective of HILS is to replace the simplified signal emulators in traffic simulation with real signal controllers via controller interface devices (CID). Examples of CIDs include the *NIATT CID II* [9] and *Naztec CID* [10]. In North America, Bullock and his research group first presented the concept of HILS using CORSIM in 1998 [11], [12]. Following these earliest efforts, several variants of HILS systems were developed. One example is that Roelof and Abbas introduced a concept of Cabinet-in-the-loop (CILS) which essentially uses the whole traffic signal cabinet as a CID [13]. Liu and his research team retrieved high-resolution events from traffic signal controller and signal cabinets to estimate queue length [14], [15]. In these HILS systems, the data exchange between traffic simulation and signal controllers are based on either NEMA-TS1 or NEMA-TS2, the standard communication protocols between signal controllers and signal cabinets [16]. NEMA-TS1-TS2-based HILS has both advantages and drawbacks: a major advantage is that all collections of advanced control functions in physical signal controllers can be evaluated in simulation whereas a major drawback is that the simulation speed must be lowered to one step per second to synchronize with the on-board clock of signal controllers. With many simulation scenarios, it often takes very long simulating time.

More recently, Dixon and Islam proposed a new concept of HILS, called external logic architecture. With the external logic architecture, the control strategies are hosted in supplemental microcontrollers and real signal controllers only serve as an intermediate module to exchange data between traffic simulation and the supplemental microcontrollers via NTCIP [17]. Similarly, Head and his research group developed innovative multi-modal traffic signal control applications hosted in the road-side unit of dedicated short-range communication (DSRC) which issue control demand to traffic signal control via NTCIP [18]–[20]. A major advantage of the external logic architecture is that it can provide more flexibility of implementing control logic other than the limited capacity within the signal controllers. The HILS-NG simulation framework presented in this paper shares some similarity with the framework of Dixon and Isam's work and Head's work.

C. Software-in-the-Loop System (SILS)

The objective of SILS was to overcome the drawbacks of EILS and HILS. Some early efforts include integrating centralized adaptive signal control systems, such as SCOOT [21] and SCATS [22], with VISSIM [23]. Nowadays the software in signal controllers is often modulated and segregated from hardware for multiple hardware platforms. This design method makes it possible to integrate real control software with traffic simulation. A well-known SILS system was developed based on the ASC/3 control software from Econolite Inc. and VISSIM from PTV [2]. In this system, the ASC/3 control module is fully functional and the same as the firmware in real ASC/3 signal controllers. SILS almost overcomes all the aforementioned drawbacks of EILS and HILS and is considered the latest development of traffic signal simulation. Nonetheless, because the ASC/3 SILS is a real control software for practice, it does not provide flexible approach for non-conventional signal timing designs, creating barriers for researcher to develop innovative control logic. Based on the SILS system, Stevanovic *et al.* developed a simulation-based optimization system [24] and then later optimized traffic signal timing for over congested traffic conditions [3], [25]. Park *et al.* designed and evaluated innovative traffic signal control logic in the SILS environment [26].

D. *System-in-the-Loop*

The system in this context refers to high-level regional traffic management systems, such as Advanced Traffic Management Systems (ATMS), which includes traffic signal control, equipment health monitoring and traffic data capturing, etc. In other words, the scope of system-in-the-loop can be beyond traffic signal systems. To the authors' best knowledge, in North America, there is only one such simulation system reported to couple a ATMS system with PTV VISSIM in order to evaluate an adaptive signal control system [4]. While VISSIM is running, the detector statuses are retrieved from the ASC/3 control software in VISSIM and sent to the ATMS system. The concept of system-in-the-loop is rather broad and it can be used not only for traffic signal control but also for many other traffic managements.

III. Significance of the Research

An ideal roadmap to develop innovative signal control strategies may start with designing control logic and then evaluate in simulation as well as in the field. Eventually, the new signal control strategies can be built into controller software by traffic signal manufactures and widely deployed. However, only a small portion of innovative control strategies can complete this journey compared to the numerous research efforts. In practice, the signal manufactures may concern about the risk of deploying forward-looking control strategies and therefore they are hesitant to incorporate new control strategies into their control software before extensively tested in the field. On the other hand, many innovative control strategies are so pioneering that they require significant changes to the existing control framework, discouraging traffic practitioners to accept. Furthermore, many pioneering signal control strategies involve intensive computing and optimization and the computing demand will be too high for most mainstream controllers' CPUs. In order to promote the development of traffic signal research, it is important to provide addition computing power for traffic signal controllers both in simulation and in the field; it will be also necessary to take into account the current hardware constraints in the existing signal control systems to avoid requiring fundamental and costly changes.

With the proposed HILS-NG framework, any new control strategies developed for simulation can be easily and safely evaluated in the field. As an immediate result, the new framework will facilitate traffic signal researchers to evaluate their control strategies both in simulation and in the field. In the meantime, keeping the existing signal controller in the loop will also guarantee that any innovative control strategies will only need reasonable changes to the existing signal systems.

IV. HILS-NG Traffic Signal Simulation Framework

Compared with the other NTCIP-based signal simulation systems, such as the external logic architecture [17], the new framework in this paper contains some differences. If a traffic simulation system is based on hardware signal controllers and hardware CIDs, it will require at least one hardware signal controller and CID at each signalized intersection, which may be prohibitively expensive for those scenarios with many intersections or not even practical due to CID's limited availability. In addition, the simulation speed must be slowed down to the real-world time due to the on-board clock in physical signal controllers. By contrast, the HILS-NG framework in this paper utilizes the SILS emulator to play a similar role of hardware CID and signal controllers. Through using "GET" (read up) and "SET" (write down) NTCIP messages, it is possible to retrieve the detector statuses and signal timings as well as adjust the signal timings in each SILS emulator in a real-time manner. Also, NTCIP data exchange and control logic on highly-powered SBCs is almost instantaneous on non-sharing Ethernet and faster than the simulation engine at its maximum speed. Therefore, HILS-NG can also be used within a fast-pace simulation environment.

Fig. 1 shows the communication architecture and work flow of the proposed framework. After VISSIM is launched, all pre-configured SILS emulators will be populated and each SILS emulator will create a User Datagram Protocol (UDP) server on the VISSIM host computer. The SBC hosting the new control strategies will be assigned with a different IP address within the same subnet as the VISSIM host computer's. While VISSIM is running, the SBC continuously communicates with SILS ASC/3 emulators using NTCIP messages.

In order to capture certain instantaneous events within signal controllers, such as the detector pulses, the communications between the SBC and the SILS emulators needs to be short but frequent. As such, the Simple Transportation Management Protocol (STMP) is selected over the popular Simple Network Management Protocol (SNMP) to set up such communications. STMP is defined in NTCIP 1103 and particularly designed to meet to the short-but-frequent communication pattern in traffic signal systems [1]. Each STMP message is built from a user-defined NTCIP object ID (OID) collection, also known as the *dynamic objects*. If the SBC and SILS emulators have the same prior knowledge of the customized dynamic objects such as: version, MIB collection and SET/GET requests, the STMP messages can significantly reduce the overhead as required in the standard SNMP messages. To ensure both communication sides hold the same prior knowledge, it is necessary to customize the dynamic objects in the SILS emulator first before the SBC and SILS emulators can exchange STMP messages. For more details of the STMP configuration, readers are suggested to refer to DeVoe *et al.*'s work [27].

After the dynamic objects in the SILS emulators are initialized, the SBC can either retrieve the information of detectors and phases by sending a STMP "GET" message or modify the signal timings by sending STMP "SET" messages to the SILS emulators. The GET-SET process is repeated during the simulation. After simulation is finished, the users can either retrieve the measures of effectiveness (MOE) from the traffic data log files in SBC or retrieve the MOEs summarized in VISSIM.

After extensive evaluation in VISSIM, the same SBC can be directly connected to hardware signal controllers in the field. Like in simulation, the dynamic objects in the real controllers must also be initialized first using the same routine in

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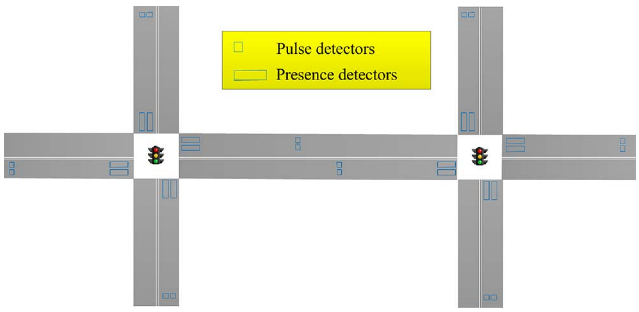

Fig. 2. Detector configuration for the new adaptive control strategies.

the SBC and then the SBC can continuously retrieve traffic data or modify signal timings using STMP "GET" or "SET" messages. The results can be archived in the SBC for post processing.

V. Development of Non-Conventional Signal Control Strategies With the Field-Ready Traffic Signal Simulation Framework

In this section, we demonstrate how to develop non-conventional control strategies with the proposed HILS-NG framework. In addition to the traditional signal control functions design for SBC, the corresponding NTCIP communication stack and dynamic objects between SBC and traffic signal controllers also need customization to meet the requirements by any proposed signal control logic.

According to a report published by US Federal Highway Administration, the evolution of signal control systems can be divided into four distinct generations [28]: 1. fixed signal control strategies with pre-stored timing plans; 2. responsive signal control strategies with automated selecting and loading of existing timing plans; 3. Periodical adaptive signal control strategies (ACS) to generate dynamic timing plans according to the latest aggregated detector data (e.g., in 15 minutes); 4. Continuous adaptive signal control strategies with dynamic timing plans generated according to high-resolution signal events, such as detector pulses or phase changes.

The proposed signal control strategy in this paper combines the advantages of the 3rd and 4th generation of ACS concepts in the sense that it optimizes the timing plans periodically according to the latest traffic data whereas it is also capable of responding to certain high-resolution events within each cycle, such as platoon identification and accommodation. In the meantime, the adaptive signal control strategy presented in this paper is solely based on fixed-spot detectors because the fixed-spot detectors are still the primary data inputs for most traffic signal systems today. A typical detector configuration is illustrated in Fig. 2.

Fig. 3 demonstrates the concept of the new signal control strategy. The main input is the detector events. The signal timings are adjusted periodically (e.g., 15 minutes). If an approaching platoon on the mainline is identified and the control strategy will truncate the current mainline red to accommodate the platoon.

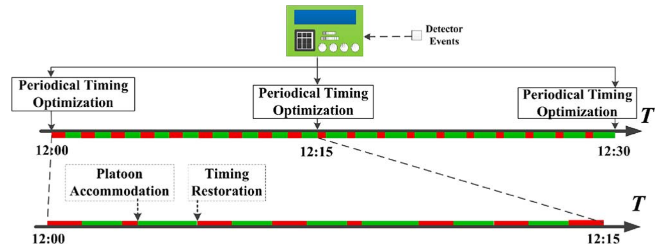

Fig. 3. Demonstration of the adaptive signal control strategy.

A. Periodical Signal Timing Optimization

The signal timings at intersections are optimized and adjusted every 15 minutes. The objective function is based on the control delay estimation model in the HCM 2010 [29] proposed by Strong and Rouphail [30] through (1) through (5);

$$d_1 = \frac{0.5\sum_{i=1}(Q_{i-1}+Q_i)t_i}{qC} \text{(Shared left-through lane group)} \tag{1}$$

$$d_1 = \frac{0.5C\left(1-\frac{g}{C}\right)^2}{1-\left[\frac{\min(1,X)g}{C}\right]} \text{(Other types of lane groups)} \tag{2}$$

$$d_2 = 900T\left[(X_A-1)+\sqrt{(X_A-1)^2+\frac{8kIX_A}{C_AT}}\right] \tag{3}$$

$$d_3 = \frac{3{,}600}{vT}\left(t_A\frac{Q_b+Q_e-Q_{e\mathbf{0}}}{2}+\frac{Q_e^2-Q_{e\mathbf{0}}^2}{2C_A}-\frac{Q_e^2}{2C_A}\right) \tag{4}$$

$$d = d_1+d_2+d_3 \tag{5}$$

where:

- D: total control delay;
- d_1: uniform delay;
- d_2: incremental delay;
- d_3: initial queue delay;
- t_i: duration of the ith section in the Incremental Queue Accumulation diagram;
- T: analysis period (in hours)
- C: cycle length;
- g: effective green;
- v: traffic volume
- Q_i: the number of vehicles in Queue after the ith section;
- C_A: the average capacity based on the saturation rate 1,900 vehicles per hour per lane;
- X_A: the average v/c ratio;
- I: upstream filtering adjustment factor;
- Q_b: initial queue length (veh);
- Q_e: queue at the end of the analysis period (veh);
- $Q_{e\mathbf{0}}$: queue at the end of the analysis period when $v \geq C_A$ and $Q_b = 0.0$ (veh);

Estimate the maximum queue length: assuming no residual queues, the maximum queue length for each lane group within each cycle can be estimated as:

$$Q_{\max} = v_r * r \tag{6}$$

where:

- v_r is the traffic volume during red; and
- r stands for the red duration;

In order to balance the delays on the main line and minor approaches, the objective function is designed as follows:

$$\min D_m \left(1 - e^{-\frac{\max(D, D_2, \ldots)}{30}}\right) \tag{7}$$

where:

- D_m: the mainline control delay;
- D_t: the control delays on the minor streets;

In (7), the major objective is to minimize the mainline delay with a discount factor between 0 and 1. If any minor approach has excessive delay under a particular timing plan, the resulting discount factor will become close to 1 and therefore the corresponding timing plan will not generate the minimal delays. This form of objective function will guarantee the solver can consider the mainline delay and minor approach delay together. It should be noted that maximum green and minimum green constraints (8) on green times will help avoid unrealistic solutions.

The constraints are needed not only to guarantee the ring structure of NEMA signal controllers but also to guarantee the maximum queue length estimated with (6) is shorter than the corresponding link length. Using the standard 8 NEMA phases are used as the example, the constraints can be expressed as:

$$\begin{cases} g^1 + g^2 = g^5 + g^6 \\ g^3 + g^4 = g^7 + g^8 \\ g^1 + g^2 + g^3 + g^4 + L = C \\ Q^n_{\max} < l^n \\ g^n > g^n_1 + g^n_2 (n = 1, 2, \ldots, 8) \\ g^n > \begin{cases} G^n_{\min} (\text{No ped phase enabled}) \\ \max\left(G^n_{\min}, G^n_{\text{walk}} + G^n_{\text{Ped\_clear}}\right) (\text{Enabled ped phase}) \end{cases} \end{cases} \tag{8}$$

where:

- L: lost time with each cycle
- l^n : the length of approach n *in terms of the number of vehicles*;
- g^n: effective green on approach n;
- $G^n_{\min}$: minimum green on approach n;
- G^n_{walk}: pedestrian walk time on approach n; and
- $G^n_{\text{ped\_clear}}$: pedestrian clearance on approach n;

A robust open-source solver developed by the Sandia National Laboratories of USA was selected to solve the above optimization problem, named OPT++plus; [31]. Using an ARM-9 800 MHz CPU on the SBC, the solver in general gets a global optimum or a quansi-optimum solution to the above problems within 1-2 seconds.

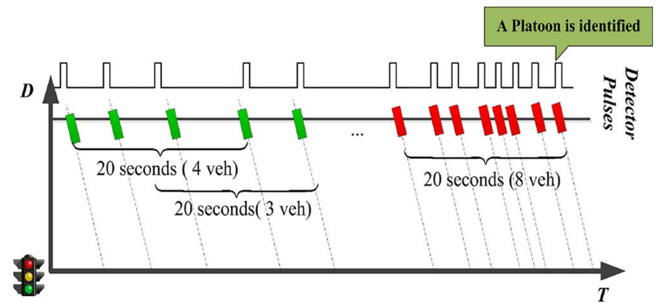

Fig. 4. Platoon identification based on mid-block detectors.

B. *Platoon Identification and Accommodation*

Under actuated control mechanism, any unused greens on side streets are likely returned to the main line in order to increase the mainline throughput. This phenomenon is referred as "early return to green" [32]. As a result, the upstream queue may reach the downstream intersection before the downstream green starts, increasing the vehicle stops and degrading the traffic progression. Obviously, the best time to start the downstream green varies from cycle to cycle, depending on when the upstream queue is released. There is no one single offset value effective all the time.

If a platoon can be identified in advance by the downstream intersection, the downstream intersection can either extend the current mainline green or truncate the mainline red to ensure the platoon crosses the downstream intersection without stopping. It is necessary to continuously monitor the traffic, identify arriving platoons in advance and adjust the downstream signal timings properly. Therefore, this function belongs to the 4th generation of signal control systems. Fig. 4 illustrates the concept of platoon identification and offsets adjustments.

Compared to other headway-based platoon identification algorithms [18], [33], the proposed platoon identification method in this paper is simplified in that it does not predict vehicles' arriving time at stop lines and will respond immediately after an arriving platoon is. The rationale of this simplified method is that advance detectors are often not placed too far away from intersections, especially for those closely spaced intersections. Whenever a platoon is identified, the front vehicle of this platoon has passed the advance detector 20 seconds and is most likely close to the downstream intersection and needs immediate reaction. As in Fig. 4, whenever a new vehicle is discovered by a mid-block pulse detector, the algorithm will look backward 20 seconds. A platoon will be identified if the number of discovered vehicles per lane in the last 20 seconds is equal to or greater than 8 (i.e., the average headway in the last 20 seconds is equal to or less than 2.5 seconds). Chaudhary *et al.* used similar thresholds to identify platoons [33].

To accommodate the arriving platoons, whenever an approaching platoon is identified, the control strategy at the downstream intersection will first examine the current mainline phase status. If it is already green, it means the mainline phase at the downstream intersection also returns to the green earlier than schedule within the current cycle and it is likely for the platoon to cross the next intersection without stopping. If the current

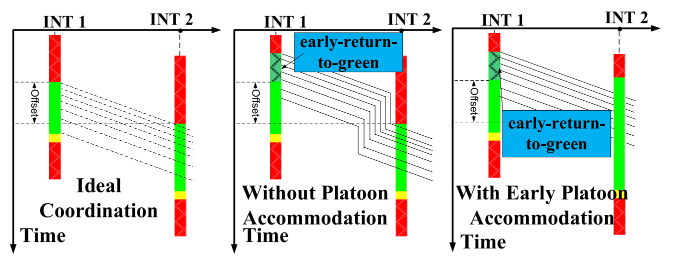

Fig. 5. Platoon accommodation.

mainline phase at the downstream intersection is red, it will be truncated to ensure the mainline green starts before the platoon arrives and increase the probability that the platoon crosses the downstream intersection without stopping. Fig. 5 shows the concept of platoon accommodation.

When the mainline red needs to be truncated, the current greens on minor approaches are reduced as:

$$g_i = \max(0.5g_{i0}, G_{\min,i} + y_i + r_a) \tag{9}$$

where:

- g_i: green duration after adjustment;
- g_{i0}: programmed max green duration;
- $G_{\min,i}$: minimum green of phase i;
- y_i: yellow time; and
- r_a: all red clearance;

In case that the current green time on the minor approach exceeds the reduced green time, the current green will be terminated immediately.

When a queue spillback, the mid-block loops will be occupied by vehicles for a long time. As a result, the loop's presence channel will be constantly on a LOGIC ON while the counting channel has zero counts (we assume each queue detectors are accommodated with both presence channel and count channel). In that case, a queue spillback occurs. If the green on a minor approach maxed out with the last cycle, or the corresponding queue detector is currently occupied, this phase will not be shortened for the platoon accommodation. If the subject phase gaps out with the last cycle (either under the programmed maximum green or shortened maximum green), its programmed green will be shortened to favor the mainline progression when needed.

C. NTCIP Communication Stack and Dynamic Objects Design

To accommodate the aforementioned control functions, the necessary NTCIP objects as summarized in Table I.

1) Periodical Signal Timing Adjustment: The base signal timing is implemented in the coordination mode. In each coordination pattern, there is a split pattern, cycle length and offset. Whenever the optimization module in the SBC generates new timing plans, the communication module in the SBC will send the new signal timings to the ASC/3 emulator(s) using STMP "GET" or "SET" messages containing the above OIDs.

TABLE I
COLLECTION OF NTCIP OBJECTS NECESSARY FOR THE PROPOSED CONTROL FUNCTIONS

Function Name	Required NTCIP Objects
Periodical Signal Timing Adjustment	SystemPatternControl PatternCycleTime PatternOffsetTime PatternSequenceNumber SplitTime SplitMode SplitCoordPhase:
Max-out Identification	PhaseStatusGroupReds PhaseStatusGroupYellow PhaseStatusGroupGreens PhaseStatusGroupWalks PhaseStatusGroupDontWalks PhaseStatusGroupPedClearanc
Queue Identification	VehicleDecectorStatusGroupActive
Platoon Identification	VehicleDecectorStatusGroupActive SystemPatternControl PatternSequenceNumber SplitTime SplitMode SplitCoordPhase

2) Platoon Identification: The platoon identification is based on the high-resolution events of pulse detectors. To capture such events, it is necessary to continuously poll the corresponding detector channels. The frequency of such polling must be equal to or higher than 10 Hz to avoid missing any high-voltage events.

3) Phase Max-Out Identification: Several OIDs of phase status should be polled continuously so as to understand the green usages of each phase. If the actual minor-street green within a cycle is equal to the programmed values, it means a max out occurs.

4) Queue Identification: If a queue detector is on LOGIC ON constantly, it means a queue has spilled back.

5) Platoon Accommodation: Whenever the downstream intersection needs to respond to an approaching platoon, the control logic will replace the current coordination pattern with a new coordination pattern with the same cycle length and offset but different signal timing. The new timing plan will have shorter greens on the minor streets and longer mainline green(s) consequently. As a result, the current greens on the minor approaches will be forced off and the mainline green(s) will start before the platoon reaches the intersection. After the current cycle ends, the original coordination pattern will be restored. Since the cycle length and offsets are not changed, this method can prevent the controller from the lengthy process of coordination recovery.

VI. CASE STUDY: SIMULATION STUDY ON THE 124TH STREET CORRIDOR IN EDMONTON, CANADA

The aforementioned adaptive signal control logic is also practicable in the real world. In this section, a simulation-based case study is conducted to evaluate the potential benefits of

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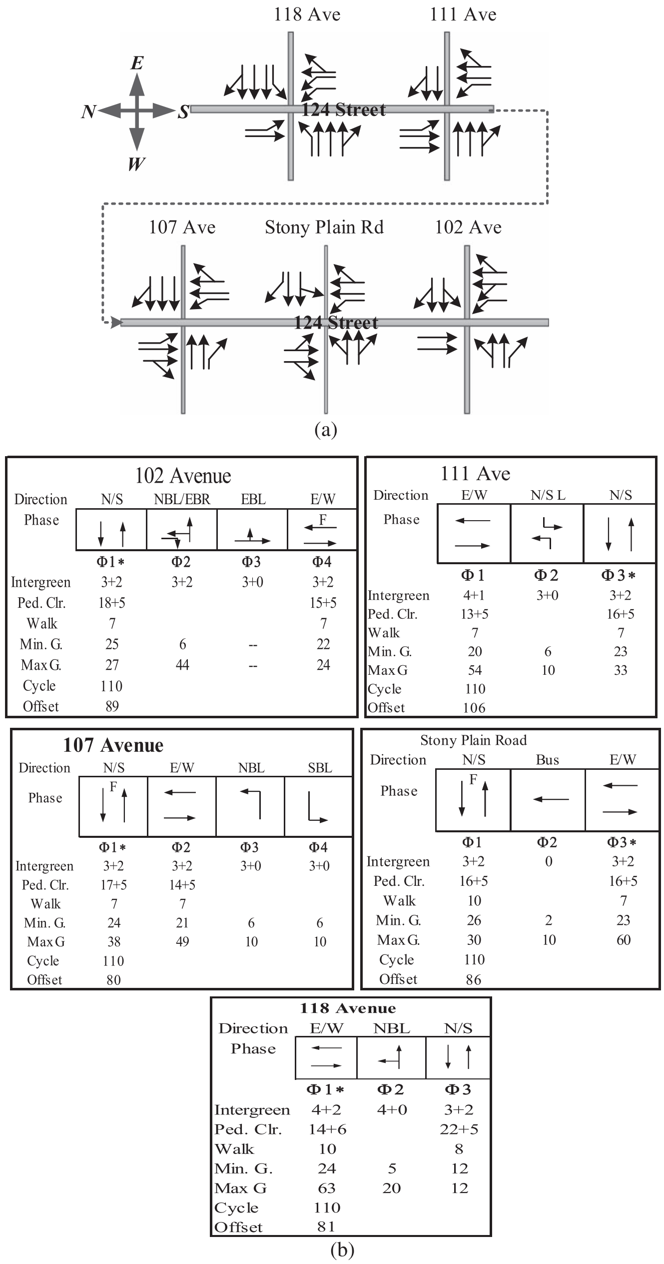

Fig. 6. Road layout and signal configuration on the 124th street.

the new control strategies. The selected road segment is 3.22 kilometers long with five coordinated intersections on the 124th Street in Edmonton. The actual signal timings in Fig. 6 were just optimized with SYNCHRO 7 by the City of Edmonton according to the turning movement counts as in Table II. As such, it was assumed that the baseline signal timings shown in Fig. 6 were optimal and any improvements in traffic mobility were counted on the new control strategy.

A. Simulation Model Calibration

Simulation models must be well calibrated before evaluation. Two elements were considered for the calibration: the link travel time and turning movement counts at the intersections. The calibration results of all five intersections are very similar and therefore we only show one as an example. From Figs. 7 and 8, the link travel time and the turning movement counts based on individual vehicle records at one major intersection are highly consistent with the field observation. Therefore, the simulation model was valid for evaluating the new control strategy.

TABLE II
TURNING MOVEMENT COUNTS AT THE PM PEAK HOURS

	Approach: North			Approach: East		
	L	T	R	L	T	R
118 Ave	84	196	27	76	1480	148
111 Ave	121	790	124	3	1223	116
107 Ave	1	1028	325	0	530	213
Stony Plain Rd	66	509	67	1	1845	159
102 Ave	No LT	306	86	14	305	72
	Approach: South			Approach: West		
	L	T	R	L	T	R
118 Ave	401	278	128	24	1185	231
111 Ave	135	619	56	98	407	94
107 Ave	223	701	36	147	383	63
Stony Plain Rd	98	599	53	34	664	57
102 Ave	1163	279	5	53	98	607

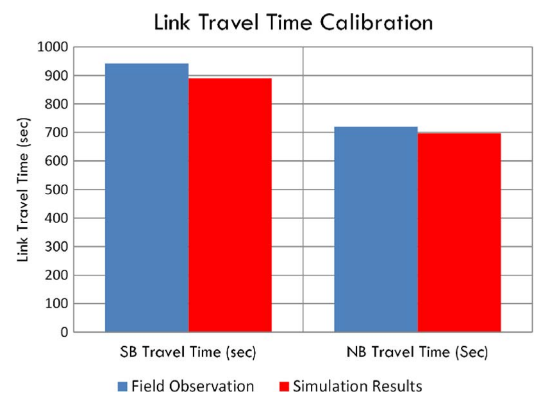

Fig. 7. Link travel time comparison between simulation and the field observation.

B. Performance Evaluation

In order to make the new control strategy fully functional, it is necessary to place additional mid-block detectors. The minimal distances from stop lines for the mid-block detectors on the main line were determined by the distance a vehicle could travel after it passes the advance detectors. In this case, the minimal distances were calculated as the 85 percentile speed [31] multiplied by 20 seconds. As for the mid-block detectors on the minor approaches, they were placed either right after the upstream intersections or empirically. The new control strategy did not optimize the cycle length, programmed offsets and phasing sequence in this case study.

The simulation model ran 10 times under the baseline signal timing and the new control strategy respectively. The selected system MOEs included the link travel time and total stops on the 124th Street. From Table III, the link travel time and total stops were both reduced. In other words, the mainline progression was improved under the new control strategy according to the simulation results.

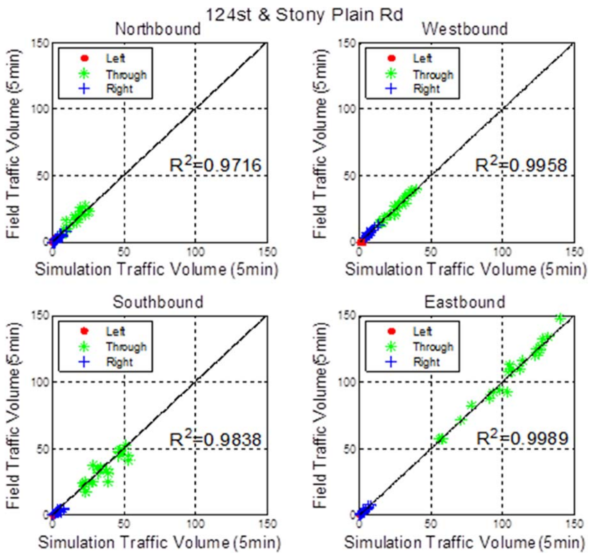

Fig. 8. Turning movement counts comparison between simulation and the field observation at the stony plain road.

TABLE III
SYSTEM EVALUATION OF THE NEW CONTROL STRATEGY

	NB Link Travel Time (sec)	SB Link Travel Time (sec)
Baseline	720	942
ACS	647	886
	NB Total Stops	SB Total Stops
Baseline	3,342	5,437
ACS	2,978	4,895

The performance of the new control strategy was also evaluated at individual intersections. From Table IV, it is clear that the control delays at all intersections were reduced by 6% to 33%. The intersections at the 118th Avenue and Stony Plain Road had less reduction of mainline delay and less reduction of maximum queue length than the other intersections. However, those two intersections also had low v/c ratios on the other approaches. It means less cycle failures on the other approaches. Such differences were caused by the platoon identification and accommodation. After the signal timings were optimized according to the latest traffic, the control delays and v/c ratios of each lane group would be optimal and last until the next time of timing optimization. The new control strategy was more responsive to the short-term traffic fluctuation compared with the traditional actuated coordination. Nonetheless, even though the periodical signal timing optimization can achieve improvement, the mainline platoons may be still released earlier than schedule due to the early return to green, degrading the mainline traffic progression. When a platoon was identified, the control strategy truncated the greens on the minor approaches. Although such efforts further reduced the mainline delays and queue lengths, the remaining queues on the minor approaches had to wait until the next cycle and the v/c ratios on the minor approaches were, consequently, increased at the 111 Avenue, 107 Avenue and 102 Avenue.

TABLE IV
EVALUATION OF THE NEW CONTROL STRATEGY AT INTERSECTIONS

MOE	Main line delay	Main line max queue	Max minor v/c ratio	Total control delay at intersections
124 Street at 118 Ave				
Baseline	34.4	83.3	0.85	35.8
ACS	32.68	77.47	0.81	31.86
Improvement	5%	7%	5%	11%
124 Street at 111 Ave				
Baseline	50.5	113.3	0.73	53.3
ACS	32.68	77.47	0.87	35.86
Improvement	35%	31%	-19%	33%
124 Street at 107 Ave				
Baseline	37.6	63.4	0.74	39.2
ACS	30.24	57.69	0.91	33.02
Improvement	19.5%	9%	-23%	16%
124 Street at Stony Plain Rd.				
Baseline	43.94	65.3	0.73	38.45
ACS	42.62	57.46	0.72	31.53
Improvement	3%	6%	1%	18%
124 Street at 102 Ave				
Baseline	69.5	74.3	0.89	71.34
ACS	59.69	63.9	0.93	67.06
Improvement	14%	14%	-4%	6%

Lastly, the mainline green durations were also analyzed with the simulation outputs. The purpose of this analysis is to identify whether the platoon identification function is important. From the log file saved in SBC, the platoon identification function was frequently called during the simulation and as a result, the effective mainline greens at some intersections were significantly longer than the programmed values as shown in Table V. Especially when the traffic on side streets is low, early returns to green on the mainline occurred a lot. Once the early return to green occurred at one intersections, most the downstream intersections triggered the platoon accommodation algorithms within the scope. By contrast, at those intersections with no platoon identification, the changes were mainly caused by the periodical signal timing adjustment and they were relatively insignificant. As such, it was concluded that the platoon identification and responding plays an important role in the new control strategy.

TABLE V
EVALUATION OF THE NEW CONTROL STRATEGY AT INTERSECTIONS

Intersections	118 Ave	111 Ave	107 Ave	Stony Plain Road	102 Ave
Cycle	110	110	110	110	110
Programmed offsets	43	106	80	36	89
Baseline programmed Green (NB)	32	33	38	30	71
Baseline Programmed Green (SB)	12	33	38	30	27
NB Effective Green	34	47	56	32	85
SB Effective Green	15	63	56	32	85

VII. CONCLUSION REMARK AND FUTURE WORK

In this paper, a new concept of hardware-in-the-loop traffic signal simulation framework, referred to as HILS-NG, is presented. The HILS-NG framework extends the current software-in-the-loop (SILS) and hardware-in-the-loop (HILS) signal simulation and places the control logic in a hardened single board computer (SBC). The HILS-NG framework can greatly bridge traffic signal research and practice because the same host SBC can be coupled with both simulation and the traffic signal controller in the field.

Compared to the other signal simulation platforms, the proposed HILS-NG framework in this paper does not require hardware control interface devices (CID) or hardware signal controllers. And computing on highly-powered SBCs and data exchange between SBC and controller (or emulator) are also suitable for fast-pace simulation environment. In other words, it addresses two major issues in the hardware-in-the-loop traffic signal simulation: Expensive equipment requirements and slow simulation speed. In addition, this framework will not compromise the safety of signal systems because the SBCs are only supplemental and will not completely replace the existing traffic controllers.

To demonstrate how to design non-conventional control logic and how to design the corresponding NTCIP dynamic objects, a set of adaptive signal control strategies is designed as well as evaluated in simulation. The new HILS-NG prevents fundamental changes to the existing signal system and can guarantee safety in the field.

Although in this paper we focus on how to facilitate researchers to try out their signal research efforts in the field, the proposed HILS-NG framework can go beyond that scope. In essence, new control logic does not have to always stay with SBCs in the field. It can also be hosted in a central traffic management system and remotely access traffic signal controllers in the field via reliable and low-latency network connections. In that sense, the proposed framework is the same helpful to practitioners to explore more innovative traffic management measures in the practice.

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