Stochastic Optimization of Group-based Signal Control and Coordination Using Traffic Simulation

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ABSTRACT

Among advanced signal controllers being deployed in urban areas, group-based signal control has become increasingly prevalent due to its ability to display flexible phases according to real-time traffic conditions. On the other hand, closely-spaced intersections are commonly operated in coordination to provide traffic progression on arterials. In many cities, coordinated signals run in an actuated mode and are based on stage-based phasing techniques while group-based signal control is usually operated in isolation. This paper proposes a feasible approach, from a practical standpoint, to coordinate group-based control in the context of LHOVRA. LOHVRA is a typical actuated group-based signal control which is widely applied in Scandinavian countries. In addition, a computational framework is implemented to facilitate optimal signal plans with respect to different policy concerns. An enhanced genetic algorithm is proposed and integrated into the optimization framework capable of accelerating the process of finding global optimum. In order to analyze impacts of group-based control and its coordination, a network in Sweden consisting of two intersections is used as a test bed. Performances of signal controls are evaluated by using an open-source microscopic traffic simulation model, SUMO. Comparison results of various optimized signal controls reveal that the use of group-based control has potential benefits in improving traffic mobility and sustainability. More importantly, it is recommended that policy makers consider signal coordination of LHOVRA control in planning and management practice so as to improve the efficiency of transportation system.
1. INTRODUCTION

Signal control is one of the most used facilities to operate traffic movements in an efficient mode. Generally, strategies of signal control are summarized from two different perspectives: signal timing and signal phasing. Settings of signal timing are adaptive to real-time traffic demands in many modern signal systems. In terms of methods for allocating signal phases, a growing number of group-based signal controllers have been applied in parallel to continuous development of stage-based controls. In addition, closely spaced intersections are usually coordinated for the purpose of generating a ‘green wave’ on arterials so that vehicles are able to progress through several signalized intersections without stopping. If lengths of signal time are flexible in such coordinated system, some specifications are required to ensure that the aforementioned feature of progression is not disrupted.

It’s long been understood that signal control schemes have profound impacts on transportation system. Theoretically, coordinated-actuated controls are capable of improving traffic mobility (1) and group-based signal control systems outperform the controllers that work with stage-based phasing techniques in many aspects (2). These benefits are mainly contributed by the flexibilities in allocations of signal times and signal phases. In order to further improve operational efficiency of signal system in practice, great attentions should be paid to the methods that optimize control parameters with respect to predetermined objectives. Previous studies have witnessed that stochastic search algorithm is recognized as a success in solving signal optimization problems (3, 4).

Microscopic traffic simulation plays a crucial role in evaluating impacts of signal controls due to its cost-effective feedback mechanisms, in a consistent accuracy, between control parameters and performances of transportation system. Despite traffic simulation is regarded as a favorable tool, utilization of its internal signal emulators of simulator is far from sufficient to implement all of the existing signal controls. One way to overcome this limitation is to apply software-in-the-loop simulation, in which high-fidelity traffic simulator is interacted with virtual and portable signal controller through a software interface.

In Scandinavian countries, LHOVRA, a typical group-based and actuated signal control, is widely deployed for isolated systems (5). Thus, extensive interests in impact analysis of such group-based control, particularly for network-wide operations, have been attracted. Few studies have proposed the method to coordinate group-based signal control. To this end, this paper attempts to make efforts to bridge the gap between group-based control and signal coordination. Specifically, coordination features for group-based control are explored and proposed in this study. Assessments of signal controls are carried out by using an open-source traffic simulator, SUMO (6). More importantly, appropriate signal parameters, according to various policy goals, are generated with the aid of stochastic optimization algorithm.

The remainder of this paper is organized as follows. Relevant works are investigated in the next section. The section after that presents principles of group-based signal control in the context of LHOVRA control. Then, optimization framework is described and an enhanced genetic algorithm, focusing on improvements on computational efficiency, is introduced in details. Finally, the proposed methodologies are applied to test-based experiments. Findings about impacts of a group-based control, LHOVRA, and its coordination are elaborated and discussed.

2. LITERATURE REVIEW

As a general trend in the development of stage-based control, recent research efforts are focused upon actuated control coupled with signal coordination. It was reported that some specifications are necessary to be specified in coordinated-actuated systems. In this regard, Sunkari et al. (7) summarized advanced coordination features for actuated signal systems, and Abbas et al. (8) introduced a transitioning algorithm to determine offset value for such systems. Besides, Day et al. (1) indicated that it is more advantageous to apply fully actuated coordinated phases compared with the scenario that coordinated phases are non-actuated.

Evaluations of already implemented group-based controls have been performed as field studies as well as by the use of traffic simulation. For example, Tang and Nakamura (9) quantified the operational benefits that group-based control brings to transportation system, in comparison to stage-based control, through Monte Carlo simulation. Furthermore, some studies adopted more detailed simulations to analyze group-based control. For instance, Young and Archer (10) investigated safety effects of a group-based controller (LHOVRA) at an isolated intersection using microscopic traffic simulation. They managed to program LHOVRA toolbox into VISSIM (commercial simulation software). It is, nevertheless, not a generic way to implement signal control in traffic simulator, particularly in the case that signal controllers are incorporated with additional features. To provide sophistication and variety of control operations, Koone et al. (11) presented a direct way, namely hardware-in-the-loop simulation (HILS), to evaluate signal plans. This is followed by Bullock et al. (12) who laid out a framework providing a reference for the application of hardware-in-the-loop simulation. Recently, some disadvantages of HILS have been observed in
research practice, for example, HILS are unable to run much faster than real time and require separate controller hardware for each intersection. Software-in-the-loop simulation (SILS), hence, becomes popular in research community. Literally, role of hardware controller in HILS is replaced by the software implementation of control logic under SILS environment.

Over the past decade, meta-optimization algorithm, such as genetic algorithm (GA), has stood out as a well-suited approach to solve optimization problems regarding traffic signal control systems. Some comparison results show that signal controllers optimized by GA performed better than the case that their signal plans are generated by traditional optimization tools, e.g. Synchro and TRANSYT (3, 4). Such stochastic optimizer, however, requires lots of computational resources. Recent studies investigated the possibility of reducing computational time. For example, Park and Lee (14) implemented shuffled frog-leaping algorithm under distributed computing environment while Jin and Ma (15) based the optimization framework on parallelized traffic simulation. Besides, various analyses of various policy goals have been taken into account in traffic signal operations. Stevanovic et al. in (16) optimized signal strategies to find the lowest fuel consumptions and CO\textsubscript{2} emissions by applying simulation-based optimization framework integrated with a micro-scale emission model, CMEM (17). In addition, Ma et al. (18) implemented a model-based framework to study the trade-offs among various objectives (e.g. travel delay, number of stops, and environmental impacts) through a real-world case study.

In (2), Wong et al. first came up with the ideas of optimization of signal strategies for group-based signal controllers. They used a macroscopic program to mimic the operation of group-based control and further optimized signal plans concerning about network performance on traffic mobility. To our knowledge, little effort has been put in optimizing signal parameters of group-based controls concerning various policy objectives, especially in a coordination case.

3. COORDINATED LHOVRA CONTROL

LHOVRA was initiated motivated by improving the efficiency of road safety and reducing delays at intersections (5). Extension signal of LHOVRA is determined by so called gap seeking algorithm. An extension signal is firstly active when the responsible detectors are occupied. During the extension time, the same vehicle can reach the following detector or another vehicle can reach the same detector. The extension signal will not be authorized if there is a sufficient time gap between vehicles or maximum green time of the active signal group has been used. Otherwise, active signal will be extended continuously. In addition, LHOVRA also employs six additional user-defined functions. Each of the letters in the LHOVRA acronym represents a unique functionality. L, H, O, V, R and A represent truck/bus priority, major road priority, incident reduction, variable yellow, red light infringement and all-red rest state, respectively. All of these functions can be used in a combination mode or individually. Among these additional functions, incident reduction function is the mostly used function in urban areas.

3.1 Group-based phasing

The basic unit of LHOVRA control is signal group. Signal group is defined as a collection of traffic lights which always show the identical indication. Usually, signal group is associated with a single movement or a small group of the movements with a same inbound direction. A phase is a set of signal groups that can proceed concurrently without conflicts between major movements. Some movements are allowed to proceed during a phase even though they cause conflicts. For example, pedestrians are commonly allowed to proceed across intersections even though right-turn movements are occurring. Figure 1(a) gives an example to depict how group-based signal control provides flexible phase structure. In this figure, traffic demands are larger in east-bound and north-bound approaches compared to the other approaches. Phase duration is represented by the length of rectangular, which is usually determined by traffic demand on the controlled approach (see Figure 1(a)). Accordingly, lengths of rectangular are relatively longer with respect to signal groups with larger demand. Traffic movements are combined based on the lengths of signal groups so that the phase sequence is displayed in Figure 1(a).
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 FIGURE 1  Mechanisms of group-based signal phasing.

(a) Example of signal phases generated by group-based phasing approach.

(b) A typical example of conflict matrix.

In the operation of LHOVRA control, once minimum green time of an active signal group is elapsed, green time of such signal group can be extended. During the extension period, the corresponding signal groups cannot be ordered to be terminated. If an active signal group does not satisfy the requirements of a further green extension, alternative signal groups will be registered to be activated. In principle, only non-conflicting signal groups can be activated at the same time so that the alternative signal groups cannot conflict with the other active signal groups in the current phase. Conflict matrix is used to represent the conflicts between signal groups. Figure 1(b) shows a typical example of conflict matrix. Gray squares basically represent that signal groups cannot be served simultaneously. As long as there are not any requests being received to active alternative signal groups, green signal can remain and such status is named as passive green. The requests are sent by detectors which are responsible for the approaches controlled by alternative signal groups. When a request of pending to activate the alternative signal groups is received, activation of alternative signal groups still have to wait until terminating signal groups pass the clearance time period. In Figure 1(b), the exact clearance times are assigned to gray squares in this conflict matrix. In the case of multiple conflicting requests, a sequence of signal groups (see the left-hand side of Figure 1(b)) is used to determine which signal group gets activated first.
3.2 Incident reduction function

Literally, incident reduction (O) function was designed for the purpose of improving safety efficiency. This function tends to reduce number of stop-or-go decisions made by drivers when they are caught in the dilemma zone at the onset of the amber signal. Correspondingly, risks of red driving and rear-end collisions can be decreased by applying incident reduction function. Incident reduction function is executed by delaying an imminent change to amber indication when vehicles are detected in dilemma zone. The continuation of green past the end of normal green time is called as past-end green (PEG). In effect, traffic mobility, nevertheless, may be reduced because only few vehicles caught in dilemma zone are able to enjoy the extension green time while vehicles on the other directions have to wait in the meantime.

Figure 2 illustrates the principle of incident reduction function with the aid of a space-time diagram. In this space-time diagram, two short detectors and one long detector are designated by their distance from stop line. In the definition of LHOVRA control, dilemma zone is identified and fixed. Dilemma zone is bordered by the maximum distance at which a driver could pass before the onset of red under a specific speed environment and the minimum stopping distance from stop line. For example, the area between detector D130 and detector D80 is defined as dilemma zone in Figure 2. If vehicles happen to drive in dilemma zone when green time is ordered to terminate, PEG is possible to be authorized to allow these vehicles to evacuate. Criteria of authorization of PEG extension are based on time gaps between incoming vehicles. For example, if vehicles arrive at detector D130/D80 with shorter headways than a predefined gap threshold, green signal will be extended. The vehicles, thus, are able to reach to D80/10 within the extension time period. Besides, indications of traffic light will keep green if vehicles are detected on the long detector, D10.

3.3 Signal coordination

In this section, a feasible approach to operating LHOVRA in signal coordination is proposed based on the principles introduced in literature. Through which coordination between actuated stage-based controllers is achieved. A specification, namely force-off mode, is applied to ensure that signal controllers return to coordinated groups at proper time points. When force-off mode is on, every signal group has to be ready to be terminated before a specified time point. Such time points are defined as force-off points. In other words, forces-off points determine the pre-programmed maximum green times of signal groups for LHOVRA. Basically, six main requirements of coordinated LHOVRA control are designed to guarantee that the progression feature of coordination is not disrupted.

1. Master intersection is defined and coordination direction is specified in advance.
2. Offset value, representing the beginning of signal relative to master intersection, is pre-determined for each intersection.
FIGURE 3 Demonstration of group-based control in signal coordination.

3. Programmed maximum cycle lengths are defined and identical for all intersections in coordination system.
4. Signal group is ordered to be terminated before the associated force-off point irrespective of when it starts.
5. Excess green time of a signal group is allowed to transfer to the subsequent signal group.
6. At one intersection, if the corresponding signal controller returns to coordinated group before the other controllers, signal’s indications will keep steady state and no detections will be reported until all of signals in system are terminated for the current cycle. On this basis, coordinated signal groups can always start at the same time points.

An example in Figure 3 is given to demonstrate requirement 4, 5 and 6. Figure 3(a) represents the signal groups used for both intersection A and B. Signal group Sₙ of intersection B is coordinated with the counterpart of intersection A. Two timelines are used to visualize the phase sequences of both intersection A and intersection B in a cycle. The timelines are drawn based on their own local clocks.
Requirement 4: Signal group $S_3$ at intersection A has to be ordered to terminate before force-off point, $P_{A3}$, even though there are still traffic demands remaining on this traffic movement.

Requirement 5: There exist excess demands for signal group $S_2$ at intersection A. After $S_2$ gaps out, green time is reallocated to the following signal group $S_4$.

Requirement 6: At intersection B, signals return to the coordinated group, $S_1$, earlier than the signals at intersection B. At intersection B, traffic lights keep green and no detections are reported until signals return to coordinated signal group $S_1$ (see red dash rectangular in Figure 3(b)).

4. SIMULATION-BASED OPTIMIZATION OF SIGNAL PLAN

4.1 Overview of computational framework

Although similar framework has been established in literature, this study applies software-in-the-loop simulation (SILS) framework (see the upper part of Figure 4) to evaluate performances of signal control system. In this framework, SILS consists of a discrete-time based microscopic traffic model (SUMO version 0.19.0), a virtual signal controller (LHOVRA coded in Python) and an interface that allows for mediation between them. Detailed implementation of SILS can be viewed in (19). Evolutionary Optimizer is a group of search methods inspired by metaphor of natural evolution process. Performance Estimator is used to generate various performance measurements. For example, CMEM emission model and mobility calculator are respectively applied to estimate performance on traffic sustainability and mobility. In present study, an enhanced genetic algorithm is integrated into this optimization framework. Procedure of this optimizer will be demonstrated in the next section.

Data flow of the optimization framework is described in Figure 4. Optimization process starts with Evolutionary Optimizer, sending initial population of signal parameters to SILS program, in which signal controller communicates with traffic simulator step by step. During the simulation period, vehicle trajectories data are registered in memory. Subsequently, dynamic traffic characteristics are treated as the inputs to Performance Estimator when the execution of traffic simulation is completed. According to the pre-defined optimization objective, performance index regarding mobility or environmental impacts is calculated and then summarized using received traffic characteristics. Thereafter, the estimated performance measures are returned to the optimizer so as to generate new signal parameters for further optimization. The whole process is repeated until the termination criteria are finally met. As reported by previous work, the optimization process is often limited by large computing requirements. Therefore, traffic simulation runs are parallelized in this application with the idea of allocating the computational intensive tasks to different processes and this method is detailed described in (15).
4.2 Enhanced genetic algorithm (EGA)

The basic procedure of genetic algorithm is that optimizer starts from a randomly-generated initial population of feasible solutions, moving towards the global optimum. To create a new population, GA normally performs selection, crossover and mutation operators. Successive generations adapt from previous ones while parents of less fitness are selectively eliminated. However, GA might converge to the local optimum or even an arbitrary point rather than the global optimum in practice. The likelihood of such occurrences depends on the size and quality of the space being explored. Enhancements in globally searching are twofold. Firstly, randomly-distributed initial population, covering global search space, is created by applying Latin Hypercube (LH) sampling algorithm (20).
This process is proven to ensure that the resultant population spans the entire exploration space, being free from any bias, and is sufficiently random. On the other hand, Srinivas (21) demonstrated that values of crossover probability and mutation probability play a significant role in the size and quality of search space. To be specific, the higher the probabilities are the bigger searching area is covered. Adaptive probabilities are, thus, applied in EGA to increase the spread of the search space during evolution.

As a matter of fact, the actual time spent by GA in performing selection, crossover and mutation can be regarded as negligible in signal optimization problem, compared with the total traffic simulation time. Motivated by such fact, some enhancements are performed to reduce total number of traffic simulations (evaluation functions) required to find the global optimum. In (22), AMGA uses of a very small population size together with an external archive that stores the best found solutions. It has been shown that a very small-size population helps to reduce the number of evaluation functions required to attain the desired convergence whilst an external archive can store a large number of better solutions to approximate the best solution accurately. On this basis, similar ideas are implemented in this GA-based optimizer. EGA works with a very small size of population but maintains a large size of an external archive, namely elitism storage. The elitism storage is updated by newly-created elite individuals with relatively better fitness values during the process of evolution.

Detailed procedure of EGA is described in Figure 5. At the beginning, inventory database is created for storing the ever evaluated results so that evaluation of duplicated sets of signal parameters can be avoided. Thereafter, initial population is generated by LH sampling. Fitness values of the initial population are estimated by running traffic simulations in parallel. Followed by that, solutions in initial population are copied to the elitism storage and also saved in the database. In the beginning each generation, a handful of good solutions, namely micro elitism solutions, are extracted from elitism storage and used as a part of parent population. The following process is to manipulate the parent population. Each individual in micro elitism solutions is in turn to be used as one parent to reproduce children with another parent that is randomly chosen from elitism storage. Basically, these two selected parents are required to be mutually different. Here, individual set of signal parameters are described by a string of bits. Therefore, binary encoding transforms signal parameters from integer to a string of bits (0 or 1) before the further manipulations of population can be carried out. The encoding scheme was originally proposed by Ceylan and Bell to represent chromosomes of signal parameters into binary strings with a pre-defined bit size (23). The lower bound value corresponds to all zero digits while the upper bound value corresponds to all one digits and the value between them are linearly scaled and associated to corresponding binary strings. Uniform crossover and bit-flip mutation are used to produce offspring population. Each part of the father’s bit string is possible to be swapped with the counterpart of the mother’s bit string in uniform crossover process. Bit-flip mutation produces spontaneous random changes in various bit strings and such changes are represented by inverting the bit (0 changes to 1 and vice versa). After reproducing the new population, chromosomes are inversely decoded from bit string to integer, interpreted as signal parameters. To get fitness values of the new population, evaluation results are either estimated by traffic simulations or extracted from the inventory database. EGA iteratively updates a population of signal parameters until the termination criteria are finally satisfied. When the whole evolution is done, optimal solution, indicated by the fitness value, is eventually generated from the elitism storage.

5. TEST-BED EXPERIMENTS

The practical experiments were performed for a network in Stockholm, Sweden. This network consists of a pair of connected intersections, Hornsgatan-Ringvägen and Hornsgatan-Rosenlundsgatan. Configuration of these two intersections is displayed in Figure 6. Traffic lights located at these two intersections are maintained either by LHOVRA controls in isolation or by fixed time (FT) control in coordination. All traffic simulations were performed for a 60-minutes interval, excluding a warm-up period of 15 minutes to prevent from initial loading effects. Once the process of simulation-based optimization was completed, the best signal plan was evaluated through 30 randomly seeded traffic simulations.

The case study firstly aims to examine the potential benefits brought by group-based control so that the optimized isolated stage-based VA control is used to compare with the optimized isolated LHOVRA control. Two criteria, average travel delay and fuel economy, are concerned. In addition, two optimized real-world control systems (isolated LHOVRA and coordinated FT) are compared with each other from traffic mobility, environmental impacts and safety perspectives. Moreover, the proposed coordinated LHOVRA control is optimized and compared to these real-world operations of signal control, isolated LHOVRA and coordinated FT. The same inputs of traffic demand and same settings of traffic models are implemented for comparison purpose. Hornsgatan-Ringvägen intersection (shown on the left) is defined as the master node in signal coordination system.
5.1 Optimization formulation

Formula for optimizing coordinated LHOVRA control is explained in this section while the other formulations for the involved controllers can be viewed in (19). Objective function can be generalized as follows because performance of transportation system is associated with a set of signal parameters and a set of random seeds when other inputs to traffic simulation model are constants.

\[ \min_{\lambda, C, \theta, x, \rho} J(\lambda, C, \theta, x, \rho) \]  

where

\[ J = \text{objective functions, e.g. travel delay, fuel economy;} \]
\[ \lambda = \text{a vector of pre-programmed maximum green times;} \]
\[ C = \text{pre-programmed cycle length;} \]
\[ \theta = \text{a vector of offset values;} \]
\[ x = \text{a vector of other inputs to traffic model, e.g. traffic demand, other signal parameters;} \]
\[ \rho = \text{a vector of random seeds.} \]

The constraints follow:

\[ \lambda_{ij} \leq \lambda_{ij} \leq \lambda_{ij}^{\text{max}} \]  
\[ C_{\text{min}} \leq C \leq C_{\text{max}} \]  
\[ \theta_{\text{min}} \leq \theta_{ij} \leq \theta_{ij}^{\text{max}} \]  

where

\[ \lambda_{ij}, \lambda_{ij}^{\text{min}}, \lambda_{ij}^{\text{max}} = \text{the value, lower bound and upper bound of maximum green time for } j^{\text{th}} \text{ signal group at intersection } i, \text{ respectively;} \]
\[ C, C_{\text{min}}, C_{\text{max}} = \text{identical value of pre-programmed cycle length, the upper bound of pre-programmed maximum cycle length and the lower bound of pre-programmed maximum cycle length;} \]
\[ \theta_{ij}, \theta_{ij}^{\text{min}}, \theta_{ij}^{\text{max}} = \text{the value, lower bound and upper bound of offset at intersection } i, \text{ respectively.} \]
5.2 Computational results and discussions

For the sake of analyzing the influences of group-based signal controls on transportation system, evaluation results of optimal signal plans are summarized in Figure 7 (a). Previous work indicated that there is an obvious trade-off between travel delay and fuel consumption in signal optimization problems (18), which can also be observed in the experiments. It is seen that solutions minimizing fuel economy and travel delay at the same time do not exist. On the other hand, it was explained in section 3.2 that incident reduction function of LHOVRA may reduce traffic performance on mobility. However, the resultant minimum travel delay of optimized isolated LHOVRA control is still lower than the counterpart of isolated stage-based VA control. To be specific, in comparison to the optimization results of VA control, LHOVRA control can make vehicles save 1.0%, or more, travel time if optimal signal parameters are used. This phenomenon may be caused by group-based mechanism, in which phase duration is better utilized due to flexible signal phase assignments.

Additionally, significant benefits regarding improvement on energy efficiency, 4.3% fuel saving, are observed if fuel economy is set as optimization objective for LHOVRA control compared with the case that average fuel consumption is minimized when stage-based VA control is implemented. As what have been addressed in literature (24), O function in LHOVRA control is likely to make some contributions to the above finding. In (24), Wu et al. considered the following situation: If the driver decides to proceed when he/she is in dilemma zone and subsequently finds that he or she cannot pass through the intersection before the signal changes to red. He or she, hence, must apply hard braking to stop the vehicle. Their study revealed that such unnecessary hard braking is a
rapid release of fuel consumption. As introduced in section 3.2, the purpose of \( O \) function is to reduce number of vehicles in dilemma zone. As a consequence, executing \( O \) function may, in return, improve energy efficiency of transportation system.

In Sweden, it is common that LHOVRA control is applied for isolated systems while signal coordination is achieved by adopting fixed time (FT) controls. Optimization results of real-world operation schemes are displayed in Figure 7 (b). Notable differences in performance on traffic mobility cannot be observed between optimized LHOVRA and optimized coordinated FT controllers when minimizing average travel delay is regarded as the policy goal. It may become one motivation to promote FT control with coordination in real-world operation because of the required high cost in installation and maintenance of LHOVRA controller. However, this study shows an impressive perspective on reducing fuel consumption when LHOVRA is deployed. As we can see from the figure above, the gain in fuel efficiency is around 5% when average fuel economy is minimized for LHVORA control compared to the case that coordinated FT control is operated and average fuel consumption is used as optimization objective. Thus, there is another trade-off, between the monetary costs and beneficial effects brought by LHOVRA, need to be considered by decision makers.

One expectation in this study is that the proposed coordinated group-based control has potential benefits to traffic system. On this basis, coordinated LHOVRA is compared to real-world operations, isolated LHOVRA and coordinated FT. The optimization results shown in Figure 7 (b) are in line with this expectation. In dependent of which one of average delay and fuel consumption is selected as optimization objective, coordinated LHOVRA control exhibits significantly better performance over all the others in the experiments. For example, about 3.0% reduction of travel time in average for vehicles is brought by optimized LHOVRA control in coordination compared to non-coordinated LHOVRA control, when average travel delay are minimized for both control schemes. Besides, optimal signal plan of coordinated LHOVRA control leads to around 100 gram fewer fuel uses per hundred kilometers per vehicle in study network than optimized LHOVRA control in isolation when fuel economy is regarded as policy goal. Therefore, a well-planned and operated LHOVRA control in coordination will be superior among these three control schemes in the aspects of traffic mobility and sustainability.

6. CONCLUSIONS

In this paper, we have proposed an approach to coordinate group-based controllers. Performances of signal controls on mobility and sustainability are evaluated by means of software-in-the-loop simulation (SUMO-based) integrated with a micro-scale emission model (CMEM). Also, a computational framework is outlined for the design of optimizing signal control strategies. This framework bases its optimization on the proposed enhanced genetic algorithm. Two aspects of enhancements of this optimizer have been emphasized on in this study, one is the capability of exploring search space and the other is the ability to fast converge.

Test-based experiments are carried out to quantitatively document the potential improvements of group-based control. In this effort, the optimization results mainly reveal the following findings:

- Benefits of traffic mobility brought by group-based mechanism can compensate the extra delay caused by execution of incident reduction function of isolated LHOVRA control.
- When energy efficient is the policy goal, isolated LHOVRA control significantly save fuel consumption of transportation system if the corresponding optimal signal plan is in used.
- Without reinventing the signal system at the study intersection, signal coordination of LHOVRA control has the potential to further improve traffic efficiency in terms of traffic mobility and sustainability.

In addition, this simulation-based framework shows its ability to optimize signal plans through experiments, especially for group-based control as well as in its coordination mode. It is ultimately a political concern to decide which signal controller is better to be deployed and what signal plans of the selected controller should be implemented in traffic planning and management practice. The proposed computational framework can be used as a tool to help policy makers to make such decisions.

In present work, the case study is limited to two intersections while one of them is a T-intersection. The authors’ future research interest is forwarded to address more sophisticated corridors or grid networks using this proposed computational framework. Note that even the optimal signal strategies are acquired, signal plans are proper if and only if the traffic pattern is steady and uniform. Therefore, robust control will be investigated in future study as well. Moreover, the effectiveness and robustness of proposed enhanced genetic algorithm will be further tested and thereafter applied to multi-objective optimization methods in the future.
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