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Research Article

Optimal Signal Control Algorithm for Signalized Intersections under a V2I Communication Environment

Eum Han,[1] Hwan Pil Lee,[2] Sangmin Park,[3] Jaehyun (Jason) So,[4] and Ilsoo Yun [3]

[1] Department of Traffic Safety Facilities and Enforcement System, Korea Road Traffic Authority, Wonju-si 26466, Republic of Korea
[2] Corporate Strategy and Policy Research Division, Korea Expressway Corporation Research Institute, Hwaseong-si 18489, Republic of Korea
[3] Department of Transportation System Engineering, Ajou University, Suwon-si 16499, Republic of Korea
[4] Division for Smart City and Transport, The Korea Transport Institute, Sejong-si 30147, Republic of Korea

Correspondence should be addressed to Ilsoo Yun; ilsooyun@ajou.ac.kr

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This study aims to develop an optimal signal control algorithm for signalized intersections using individual vehicle's trajectory data under the vehicle-to-infrastructure (V2I) communication environment. The optimal signal control algorithm developed in this study consists of three modules, namely, a phase group length computation module, a split distribution module, and a phase sequence assignment module. A set of analyses using a microscopic simulation model, VISSIM, was conducted for evaluating the effectiveness of the V2I-based optimal signal control algorithm proposed in this study. The analysis results show that the performance of the V2I-based optimal signal control algorithm is superior to the actuated as well as the fixed signal control methods in an isolated intersection and a 2X3 signalized intersection network. In addition, this study investigated the minimum market penetration rate of V2I equipped vehicles for which the V2I-based optimal signal control algorithm is applicable.

1. Introduction

1.1. Background and Purpose. Traffic congestion has been a critical issue in our automobile-centered modern society for a long time. Many urbanized areas have also suffered from chronic socioeconomic damage owing to growing traffic congestion. To address urban traffic congestion, traditional alternatives to increase road capacity, such as new buildings and road network expansion, are necessary. However, such alternatives have certain limitations in solving congestion, such as the need for large capital investment and the lack of land availability for construction. The Intelligent Transport System (ITS) has been deployed and operated since the 2000s. Various efforts have been trying to promote the efficiency of the existing transportation facilities utilizing diverse ITS services. For example, COSMOS, which is an advanced traffic responsive control system using loop detectors, has been developed and applied to some major cities in Korea. Recently, a variety of adaptive traffic signal control systems based on loop and image detectors are being operated worldwide. Some traffic signal control systems try to use the insights provided by artificial intelligence (AI). Nonetheless, it is still a challenge to reduce congestion and prepare for the expected change of the traffic environment in the near future using the existing traffic signal control system [1]. At present, the ITS has been expanded rapidly to the next stage, called the Cooperative ITS (C-ITS) taking advantage of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Certain nations have already utilized V2V/V2I communication technologies in various traffic applications. As a result, many studies have specifically focused on traffic safety through vehicle-to-everything (V2X) technology between road and vehicle, but research efforts on the V2X-based traffic signal control system have not yet been succeeded in overcoming the chronic congestion at signalized intersections.

Therefore, there has been a strong demand to address traffic congestion using C-ITS technologies such as V2X. To this end, this research aims to develop a real-time and optimal signal control algorithm for a signalized intersection under a V2I communication environment.

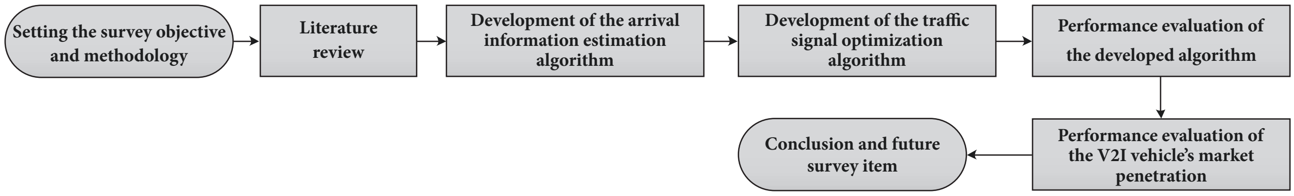


Figure 1: Research procedure.

1.2. Methodology and Research Procedure. Traditional signal control methods have utilized various macroscopic variables, such as queue length and average control delay, using complex models or simple equations for computing optimal signal timing. Beyond this traditional approach, this study proposes a new approach based on the V2I communication and its capability in collecting vehicles' trajectories. Under the V2I communication environment, movements of individual vehicles can be traced using a basic safety message (BSM). The BSM is used to exchange vehicle status information using Dedicated Short Range Communications (DSRC) readers (typically roadside equipment, RSE) allowing the data collection of vehicles' movement and location information along a specific segment of road [2].

With this benefit of V2I communication in mind, the proposed algorithm in this study predicts the arrival time of individual vehicles based on the subject signal control and estimates the stopping delay at each approach in a short-term period. Note that the vehicle's stopping delay can be estimated if the vehicle's arrival time to the end of a queue and the traffic signal phase status are known.

For the details of the proposed methodology in this study, a vehicle arrival information estimation algorithm based on raw data collected through the V2I communication environment is firstly developed, and short-term movements of individual vehicles at a certain road section are estimated based on the vehicle arrival estimation algorithm. Second, an optimal signal control algorithm is developed. This consists of three modules, namely, a phase group length computation module, a split distribution module, and a phase sequence assignment module. Last, the performance of the V2I-based signal control algorithm proposed in this study is evaluated using a microscopic traffic simulation model, VISSIM, in which various traffic environments can be realized. In order to assess the benefit of the proposed algorithm compared to the traditional signal control methods, the performance of the V2I-based signal control algorithm is compared with those of the fixed signal control method and actuated signal control method. Furthermore, the effectiveness of the proposed algorithm is evaluated under different market penetration rates of V2I-equipped vehicles. Finally, this study investigates the minimum market penetration rate of V2I-equipped vehicles in which the V2I-based signal control algorithm performs well. Figure 1 shows the study procedure utilized in this study.

2. Literature Review

The traditional ITS data collection method is to gather vehicle information using a variety of technologies while the vehicle passes through a certain point (e.g., a loop detector). However, under the C-ITS technology, individual vehicle's location information can be collected in real-time through the communication between the on-board unit (OBU) in the car and RSE. In addition, information can be transmitted through the vehicles in the communication boundary. The first is referred to as vehicle-to-infrastructure (V2I) communication and the latter is called vehicle-to-vehicle (V2V) communication. The term vehicle-to-everything (V2X) includes both these types of communication. The information of the collected individual vehicles can be utilized for traffic operation and traffic safety. Therefore, there have been many research efforts on utilizing the data collected from V2X in traffic operational applications.

Kattan et al. [3] investigated the impact of the presence of V2V vehicles on the entire transportation network. Specifically, they focused on measuring the quantitative impact of vehicles involved in an accident, on the traffic network. They proved that the accident occurrence rate was decreased when the proportion of V2V vehicles increased.

Stevanovic et al. [4] applied the Green Light Optimized Speed Advisory (GLOSA) application. This system uses real-time and accurate information about traffic signal timings and traffic signal locations to guide drivers via V2I communication with speed advisories, to enable more uniform movement with less stop time at traffic signals. A traffic network consisting of two intersections was modeled and calibrated in VISSIM. Higher penetration rates and more frequent GLOSA activation resulted in better traffic performance than fixed-time signals.

Goodall et al. [5] applied the rolling horizon algorithm to assign the signal phase while estimating the vehicle location by a short interval, thereby measuring the platoon's move and waiting time. This algorithm optimizes the objective function on a future 15-s interval and assigns a phase based on the result. The objective function can be defined as a combination of delay, number of stops, acceleration, and other factors. As a result, the proposed method performed better than general actuated signal control. However, it is difficult to achieve reliable performance under saturated and oversaturated traffic conditions. The algorithm showed better operation results from the perspective of delay and number of stops when the market penetration of connected vehicle exceeded 50%.

Kesur [6] used a modified genetic algorithm to verify that an individual cycle for each intersection is more efficient than a mixed cycle in the aspect of network management, even though there is a difference in the number of vehicles passing at each intersection. This result was contrary to existing research results, which state that using individual cycles in a network is an unreasonable method for the network management. However, it potentially indicates that it should be possible to apply traffic demand signal control at each intersection if enough vehicle information was available.

Feng et al. [7] suggested a real-time actuated traffic signal control algorithm based on connected vehicle's data. The optimal signal control algorithm was divided by upper and lower levels; the upper level consisted of forward and backward recursion. This algorithm's objective function was the minimization of total delay and queue length. In order to estimate arrival information, EVLS (Estimation of Location and Speed) was adopted. The analysis result showed that total delay and queue length was decreased under 100% market penetration. When the market penetration was at least 50%, the algorithm could operate effectively. It was also found that the error would decrease by the growth of connected vehicle occupancy rate in case of high demand.

Minelli et al. [8] evaluated the effectiveness of the connected vehicles among the mode choice and transportation network mobility. The evaluation step consisted of mode choice and traffic assignment. The analysis illustrated that the average travel time of all vehicles decreased as the number of connected vehicles increased. It was estimated that this phenomenon was owing to the dynamic travel guidance system.

Blokpoel and Vreeswijk [9] proposed the use of probe vehicle data in traffic signal control. In this study, they explained two limitations of traditional loop detectors as follows: First, traditional sensors like inductive loop detectors have significant installation and maintenance costs. Second, the prediction of the vehicle dynamics is limited due to the fixed locations of the detectors because loop detectors provide only point data based on vehicles passing or occupying the loops. In the study, they introduced a cooperative vehicle—infrastructure technology which provides detailed information of approaching vehicles as they frequently transmit a Cooperative Awareness Message (CAM) containing all required relevant information, including GPS data. Based on the data from CAM, they propose three algorithms that estimate queue length for each signal group. The first algorithm uses GPS data only. The second algorithm uses information of the traffic light status and determines the queue length at the start of green by using a model of the wave speed of accelerating vehicles. The last algorithm combines traditional stop-line detection with cooperative detection to estimate queue length. The three algorithms showed better performance than the traditional queue estimation method, about 30% reduction in delay time.

Choi et al. [10] developed the cumulative travel-time responsive (CTR) algorithm for guaranteeing nonstop passing at the intersection that secured and extended the "green phase on" time against vehicle's arrival under a V2X environment. This algorithm adopted the Kalman filter for applying it to the low market penetration of V2X vehicle. By the analysis result, the CTR algorithm was operated ordinarily in the case of market penetration 50–60%.

Varga et al. [11] propose an approach that reduces the aforementioned problems, improves the performance of Traffic Signal Controlling Systems (TSCSs) by decreasing the vehicle waiting time, and subsequently reduces their pollutant emissions at intersections. In this approach, a combination of V2V and V2I communications is used. The main traffic input for applying traffic assessment in the approach is the queue length of vehicle clusters at the intersections. The evaluation results show the superiority of the proposed approach. As a result of literature review, it was found that there have been active research efforts on the real-time traffic signal control. However, many research efforts did not specifically define the data type and contents which would be used in their development. Recently, BSM has been considered as the standard message set for autonomous vehicles and C-ITS applications. This study will use the BSM set as a basic input for the real-time traffic signal control which will be developed in this study.

Xu et al. [12] proposed a cooperative method of traffic signal control and vehicle speed optimization for connected automated vehicles, which optimizes the traffic signal timing and vehicles' speed at the same time. In the optimization of the traffic signal timing, they calculated the optimal traffic signal timing and vehicles' travel time to minimize the total trip time of all vehicles. For the optimal speed of individual vehicles, they optimized the engine power and brake force to minimize the fuel consumption of individual vehicles. The enumeration method and the pseudospectral method are applied in roadside and on-board optimization, respectively. Based on results simulation, they insisted that there was a significant improvement of transportation efficiency and fuel economy by using the cooperation method, especially for small and medium traffic demands.

As a result of the literature review, it was found that the majority of early studies focus on the optimal control of the traffic signal using the probe vehicle information produced in the V2X communication environment and the various algorithms. Recently, it has been confirmed that many study efforts are trying to combine not only traffic signal control but also safety service such as vehicle speed harmonization by using probe vehicle information.

3. Algorithm Development

3.1. Algorithm Configuration. The V2I-based signal control algorithm proposed in this study utilizes the information that is collected from individual vehicles that are approaching an intersection under the V2I communication environment. This information is written in the format of BSM. BSM is a standard message set established by the Society of Automotive Engineers (SAE) in terms of SAE DSRC J2735. It includes vehicle ID, collected time, vehicle location, speed, moving direction, acceleration, and vehicle length, as listed in Table 1. However, the information in BSM does not include data related to traffic trajectory because the vehicle trajectory is a security related subject for protecting privacy information by the National Highway Traffic Safety Administration (NHTSA) [13]. BSM can be transmitted by the V2I communication between RSE and OBU. In this study, BSM transmission is assumed to be available all the time.

The V2I-based signal control algorithm consists of two parts, namely, the arrival information estimation algorithm

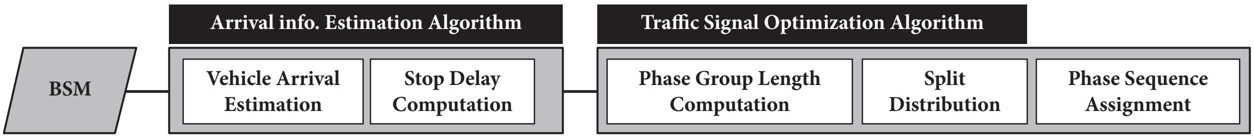


FIGURE 2: Configuration of the V2I-based signal control algorithm.

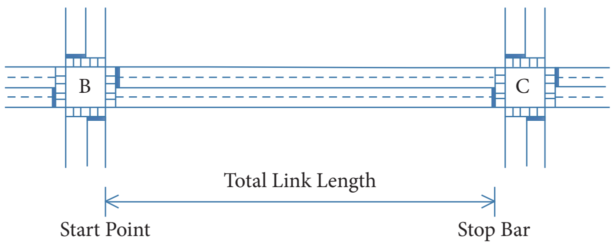


FIGURE 3: Coverage of the total link length.

TABLE 1: Basic information for BSM.

Basic Description
Message Sequence Number
Temporary ID
Time
Position Latitude, Longitude, Elevation, Accuracy
Vehicle Speed, Heading
Vehicle Acceleration
Vehicle Length

Source: SAE J2735 DSRC Message Dictionary

and the traffic signal optimization algorithm. Each algorithm has certain associated modules as shown in Figure 2.

3.2. Arrival Information Estimation Algorithm. The arrival information estimation algorithm is intended to produce the input variables for the traffic signal optimization algorithm. This algorithm consists of the vehicle arrival estimation module and stopped delay computation module.

Vehicle Arrival Estimation Module. The vehicle arrival estimation module estimates the arrival information of individual vehicles in each approach through vehicle ID, speed, approaching direction, and location in BSM data. The procedure is as follows: The first step is to identify the driving lane for individual vehicles (i.e., vehicle i in (1)) using location data given in BSM of individual vehicles. In order to detect the driving lane, it is necessary to compare the GPS coordination of the vehicle with the intersection's geometric data in detailed digital map for autonomous driving.

The second step is to compute the distance remaining up to the stop-line for individual vehicles. The intersection's start point is set at zero and the stop-line sets the total link length as shown in Figure 3.

And then, the module calculates the distance up to the stop-line. The third step is to estimate the queue length of the lane where vehicle i is running. The queue length can be obtained by subtracting the location of the last vehicle in the queue from link length. However, in an actual scenario, there may exist some stopped vehicles owing to an unforeseen incident in the approach. Therefore, the sum of the vehicle lengths in the queue and the waiting length are compared. If the two values show a significant difference, the sum of the vehicle lengths is considered as the length of the queue in this step. This step can contribute to the reduction of the estimation errors even when the V2I market penetration is less than 100%. The last step is to estimate the arrival time of vehicle i at the end of the queue. The arrival information can be computed at every second by (1).

$$\mathrm{AT}_i = \frac{DR_i^{j,k} - QL^{j,k}}{v_i}, \tag{1}$$

where

AT_i is the arrival time of vehicle i on the stop-line or the tail of the queue in seconds,

v_i is the current speed of vehicle i in m/s,

$DR_i^{j,k}$ is the remained distance of vehicle i at k lane in j link in meters,

$QL^{j,k}$ is the queue length of k lane, j link in meters.

It should be noted that the accuracy of location is assumed to be correct enough for the estimation. In reality, there may be some problems in collecting the exact GPS coordinates of individual vehicles based on current infrastructure. However, the accuracy of the GPS coordinates has been continuously improved due to recent positioning technology development. Therefore, it is expected that highly accurate GPS information can be utilized at the time when the autonomous vehicle or C-ITS is introduced in real roads. For example, Meng et al. [14] proposed a global navigation augmentation system based on low earth orbit communication constellation. In the system, the low orbit satellites can serve both as space-based monitoring stations and as navigation information broadcasting sources. For the navigation precision augmentation for GPS, an additional navigation augmentation signal is broadcasted to realize global precise point positioning with sub-meter positioning precision level in dynamic mode and sub-decimeter precision level in static mode.

3.2.1. Stopped Delay Computation Module. The stopped delay computation module estimates the stopped delay in each approach or heading direction based on the result of the vehicle arrival estimation module. The vehicle arrival estimation module estimates the status of all the vehicles every second, so the stopped delay is the number of summations of stopped vehicles on each approach every second. In addition, the stopped delays of all approaches will be aggregated in the interval of 30 seconds. This module uses the number of accumulated waiting vehicles for 30 seconds using (2).

$$SD_{30}^{j,k} = \sum_{t=0}^{30} n_t^{j,k} \tag{2}$$

where

$SD_{30}^{j,k}$ is the total stopped delay for 30 seconds of k lane, j link,

t is the time in seconds, $t = 0$ denotes the present time,

$n_t^{j,k}$ is the number of total waiting vehicles at time t of k lane, j link.

3.3. Traffic Signal Optimization Algorithm. The traffic signal optimization algorithm consists of the phase group length computation module, split distribution module, and phase sequence assignment module.

3.3.1. Phase Group Length Computation Module. The phase length computation module aims to attain the maximum green time, which is able to minimize the delay of each phase group. Webster suggested a cycle length estimation method through computing the length of each group or approach [15]. In this module, the optimal phase group length uses the maximum value between the values of the Webster method and the summation of the minimum green time for each phase in the group, as expressed in (3). Here, the NEMA means the National Electronic Manufactures Association, which is the largest trade association of electrical equipment manufacturers in the United States. The NEMA established the hardware and software specifications related to the traffic signals and traffic signal controllers. For example, according to phase numbering as defined by NEMA, the phase numbers of the major street are phases 2 and 6. In addition, in (3), the total lost time is determined in a way proposed in the Highway Capacity Manual [16].

$$x_{g1}^{max} = \max\left(G_{min}^{p_2} + G_{min}^{p_6}, \frac{1.5 \times L_{g1} + 5}{1 - \sum_{i=1}^{n} y_{g1}}\right) \tag{3}$$

where

p is the phase sequence number of the NEMA phase, and P_2 and P_6 means the through movement for the major streets,

G_{min}^{p} is the minimum green time of phase number p,

x_g^{max} is the maximum allowance time of group g,

L_g is the total lost time of group g,

$\sum_{i=1}^{n} y_g$ is the summation of the saturation flow rate for group g.

3.3.2. Split Distribution Module. The split distribution module calculates the phase length. The ratio of through and left-turn volumes is used to distribute the split using the expected next 30 seconds' arrival vehicle volume. In detail, the through phase length can be calculated by (4) at first and then it is subtracted from the maximum length of the phase group in order to make the left-turn phase length. Here, the 30 seconds' expected traffic volume (n_i^T) is calculated in the vehicle arrival estimation module.

$$G_{max}^{T} = \max\left[G_{min}^{T}, \left(x_g^{max} \times \frac{n^T/n_i^T}{n^T/n_i^T + n^L/n_i^L}\right)\right] \tag{4}$$

where

G_{max}^{T} is the maximum through phase green time of the NEMA phase ring combination,

G_{min}^{T} is the minimum through phase green time of the NEMA phase ring combination,

n_i^T is the 30 seconds' expected traffic volume of the NEMA phase ring combination,

n^T is the number of through lanes of the NEMA phase ring combination.

3.3.3. Phase Sequence Assignment Module. The arrival information estimation algorithm can predict the vehicle arrival time and queue length in the short term so that the algorithm is able to produce resulting stopped delays according to the change in the phase sequence based on the phase group length and split. The phase sequence can be determined by the stopped delay for the maximum green time of each phase. Each phase sequence is assigned by (5).

$$\min\left(\mathit{firstphase}\ T,\ \mathit{firstphase}\ L\right) \tag{5}$$

where

$\mathit{firstphase}\ T = \sum_{t=0}^{G_{max}^{T}} SD_t^L + \sum_{x_g^{max}-G_{max}^{T}}^{x_g^{max}} SD_t^T + [1.63 \times (n_{t=0}^{T} + n_{t=G_{max}^{T}}^{L})]$,

$\mathit{firstphase}\ L = \sum_{t=0}^{G_{max}^{L}} SD_t^T + \sum_{x_g^{max}-G_{max}^{L}}^{x_g^{max}} SD_t^L + [1.63 \times (n_{t=0}^{L} + n_{t=G_{max}^{L}}^{T})]$,

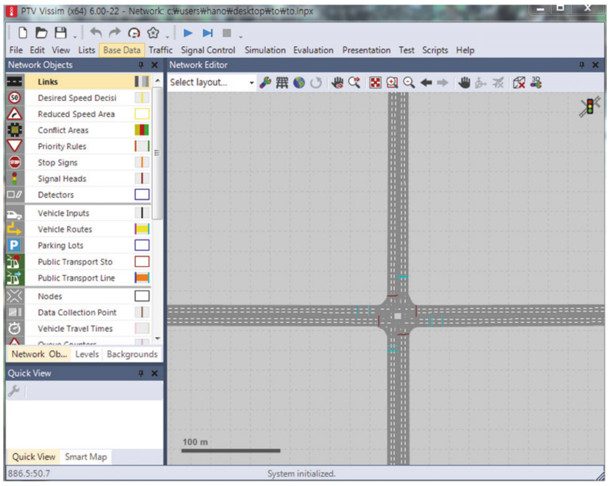
SD_t^L is the stopped time day of time t,

$n_{t=0}^{T}$ is the number of stopped vehicles in the through direction at present,

1.63 is the average departure lost time.

4. Algorithm Evaluation

4.1. Simulation Implementation. The V2I communication is available at limited areas in Korea and the number of V2I vehicles is not sufficient for the proposed signal control in these days. With this limitation, a microscopic simulation model was utilized to implement the developed signal control algorithm and evaluate the performance. For the microscopic



(a) Isolated intersection

(b) 2X3 signalized network

Figure 4: Simulation networks.

traffic simulation model, VISSIM, which is capable of realizing various traffic environments and signal controls and evaluating the mobility and safety impacts of the applied traffic alternatives, was selected. The analysis consists of three steps.

First, a comparison between the V2I-based signal control algorithm proposed in this study and the fixed and actuated traffic control methods was conducted in terms of the mobility measures such as delay and speed, in order to verify the suitability of the V2I-based signal control algorithm in an isolated signalized intersection. Second, the same comparison was conducted in a 2X3 signalized network consisting of six signalized coordinated intersections. Finally, the performance was analysed with respect to market penetration changes in V2I equipped vehicle occupancy in the isolated signalized intersection.

For the first comparison, the hypothesized traffic simulation network including three lanes in each approach was developed in VISSIM ver. 9.0 as shown in Figure 4(a). For details of simulation configurations, each lane was assigned to left-turn, through, and right-turn movement, respectively; the traffic control variables were obtained by Synchro, which is a traffic signal optimization program; and the actuation was activated after minimum green time in the actuated signal control mode. Furthermore, in order to replicate the data collection under the V2I environment, the individual vehicle data (e.g., location and speed) extracted from the VISSIM COM Interface is fed into the V2I-based signal control algorithm that is utilized by Visual Basic, and the V2I-based signal control algorithm then computes the signal control variables and sends it back to VISSIM in this study.

In the case of the 2X3 network consisting of six signalized coordinated intersections, which is located at the city of Anyang near to Seoul as shown in Figure 4(b). The surrounding area is urbanized and is a somewhat congested network when commuting.

4.2. Evaluations

4.2.1. Comparison with Existing Traffic Control Methods in an Isolated Intersection. Various evaluation scenarios as presented in Table 2 were set to compare the performance of the V2I-based signal control algorithm proposed in this study with existing traffic control methods in different levels of service (LOS) in the network. The measures of effectiveness (MOE) are average control delay, average stops, average stopped delay, and average network speed for the simulation network. It is noted that the traffic volume for each LOS was determined using Synchro and Highway Capacity Manual.

As shown in Table 2, the V2I-based signal control algorithm performs better than those of the fixed control method and actuated control method. This is because the V2I-based signal control algorithm can change the phase length and phase sequence according to the fluctuation in traffic patterns, by taking advantage of individual vehicles' information. The actuated control method provides the left-turn's force-off time to the through movement phase. On the other hand, the V2I-based signal control algorithm changes the phase sequence based on the expected through and left-turn traffic volumes, thus ensuring more precise and efficient signal control. For the performance comparison, the V2I-based signal control algorithm decreased average network control delay in the range of 4% and 69% in all LOS scenarios. Under the fixed signal control, queued vehicles that cannot pass the intersection in a cycle are accumulated in the LOS F, and traffic congestion is worsen as the cycle goes. However, the actuated control and the V2I-based signal control algorithm did not take place a congestion at first, so there is not a significant difference as shown under the column of average network control delay in Table 2.

4.2.2. Comparison with Existing Traffic Control Methods in 2X3 Signalized Network. In the 2X3 signalized intersection during Peak hour, the performance of the proposed signal and the proposed algorithm is analysed. The results are shown in Table 3 . When the fixed signal control was applied in the network, the network average delay was 94.43 seconds. However, when the algorithm developed in this study was applied, it was confirmed to be 65.26 seconds, resulting in 30.9% reduction. The average number of network stops per vehicle was 1.78 when the fixed signal was used. It can be seen that the proposed algorithm is lowered by

Table 2: Simulation result for each control method in an isolated intersection.

Control methods	Level of services	Average network control delay (s)	Network average stops (freq.)	Average network stopped delay (s)	Average network speed (km/h)
Fixed signal control method	B	24.49	0.59	19.50	33.74
	C	25.61	0.62	19.52	33.18
	D	29.78	0.64	21.99	32.55
	E	38.03	0.69	30.12	28.25
	F	100.35	1.70	69.58	15.64
Actuated signal control method	B	16.63	0.53	12.07	38.36
	C	20.33	0.59	14.37	36.13
	D	25.72	0.64	18.70	33.30
	E	28.22	0.69	20.36	32.03
	F	43.49	0.85	32.19	29.37
Developed algorithm	B	14.69	0.49	10.56	39.61
	C	18.00	0.55	12.65	37.32
	D	24.30	0.67	17.33	33.39
	E	27.16	0.65	19.85	32.45
	F	31.36	0.69	22.75	30.56

Table 3: Simulation result in 2X3 signalized network.

Measures of Effectiveness	Network Average Delay	Average Number of Stops	Average Speed
Fixed Signal Control	94.43 sec/veh	1.78 stops/veh	20.02 km/h
Developed Algorithm	65.26 sec/veh	1.74 stops/veh	24.66 km/h

1.74. Likewise, the average speed increased by 23.1% from 20.02 km/h to 24.66 km/h, improving network mobility as a whole as presented in Table 3.

4.2.3. Minimum Market Penetration Rate of V2I-Equipped Vehicle. The V2I-based signal control algorithm proposed in this study would have technical difficulty in its operations if the market penetration does not reach 100%. At first, the queue length would be inaccurately estimated due to lack of individual vehicles' information, if the market penetration is under 100%. To consider the impact of market penetration rate, various market penetration rate scenarios were implemented in the simulation environment as shown in Table 4. In order to reflect the market penetration rate, as many vehicles as the market penetration rate were randomly selected during simulation runs.

As a result, in all market penetration rate scenarios, the algorithm developed in this study performed better in terms of network control delays compared to the existing fixed signal control method. However, when compared with the actuated signal control method, the algorithm shows a higher delay value in the 25% market penetration scenario. In addition, the overall performance of the V2I-based signal control algorithm decreases with a decrease in the market penetration. This is because, as the market penetration decreases, the estimation error of the predicted traffic volume in the vehicle arrival estimation module increases. This error causes the phase length selected in the phase group length computation module to be smaller than the optimal phase length. Therefore, even though there is a vehicle on the actual network, the V2I-based signal control algorithm closes the associated phase earlier. Based on the results of the analysis, we estimate the time of introduction of this algorithm. If more than 25% of vehicles capable of V2I communication exist on the network, this algorithm proves to be more effective than the existing fixed signal control method. Further, if more than 50% of vehicles can communicate with V2I, the algorithm is more effective than the actuated signal control method.

5. Conclusions

This study developed an optimal real-time signal control algorithms for the control of signalized intersections using the individual vehicles' BSM data collected under the V2I communication environment, in order to minimize traffic congestion in urban areas. The V2I-based optimal signal control algorithm consists of vehicle arrival information estimation and traffic signal optimization. A microscopic simulation was used to implement the proposed algorithms and evaluate their performance in terms of delay and LOS at signalized intersections. In addition, this study investigated a minimum market penetration rate of V2I-equipped vehicles based on the simulation results. As a result, the V2I-based signal control algorithm performed better than the fixed and actuated traffic signal control methods representing conventional signal controls; the V2I-based signal control algorithm performed better than the fixed traffic signal control when a market penetration rate was more than 25%, i.e., at least 25% market penetration could be applied; and it performed better

Table 4: Simulation results with different market penetration rates.

Market Penetrations	Level of service	Average network control delay (s)	Network average stops (freq.)	Average network stopped delay (s)	Average network speed (km/h)
100%	B	14.69	0.49	10.56	39.61
	C	18.00	0.55	12.65	37.32
	D	24.30	0.67	17.33	33.39
	E	27.16	0.65	19.85	32.45
	F	31.36	0.69	22.75	30.56
75%	B	16.16	0.52	11.61	38.42
	C	19.80	0.57	13.91	36.20
	D	25.52	0.69	18.07	33.39
	E	27.71	0.67	20.14	32.27
	F	35.81	0.79	25.86	28.62
50%	B	16.55	0.52	12.04	38.39
	C	20.28	0.58	14.33	36.16
	D	25.67	0.69	19.40	33.12
	E	28.09	0.67	20.30	32.21
	F	43.17	0.85	32.15	28.59
25%	B	19.03	0.60	13.84	36.94
	C	25.20	0.69	19.32	33.28
	D	28.40	0.66	21.27	31.73
	E	29.42	0.68	21.56	31.22
	F	54.80	1.16	38.29	22.91

than the actuated control when 50% market penetration rate was secured.

The authors believe that the V2I-based optimal signal control algorithm will be enhanced based on the capability of probe vehicle data (PVD) message beyond the BSM-based data exchange standard. The PVD is generally used to exchange vehicle status information via RSE as a message collecting information on vehicle driving behavior, and the production frequency is much longer than those of BSM, while the BSM aims only to convey safety information, with transmission period being typically 10 times per second. Therefore, the capabilities (i.e., production frequency and information contents) of PVD will be beneficial for effective traffic signal controls, and this should be investigated through further studies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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