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Research Article

Real-Time Incident-Responsive Signal Control Strategy under Partially Connected Vehicle Environment

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The performance of the traffic system can drastically drop when nonrecurrent congestion caused by incidents occurs. Early detection and clearing of traffic incidents will enable the mitigation of the congestion and early restoration of normal traffic conditions. The research in this paper utilized the vehicle information from the recent technological advancement in transportation systems, connected vehicles (CV), and loop-detector information for nonconnected vehicles (NCVs) and developed a novel algorithm to (1) control traffic signals for normal traffic conditions in the absence of incidents, (2) detect traffic incidents using CV/NCV information, and (3) control traffic signals during the occurrence and dissipation of incidents. All the 3 strategies were integrated into one algorithm, which runs as per the real-time traffic conditions, in the presence or absence of incidents. Space-mean speeds of the vehicles on nonincident lanes and throughput maximization criteria were taken as the indicators for the activation of specific signal timings directed at the incident-affected approach. Diverse incident scenarios were tested on a four-legged isolated intersection using the VISSIM simulation tool. Incident detection results showed a higher detection rate and lower mean detection time at higher CV penetration and higher traffic volumes, and at the incident locations nearer to the stop-line. The proposed incident-responsive signal control strategy at 40% and higher CV penetration showed better performance over EPICS adaptive signal control solution, in reducing average travel time delay and the average number of stops per vehicle.

1. Introduction and Background

Nonrecurrent congestion caused by traffic incidents remains a critical problem in urban areas. Traffic incidents such as vehicle collisions, vehicle breakdowns, unscheduled road maintenance, and illegally parked vehicles temporarily disrupt the traffic flow on the roadway, resulting in frustrating delays to the road users and even extending the queues to the neighbouring roads if not compensated in a timely fashion [1–3]. More than 25% of congestion is caused by nonrecurring incidents that block a part of the road section from use [4, 5]. Prompt and accurate detection of traffic incidents in real time can lead to mitigation of the congestion and early restoration of normal traffic operations of the affected roadway.

Usually, traffic on arterial streets features a greater dynamic and is subject to greater disruptions due to the influence of traffic signal control, pedestrian crossings, parking manoeuvres, bus stops, road works, etc., which can create incident-like traffic patterns [6, 7]. Due to these factors, from the past three decades, research has been dedicated to developing incident detection algorithms specifically for signalized arterials. With the availability of new vehicle detection technologies, automatic incident detection algorithms (AIDA) were developed in recent years. AIDAs use real-time traffic data, from traffic sensors such as inductive loop detectors (ILD), video-based sensors, and probe vehicles to automatically detect incidents, when abnormal changes in traffic data are identified [8].

Ahmed and Hawas [7] developed a general linear regression model, which uses a threshold value to predict the incident status. If the estimated dependent variable is higher than the threshold value, an incident is indicated. Results showed that the detection rates and false alarm rates ranged from 23% to 87% and 0% to 20%, respectively. Ghosh and Smith [9] customized three artificial neural network (ANN)-based and one support vector machine (SVM)-based freeway algorithms and applied them to signalized arterial roads to detect incidents. Volume, speed, and occupancy data from ILDs were used as input parameters to the four chosen AIDAs. Asakura et al. [10] used travel time data from probe vehicles to predict the time and location of traffic incidents, using shockwave theory. Yu et al. [11] developed a comparative incident detection algorithm using arterial travel time data from a Bluetooth-based vehicle re-identification system and one year of corresponding incident data. Historical travel time data were compared with real-time samples and unusual deviations from normal traffic behaviour were used to identify potential incidents. Oskarbski et al. [6] modified an existing highway AIDA (TRISTAR) for signalized intersections. Travel times obtained from Bluetooth and Wi-Fi detectors were compared with historical reference values, and alerts were raised using an algorithm based on a Kalman filter when significant differences were identified. Ren et al. [12] proposed a video-based method to detect and locate an incident on a road segment. Each lane was divided into a cluster of cells, and traffic states in the cells were judged by a fuzzy-identification method, and then, an SVM classifier was applied to the congested cells to detect an incident and locate its position. Gu et al. [13] combined the data sources from Twitter and incident records and employed semi-Naive Bayes classification to detect five major types of incidents. D'Andrea and Marcelloni [14] detected traffic incidents using real-time data from GPS trackers and drivers' smartphones. Initially, a traffic state was assigned to each road segment based on the speeds of the vehicles, and then, based on the spatiotemporal analysis of the road segments, traffic state (e.g., incident, slowed traffic, and blocked traffic) and the estimated speed of vehicles were determined. Results showed a detection ratio of 91.6% and an average detection time of 7 minutes. Using data from ILDs, Rizvi et al. [15] proposed a data-driven framework to detect traffic incidents in real time and to estimate road capacity and incident location. Incident was detected when variation in speed and occupancy of the traffic flow exceeds predefined threshold limits. Sheikh et al. [16] proposed an AIDA based on a lane-changing speed mechanism for highway traffic using V2I communication. When the average change in vehicle speeds during the lane-changing process takes longer than the time taken during nonincident conditions, an incident was assumed to be detected. Simulation results showed 30% faster detection compared with other methods. Zaitouny et al. [17] proposed a Quadrant Scan methodology as a tool to analyse traffic volume data to detect incidents by integrating multiple sensors' data. The proposed method also distinguishes nonrecurrent traffic congestion caused by incidents from recurrent congestion. Liang et al. [18] used surveillance video stream to detect traffic objects and proposed an algorithm to detect traffic incidents based on a spatiotemporal map of vehicle trajectories. According to the vehicle trajectory and vehicle position in each frame, the vehicle is re-identified across frames to associate the same vehicle between different frames and a global spatiotemporal map of the trajectory was generated under the current road segment. Traffic incidents such as traffic congestion, vehicle speeding, and illegal parking were analysed using the trajectory state.

Besides detecting incidents in real time, a few researchers have focussed on methods to curtail incident-induced congestion through traffic signal control, which is essential for an effective incident management system. Sheu [3] developed a stochastic optimal control-based algorithm to tackle lane-blocking incidents at isolated intersections. The proposed method controlled traffic signal timings by minimizing a time-varying cost function, which was measured based on comparing the real-time estimates of interlane and intralane traffic states with their ideal values. Lu et al. [19] developed an incident-responsive optimal signal control solution using historical and real-time volume and occupancy data collected from the sensors. Total delays around the incident location were minimized by the optimization model. Simulation results from VISSIM showed a 39.5% reduction in delay under heavy flow situations. Long et al. [20] extended a cell transmission model (CTM) and applied it to simulate incident-based jam propagation in two-way rectangular grid networks. Four control strategies were proposed based on the concept of a vehicle movement ban for dispersing incident-based traffic jam. Qi et al. [1] developed a traffic-light control system at a signalized intersection to reduce incident-based traffic congestion. By adopting additional traffic warning lights, ban signal and warning signal strategies were used to disperse the traffic congestion. Timed Petri nets were used to describe the cooperation between traffic lights and warning lights. Mao et al. [21] developed a signal control optimization method for urban networks affected by incidents. Genetic algorithm (GA) was used to minimize the total travel time of a four-intersection testbed network. Simulation results in AIMSUN showed a 40.7% reduction in total travel time compared with the incident scenario without GA traffic control optimization. Wang et al. [22] proposed a traffic signal optimization strategy to maximize the throughput of a two-phased signal control isolated intersection while restricting the queue length caused by traffic incidents. Numerical results showed significant improvement in intersections' throughput when compared to a fixed-time control. Yao and Chen [23] proposed an adaptive traffic signal control strategy that responds to traffic disruptions at an isolated intersection. Dynamic phase selection is applied to adjust the traffic signal control plan adaptively during the incident stage, while the queue length dissipation algorithm is adopted to carry out optimal green time calculation during the incident recovery stage. The proposed signal strategy was found to improve the resiliency of a typical intersection against disruptions by clearing queues faster and reducing overall traffic loss time over conventional fixed and actuated traffic signal plans.

In summary, most of the incident-related state-of-the-art literature work was focussed on developing the methods to identify the occurrence and location of incidents using fixed sensors or probe vehicle data. Quite limited research was available on real-time incident-responsive signal control for isolated intersections. Furthermore, there seems to be an opportunity for testing the potential of the latest technological advancements such as connected vehicles (CV) to tackle incident-related traffic problems.

In recent years, CV technology has been getting attention as a step towards the next generation's transportation system. Traffic signal systems under CV environment can use wireless information transactions between vehicles (V2V), vehicles and infrastructure (V2I and I2V), and vehicles and handheld devices (V2D), which are collectively referred to as V2X (vehicle to anything) communication, thus enabling the access to detailed and instantaneous vehicle information such as its speed and location [24–26]. Such real-time information has the potential to be used to detect incidents in a timelier fashion than traditional detection techniques and to support the design and operation of signal control strategies to efficiently mitigate incident-based congestion. The current main drawback of this technology is that its low penetration market makes it less beneficial to exchange CV information. According to the forecasts of Capgemini Invent [27], in 2023, 352.9 million connected cars will be on the road, which corresponds to 24% of all cars globally. At 97%, the United States is anticipated to have the highest penetration rate of CVs in 2035 [28]. Therefore, it is a forthcoming challenge to utilize this emerging technology in its early developmental stage to improve the existing transportation systems, during a time when the connected vehicle penetration takes more than a decade to reach 100% [24].

Recently, Chandan et al. [29] proposed a connected vehicle-based signal control algorithm (CVSC) for an isolated intersection, which utilized the speeds and positions of CVs, assuming 100% connected vehicle penetration (CVP). Furthermore, to tackle the real-life situations where the CVP is less than 100%, Chandan et al. [30] also presented an algorithm that utilized both ILD and CV information, to estimate the speeds and positions of the nonconnected vehicles (NCV) (those not equipped with V2X communication devices), and then fed the estimated NCV data to the CVSC algorithm, to adjust the traffic signal timings dynamically and more efficiently.

In this research work, a novel algorithm is proposed for isolated intersections that integrate a signal control strategy for normal traffic (nonincident) conditions, an incident detection method, and a traffic signal control strategy during the occurrence and dissipation of incidents. The integrated algorithm is also a distinctive feature of the subject area, since, to the best of the authors' knowledge, studies tackling both the aspects of incident detection and incident-responsive signal control were not found in the literature. The objectives of the research presented in this paper are threefold: (1) improve the signal control strategy (for nonincident conditions) developed by Chandan et al. [29] with minor upgrades, (2) develop an incident detection technique using real-time CV/NCV information, and (3) develop an incident-responsive signal control strategy under a partially CV environment. Further, we evaluate the incident detection accuracy and the performance of the incident-responsive signal control strategy on an isolated intersection using the VISSIM simulation tool.

2. Incident Types and Durations

Traffic Incident Management Handbook [31] defines an incident as "any nonrecurring event that causes a reduction of roadway capacity or an abnormal increase in demand." "Under this definition, events such as traffic crashes, disabled vehicles, spilled cargo, highway maintenance and reconstruction projects, and special nonemergency events (ball games and concerts) are classified as incidents" [32]. Most researchers obtain incident data from various traffic incident record systems from both freeways and arterial roads, where different types of incidents and their durations were recorded. Studies on freeway incidents include various incident types, such as accident, breakdown, and debris [33]; accident and disabled vehicles [34]; accident, congestion, and reckless driving [35]; collision, debris, disabled vehicle, and abandoned vehicle [36, 37]; and crashes, hazard, and stationary vehicles [38, 39].

Compared with freeway traffic, traffic on arterial roads features greater dynamic and disruptions due to the influence of signalized intersections, conflicting movements among left and right and through traffic, pedestrian crossings, frequent vehicle manoeuvres (lane change and on-street parking), public transport stops, road maintenance works, recurrent or nonrecurrent queues, loading/unloading stops, and traffic signal malfunction [6, 11, 40]. Some studies have analysed the influence of on-street parking on traffic performance [41, 42]. On-street parking manoeuvres can often block traffic for short time causing temporary bottlenecks [43] or sometimes create start-stop traffic flow behaviour on the lanes adjacent to the parking lane [44] and can reduce the road capacity by 20–30% [45]. Some studies have also analysed the impacts of roadside bus stops, which can also disrupt the traffic flow at signalized intersections [46, 47]. Buses dwelling at the bus stops to load and unload passengers may occupy a portion of a traffic lane or a bus bay and while moving into or out of the bus stop can block the traffic flow on the adjacent lane, causing excessive delays to the road users and reduction in the capacity of the intersection [13, 48–50]. Therefore, such events, which cause minor disruptions to traffic flow, are also considered as incidents in this paper.

The duration of incidents is a major factor affecting nonrecurring congestion. According to Li et al. [51], the traffic incident duration time is "the time difference between the occurrence of an incident and the clearance of the incident site." According to Highway Capacity Manual, the total incident duration is divided into four distinct time intervals, namely, detection, response, clearance, and recovery times [52, 53]. Many researchers have analysed the duration of incidents (obtained from various incident record systems) in their case studies on both freeways and urban arterials. Few studies include total incident duration, while others focussed on clearance time, a combination of response and clearance times. From the vast literature, several relevant studies corresponding to various incident types and durations are presented in Table 1.

The incident durations from various databases varied from 2 seconds (parking manoeuvre) to 120 minutes (crashes), indicating a wide distribution of traffic disruption times. Hence, the research presented in this paper developed (1) an incident detection algorithm that can detect any type of incident with any incident duration that can cause minor or major disruptions to traffic flow and (2) a CV-based traffic signal control strategy to respond to any kind of traffic incident.

3. Modelling Approach

Real-time CV information such as speeds and positions of individual vehicles is a valuable resource to detect incidents upstream of the traffic signals and develop better signal control strategies during such situations. However, the current real-life CV penetration rate will take some years to reach 100%. Under such low penetration situations, it is, thus, important to be able to detect the incidents as early as possible after their occurrence and to act under that knowledge, to minimize its impact. This section presents strategies to detect incidents and control the traffic signal times in real time, during the presence and absence of incidents. The modelling approach is divided into 3 parts, namely, incident absence connected vehicle signal control strategy (IA-CVSC), identification method of incidents' occurrence and clearance, and incident-responsive connected vehicle signal control strategy (IR-CVSC).

3.1. Incident Absence Connected Vehicle Signal Control Strategy (IA-CVSC). In this section, a CV-based signal control strategy is presented for normal traffic without incidents (therefore, the acronym IA-CVSC). The strategy is adopted from Chandan et al. [29] with minor upgrades as presented below. The objective of this strategy was to develop a traffic signal timing algorithm for an isolated intersection, which minimizes average delay and stops, considering the arrival and departure flows of all vehicles on all the approaches of the intersection at every time-step. This strategy utilizes CV data, assuming that all vehicles would share their information (such as acceleration, speed, and location) at every time-step to the signal controlling algorithm, through V2X communication devices. The algorithm obtains CV data at every time-step, from 300m before the stop-line (which is within the DSRC range of 100 m–1000 m [58]) until it crosses the stop-line. For real-world situations, where CVP is less than 100%, NCV information can be obtained through ILDs that typically exist at the upstream of an intersection. The forward movement of NCVs towards the intersection can be estimated using Gipps' car-following model, assuming that the NCVs do not change their lanes. Utilizing the CV and ILD information, Chandan et al. [30] developed a method to estimate the speeds and positions of NCVs at signalized intersections using Gipps' car-following model and it is adopted in the current modelling approach. Detectors can be placed within 100–300 m from the stop-line depending on the general queue length of the intersection, but the closer to the stop-line they are placed, the less the occurring lane changes, and, thus, the better the NCV information estimation accuracy. Here, ILDs are placed on each lane at 150 m before the stop-line. The IA-CVSC strategy (see Figure 1) is explained step-wise as below.

Step -3.1.1: CV and NCV data collection—obtain and update the arrival and departure information of CVs and NCVs from V2X devices and ILDs, respectively.

Step -3.1.2: NCV information estimation—estimate and update the forward movement of NCVs (speed and position) applying Gipps' car-following model.

Step -3.1.3: Speed ratio check—during the green phase, initially green time is provided (limiting to maximum green) until the space-mean speed of all vehicles in the current green phase reaches 90% of their desired speed. This is defined by a metric called speed ratio in equation (1). The average desired speed of the vehicles is to be calibrated in advance for any intersection. Speed ratio check ensures that all the vehicles that were in queue during the red interval are served, and the approaching vehicles are moving close to their free-flow speed, at which time the green phase is re-evaluated.

$$\text{Speed ratio} = \frac{\text{Actual space mean speed of all vehicles at current time step} \times 100}{\text{Desired space mean speed of all vehicles at current time step}}. \quad (1)$$

note that the maximum green time is taken as 1.3 times the average actual green time of the past five cycles [59]. This factor accommodates well most fluctuations in vehicle arrival rates.

Step -3.1.4: Reserve-time and throughput ratio—At the time-step when speed ratio reaches 90%, the strategy aims at maximizing the throughput of the intersection considering the cumulative arrival and departure flows on all the approaches of the intersection. This is done during the time that is remaining between the current time-step and the maximum green period, termed as reserve-time period, as shown in equation (2). Throughput ratio is calculated as the ratio of the sum of departure flows of all the phases to the sum of arrival flows of all the phases, as shown in equation (3). Throughput ratio minimizes the differences between the arrival and departure flows on all approaches of the intersection, by maintaining its value as near as possible

Table 1: Studies on incident types and duration time analysis.

Study	Incident type	Duration
Alkaabi et al. [54]	Accidents	Clearance time—26 minutes
Ahmed and Hawas [7]	Simulated incidents	Incident duration—6, 8, and 10 minutes
Hou et al. [55]	Disabled vehicles, abandoned vehicles, debris, collision, and others	Response time—9, 7, 8, 8, and 8 minutes, respectively
Tavassoli Hojati et al. [38]	Crash, hazard, and stationary vehicle	Incident duration—120, 103, and 76 minutes, respectively
Ghosh et al. [56]	Abandoned vehicle, flat tire, out of gas, clearing debris, directing traffic, towing, mechanical problems, and others	Clearance time—9 minutes
Ding et al. [57]	Disabled vehicles, abandoned vehicles, debris, collision, and others	Response time—10 minutes; clearance time—28 minutes
D'Andrea and Marcelloni [14]	Simulated incidents	Incident duration—15, 20, and 30 minutes
Shang et al. [33]	Accidents, breakdowns, and debris/pedestrian	Incident duration—27, 25, and 10 minutes, respectively
Tang et al. [37]	Disabled vehicles, abandoned vehicles, debris, and others	Clearance time—13 minutes
Chavis and Christofa [48]	Bus stop	Dwell time—40 seconds (mean); 30 seconds (standard deviation)
Ghasemlou et al. [50]	Bus stop	Dwell time—20, 30, and 40 seconds
Liang and Ma [46]	Bus stop	Dwell time—10 to 20 seconds
Liu and Jian [47]	Simulated incident—bus stop	Dwell time—35 to 55 seconds
Cao and Menendez [43]	Parking manoeuvre	Incident duration—2 to 32 seconds

to 1.0. Since throughput ratio considers the combined effect of vehicle arrivals and departures on all approaches of all phases, if the green time is extended (limiting to the maximum green period) as long as the throughput ratio is nearer to 1.0, the performance of the entire intersection can be improved reducing the congestion.

$$\text{Reserve} - \text{time} = \text{Maximum green time} - \text{Time when the speed ratio reaches } 90\%, \quad (2)$$

$$\text{Throughput} - \text{ratio} = \frac{\sum_{p=1}^{P} (\text{Cumulative departure flow})_p}{\sum_{p=1}^{P} (\text{Cumulative arrival flow})_p}, \quad (3)$$

where p = phase, P = total number of phases.

Step -3.1.5: Green phase termination check—during the reserve-time period, using the updated CV and NCV information, throughput ratio is calculated as a rolling horizon at every time-step and the green time is extended until the throughput ratio values stop increasing in comparison with the previous one or until the maximum green period is reached, whichever is earlier. Throughput ratio stops increasing as the arrival flow builds up in the other phases, at which point the current green phase is terminated and switched to the next phase.

3.2. Incidents' Occurrence and Clearance Identification Method. When an incident occurs on a lane, vehicles on that lane queue up behind the incident location, and the queue length increases, and the average speed of the vehicles on that approach decreases, or sometimes the vehicles come to a halt. If a halted vehicle does not move from its position after some threshold time, a potential incident can be supposed. During the red interval, as all the vehicles come to a halt, it is difficult to identify if the vehicles stopped due to the influence of an incident or the red signal. Hence, the incident's occurrence is identified from the start of the green interval. The step-wise incident detection procedure (see Figure 1) is explained below.

Step -3.2.1: CV and NCV information at halt—at every time-step from the beginning of the green phase, we obtain the positions of all the CVs whose speeds are 0 kmph, in each lane, and those of NCVs, if stopped on ILDs with 0 kmph.

Step -3.2.2: Incident identification—we calculate the time required for the halted CVs/NCVs to cross the stop-line, as below

$$T = L + h \cdot N, \quad (4)$$

where T is the time required for the Nth vehicle in the queue to cross the stop-line, L is the start-up lost time, and h is the saturation headway in seconds. The values

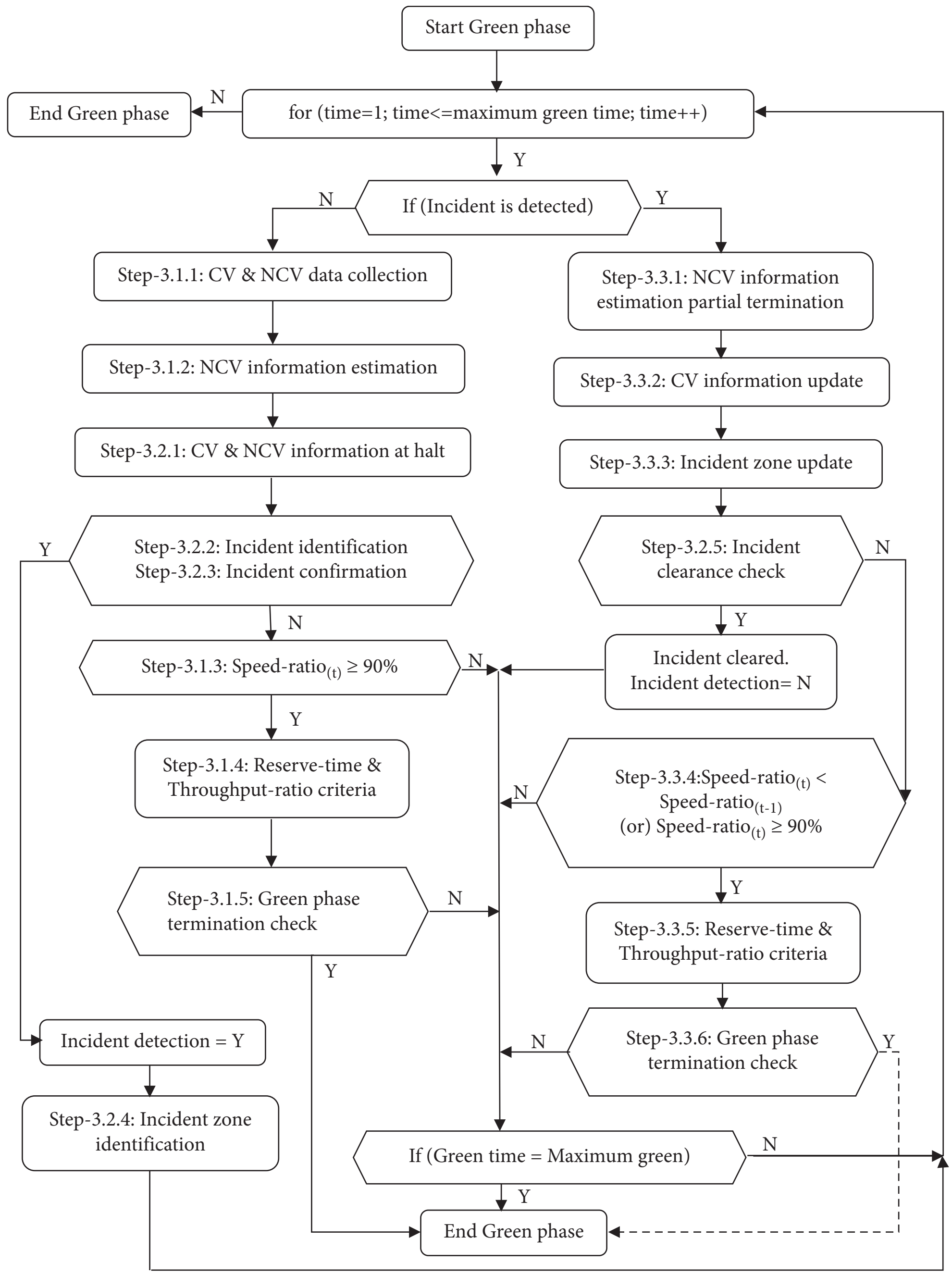


Figure 1: Integrated algorithm of IA-CVSC, incident detection, and IR-CVSC strategies.

of L and h are to be calibrated in advance for any intersection.

It is assumed that if a vehicle at a halt (during red or green interval), which can take at least T seconds to cross the stop-line, fails to move from its position within some threshold time (to be calibrated based on real-world data), incident's occurrence can be presumed on the corresponding lane. Here, a threshold time of $T/3$ seconds is assumed as an upper limit for a CV/NCV to move from its stopped position, if the traffic is normal without any incident. A longer threshold time implies higher incident detection time and vice versa, for a shorter threshold time. The halted CV's position (or NCV's position on an ILD) is checked for its forward movement, at every time-step until the threshold time irrespective of the signal state (green/amber/red). Figure 2 shows the movements and positions of different vehicles considered during the incident identification process.

If an incident occurs during the amber or red interval, the algorithm continues to obtain the information of all the vehicles and updates their positions at every time-step. During these intervals as all the vehicles slow down and come to a halt, based on the updated vehicles'

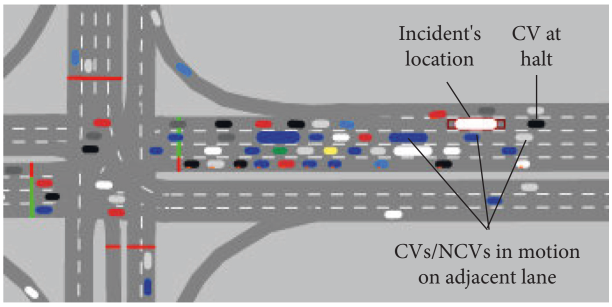


FIGURE 2: Vehicles' movements and positions during an incident.

positions, the algorithm calculates the stop-line crossing time (T) of the halted vehicles. As the halted vehicles start to move from the beginning of the green phase, the algorithm applies the threshold-time ($T/3$) criteria to check for the incidents' occurrence. If the incident occurs in the middle or end of the green interval, threshold-time criteria are applied from the time-step when a vehicle comes to a halt until the threshold time is reached irrespective of amber/red interval.

Step -3.2.3: Incident confirmation—this step is used to endorse the confirmation of the incidents' occurrence in the previous step, as well as to reduce the false alarm rate. If a CV/NCV at a halt (on the incident lane) fails to move from its position within the predefined threshold time, and if there is at least one CV (beside or behind the subject CV/NCV at the halt) in motion on the adjacent lane (see Figure 2), incidents' occurrence is confirmed.

Step -3.2.4: Incident zone identification—in this step, the proximity of the incident location, referred to as the "incident zone," is identified. Generally, when an incident occurs, the vehicles behind the incident location move to the adjacent lane and travel towards the intersection either on the adjacent lane or by moving back to the incident lane after crossing the incident's location. Therefore, a certain portion of the incident-affected lane remains unused due to vehicles' lane changes or traffic diversions by the incident response teams. The unused portion of the traffic lane near the incident location is referred to as the incident zone (see Figure 3). In other words, the incident zone is the empty portion or gap in front of the incidents' location, where vehicles do not traverse due to the influence of the incident.

To identify the incident zone in real time using CV information, first, the portion of the incident-affected lane that is between the stop-line and the location of the subject CV/NCV (through which incidents' occurrence was identified) is divided into segments of 1-metre length. Second, at every time-step, with the updated location information of all CVs, each 1-metre segment is checked for the presence of vehicle movement. The length of the road segments, which are not traversed (between the stop-line and the location of the subject CV/NCV) by any vehicle, is taken as the updated incident zone.

Step -3.2.5: Incident clearance check—as more vehicles traverse the road segments in the incident zone, the length of the incident zone decreases (see Figures 3(a) and 3(b)). At every time-step, the incident zone length is updated based on the updated CV's location and the length of the road segments traversed. An incident is cleared, when all the 1-metre road segments in the incident zone are traversed by the CVs.

3.3. Incident-Responsive Connected Vehicle Signal Control Strategy (IR-CVSC). When an incident occurs on a lane, all the vehicles behind the incident's location gradually slow down and come to halt, while the vehicles on the adjacent nonincident lanes continue to move to cross the intersection (see Figure 4). During the green phase, the platoon of halted vehicles on the incident lane try to change their lane as soon as they find a gap on the adjacent lane and then pick up their speeds to cross the stop-line (see Figures 5(a) and 5(b)). This lane-changing pattern can decrease the space-mean speed of the vehicles on the nonincident lane. The time taken by the halted vehicles behind the incident location during the process of lane-changing and attaining the speed to cross the stop-line can increase the delay time of the vehicles that are waiting for the green signal on the other approaches. At that situation, the green time for the incident phase can be terminated and the traffic of the next phase can be served. Hence, for the incident-occurring phase, the space-mean speed of the vehicles on the nonincident lane and the ones in front of the incident's location is taken into consideration for the extension/termination of green interval. The step-wise signal control procedure of the IR-CVSC strategy (see Figure 1) is explained below.

Step -3.3.1: NCV information estimation partial termination—during the incident, as the queued-up vehicles behind the incident location try to change their lane, the NCV information estimation is aborted for the incident-occurring phase, as the car-following algorithm does not predict the lane changes of the NCVs, and it is resumed only after the incident is cleared. However, the IA-CVSC strategy with the NCV's information estimation procedure is continued to be in effect for all the other phases that are not affected by the incident.

Step -3.3.2: CV information update—we obtain and update the arrival, departure, speed, and position information of CVs on each lane of the incident approach, using V2X devices.

Step -3.3.3: Incident zone update—from the updated CV's position information, the length of the incident zone is updated (as in Step -3.2.4).

Step -3.3.4: Speed-ratio check—for the incident's phase, initially green time is provided until the vehicles in front of the incident zone and the ones on the adjacent (nonincident) lane are served. During this period, the halted vehicles behind the incident location try to find a gap on the adjacent lane and interrupt the traffic while entering the lane (see Figure 5). In this situation, the space-mean speed of the vehicles on the nonincident

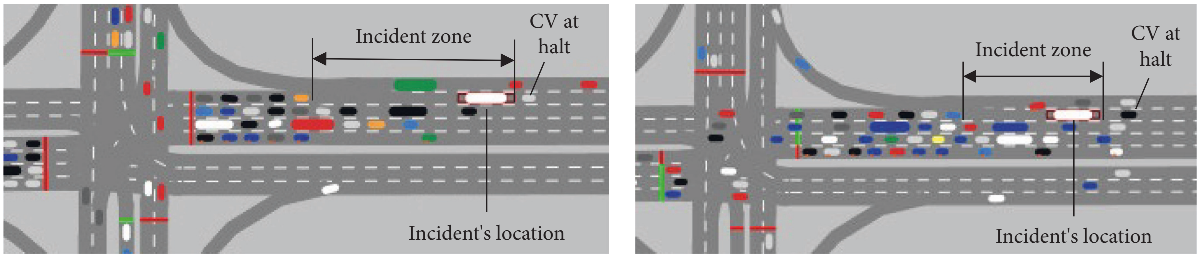
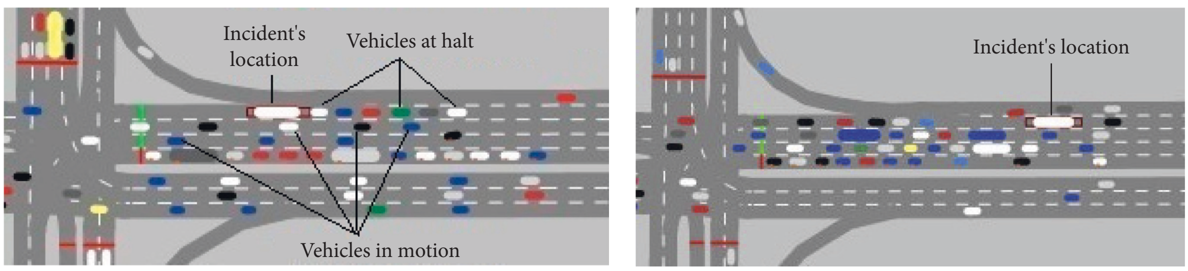
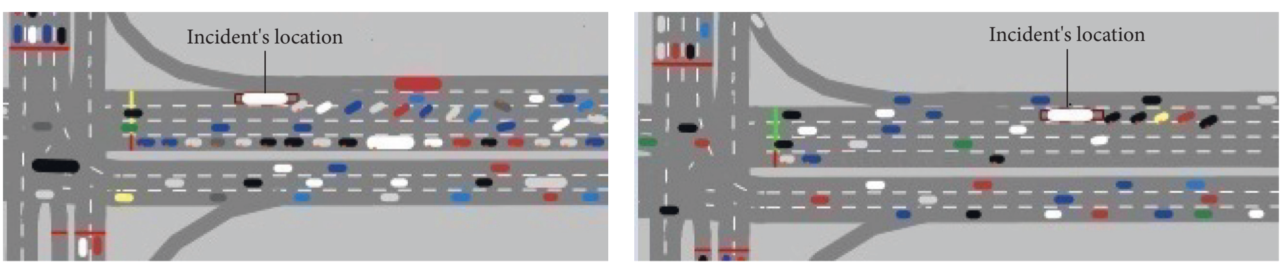


Figure 3: Depiction of the incident zone.



(a) (b)

Figure 4: Traffic flow depiction during the occurrence of an incident.



(a) (b)

Figure 5: Vehicles' lane-change behaviour and during an incident.

lane decreases, indicating the need to re-evaluate the current green phase. During undersaturated traffic conditions, the space-mean speed of the vehicles on the nonincident lane might not get affected when the halted vehicles change their lane.

In another situation, the halted vehicles behind the incident location might not be able to find a gap due to a continuous demand on the nonincident lane (see Figure 4). In this situation, the space-mean speed of the vehicles on the nonincident lane increases, indicating the need for the green time extension.

Therefore, to tackle the above situations, green time is provided until the speed ratio of the vehicles on the nonincident lane decreases when compared to the previous time-step or the speed ratio reaches 90%, at which point, the algorithm moves to the next step.

Step -3.3.5: Reserve-time and throughput ratio—depending on the cumulative arrival and departure flows on all the approaches, throughput ratio criteria define whether to extend or not further the green period. As in the IA-CVSC strategy, reserve-time is calculated, and throughput ratio criteria are applied as rolling-horizon at every time-step to extend the green time until the throughput ratio no longer increases in comparison with its value in the previous time-step.

Figures 5(a) and 5(b) show the lane-changing behaviour of the halted CVs when they find a gap on the nonincident lanes. The difference between figures is that the throughput ratio criteria in Figure 5(a) led to the termination of the green phase (therefore, the signal light is amber) as more vehicles are waiting for the green in other phases when compared to the incident's phase, while in Figure 5(b), the situation led to the extension of green (therefore, the signal light is green) until throughput ratio value stops increasing compared with the previous time-step.

Step -3.3.6: Green phase termination check—when the throughput ratio reaches its maximum value, the green period for the incident phase is terminated and switched to the next phase.

It should be noted that the green time extension at every time step is subject to the maximum green time limit in both IA-CVSC and IR-CVSC strategies. The difference between the signal control criteria of IA-CVSC and IR-CVSC strategies is that IA-CVSC provides green time until the speed ratio of all the CVs and NCVs reaches 90% and then applies throughput ratio criteria to extend or terminate the green phase, whereas IR-CVSC strategy provides green time until the speed ratio of the vehicles in front of the incident zone and adjacent to the incident lane stops increasing in comparison with the previous one (as the halted CVs behind the incident location move to the nonincident lane, causing the decrease in speed ratio) and then applies the throughput ratio criteria to extend or terminate the green phase. Figure 1 shows the flowchart that includes all the steps of IA-CVSC, incident detection, and IR-CVSC strategies integrated into one algorithm, which is applied during the green phase. During the red and amber intervals, the algorithm obtains and updates the CV and NCV information and estimates the forward movements of NCVs.

4. Testing and Evaluation of the Proposed Strategy

4.1. Tested Incidents. A variety of incident scenarios such as vehicle breakdown, road maintenance works, bus stop, illegal parking, and vehicle loading/unloading can be tackled by the integrated algorithm. For a robust evaluation of the algorithm, three types of incidents were tested (see Table 2), and each applied in different contexts and within a wide range of specifications, including different locations of incidents' occurrence, with varied frequencies and duration times, which can disrupt the normal traffic flow and allows the possibility to study the effects of incidents and the vehicles' behaviour in such situations.

4.2. Intersection Layout and Traffic Demand Patterns. Simulations of different incident scenarios were carried out in VISSIM 8 software [60], on a four-legged isolated intersection, along Castle Downs Road and 97 Street, Edmonton (see Figure 6). The case study was based on the existing layout and traffic movements obtained from the database of Edmonton [61].

Vehicle volumes were converted to approximate different intersection saturation rates using the Intersection Capacity Utilization (ICU) metric [62]. The field recorded volumes produced 0.65 ICU across the intersection. These basic, saturated, volumes were altered by uniform factors to generate volumes of 0.35, 0.50, 0.80, and 0.95 ICU, respectively (see Table 3). To calculate the ICUs, the lost-time per phase, minimum green time, and the reference cycle length were assumed as 4, 5, and 120 seconds, respectively.

A basic, constant, split between different types of vehicles was used in the simulations: cars (95%), buses (3%), and heavy goods vehicles (HGVs) (2%). Minimum and maximum desired speeds ranges in VISSIM were set as 48–58 kmph, 40–45 kmph, and 40–45 kmph, respectively, for cars, buses, and HGVs. The average desired speed of these ranges was used in the speed ratio calculation in equation (1).

A four-phase traffic signal plan was applied with turning movements allocated to Phase 1 (NBT, NBR, SBT, and SBR), Phase 2 (NBL and SBL), Phase 3 (EBT, EBR, WBT, and WBR), and Phase 4 (EBL and WBL). The movements EBR, WBR, NBR, and SBR on the intersection have dedicated right turns.

4.3. Strategy's Evaluation Process. The testing and evaluation of the IR-CVSC strategy were performed by comparison with EPICS [63], a reference, state-of-the-art, adaptive signal control solution, that is embedded in the VISSIM 8 simulation tool, which provides a platform for the comparison procedures. The proposed algorithm was coded in C++ language and was integrated with VISSIM COM API, which enables the users to access the vehicles' speed and position, which were, then, used in the IA-CVSC and IR-CVSC strategies to control the signal timings.

Each incident event was tested for the selected set of scenarios as shown in Table 2, with varying traffic demand (ICUs—0.35, 0.50, 0.65, 0.80, and 0.95), varying CV penetration rates (100%, 80%, 60%, 40%, and 20%) to reflect different near-future possible traffic conditions, and varying incident locations from the stop-line (0 m, 25 m, 50 m, 100 m, 150 m, and 200 m). The simulation was run for 1 hour in which the first 15 minutes was for warming-up, and the rest for the incident duration and congestion dissipation. The results of the different scenarios were based on the average of 10 random seeds. A total of 29,700 simulations were run on the intersection with results being obtained for all the signal control solutions (IR-CVSC, IA-CVSC, and EPICS) analysed.

4.4. Performance Indicators. As the measure of the quality of success of an incident detection algorithm, the following measures of effectiveness (MOEs) were used:

(a) Detection rate (DR)—ratio of the number of detected incidents over the total number of actual incidents,

(b) False alarm rate (FAR)—ratio of the number of "false" detected incidents over the total number of detection algorithm decisions,

(c) Mean time to detect (MTTD)—average time interval from the moment of incident's occurrence/clearance to the moment of its detection.

To compare the relative performance of different signal control solutions (IR-CVSC, IA-CVSC, and EPICS), the MOEs used were the average travel time delay and the average number of stops per vehicle, which represent the difference between ideal travel time/stops (computed assuming no other vehicles on the network and no delays/stops at signal controls) and actual travel time/stops.

Table 2: Tested incident scenarios.

Incident	Bus breakdown	Bus stop						Illegal car parking	
	Type 1	Type 2.1	Type 2.2	Type 2.3	Type 2.4	Type 2.5	Type 2.6	Type 3.1	Type 3.2
Frequency	Once	2 min	2 min	5 min	5 min	10 min	10 min	10 min	10 min
Duration	20 min	20 s	40 s	20 s	40 s	20 s	40 s	60 s	120 s

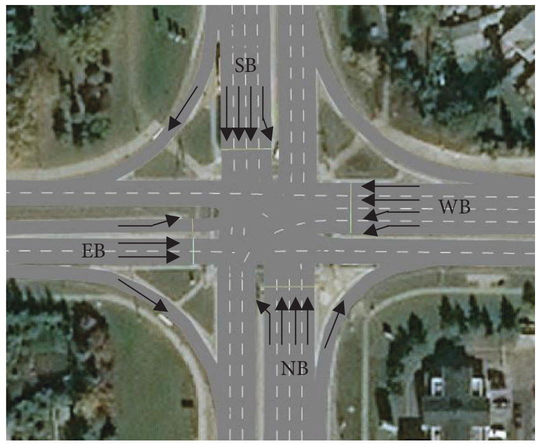


Figure 6: Snapshot of test intersection (Source: Bing maps).

Table 3: Tested volumes along the intersection.

ICU	EBL (8%)	EBT (69%)	EBR (23%)	WBL (33%)	WBT (46%)	WBR (21%)	NBL (25%)	NBT (52%)	NBR (23%)	SBL (13%)	SBT (55%)	SBR (32%)
0.35	35	296	99	159	225	103	244	514	239	108	452	268
0.50	50	423	141	228	322	148	348	735	341	154	645	383
0.65	65	550	183	296	418	192	453	955	443	200	839	498
0.80	80	677	225	364	514	236	558	1175	509	246	1033	613
0.95	95	804	267	433	611	281	662	1396	605	292	1226	728

5. Results

This section presents the simulation results of all the incident scenarios of IR-CVSC, IA-CVSC, and EPICS solutions. Evaluation of the results is divided into two sections: (1) efficiency of IR-CVSC to detect incidents, where the performance indicators of incident detection, for each incident scenario, are presented; (2) relative performance of IR-CVSC strategy, where the MOEs of IR-CVSC and its performance in comparison with IA-CVSC and EPICS are presented.

5.1. Efficiency of IR-CVSC Strategy to Detect Incidents. To evaluate the efficiency of the IR-CVSC strategy to detect the incident's occurrence (IO) and incidents' clearance (IC), the parameters MTTD-IO, MTTD-IC (95^{th} percentile), and DR-IO, DR-IC (5^{th} percentile) were chosen. The evaluation results comparing all the incident types at different CVPs, ICUs, and incident locations are presented in Figure 7.

The following basic conclusions can be drawn from the detection efficiency's results:

(1) With the decrease in CVP and decrease in ICU, DR-IO and DR-IC decreased, and MTTD-IO and MTTD-IC increased (due to fewer vehicles, more space, and more lane changes).

(2) With incidents' location away from the stop-line, DR-IO and DR-IC decreased, and MTTD-IO and MTTD-IC increased (due to more space availability for the vehicles to traverse in front of incidents' location).

(3) For a given frequency, as the incidents' duration increased (as in type 2 and type 3), DR-IO and DR-IC increased, and MTTD-IO and MTTD-IC decreased.

(4) For a given duration, as the incidents' frequency increased (as in type 2), congestion increased causing more stopping time, resulting in the increase in DR-IO and DR-IC, and decrease in MTTD-IO and MTTD-IC.

(5) For type 2 and type 3 incidents whose frequency of occurrence is more than once, DR-IO is always greater than or equal to DR-IC. This is because until the algorithm detects the incidents' clearance, the next incidents' occurrence is not detected.

(6) FAR of incidents' occurrence and clearance was 0 in all cases. This is due to the applied detection method (as in Section 3.2).

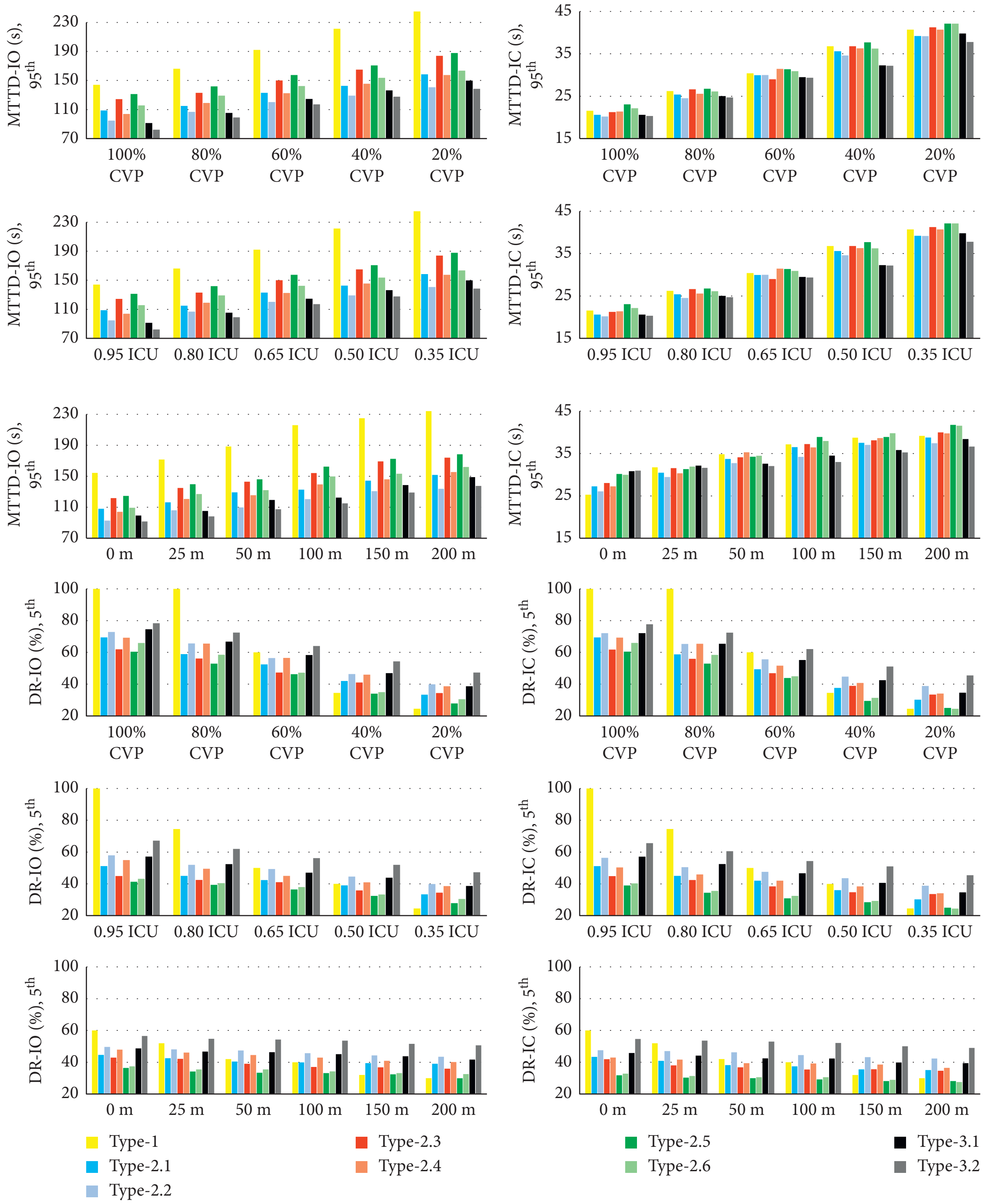


Figure 7: MTTD (95^{th} percentile) and DR (5^{th} percentile) comparison of all incident types at different CVPs, ICUs, and incident locations from the stop-line. Each bar represents an incident type.

5.2. Relative Performance of IR-CVSC Strategy. The signal control evaluation of IR-CVSC, IA-CVSC, and EPICS strategies and comparing all the incident types at all CVPs, ICUs, and incident locations are presented in Figures 8 and 9 and Table 4. It should be noted that IA-CVSC and EPICS solutions do not detect the incidents. They are, however, compared with the IR-CVSC strategy to analyse the differences in their working principles during the occurrence of incidents and also to check whether the new strategy can improve the intersections' performance in case of incidents' occurrence.

The following basic conclusions can be drawn from the signal control evaluation results:

(1) For a given frequency, as the incidents' duration increased (as in type 2 and type 3), delays and stops

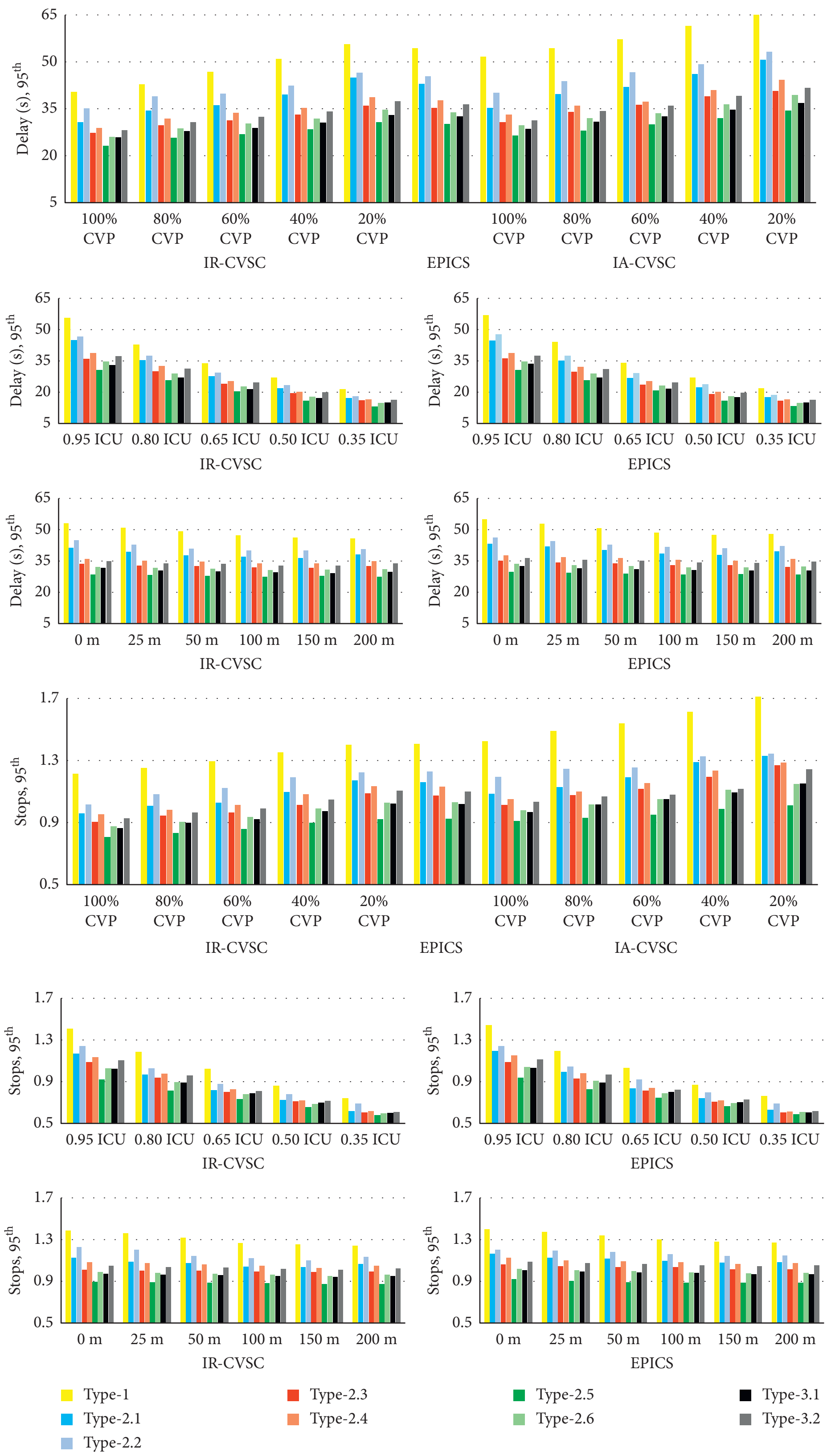


FIGURE 8: Signal control MOEs of IR-CVSC, IA-CVSC, and EPICS strategies of all incidents. Each bar represents the MOE of an incident type.

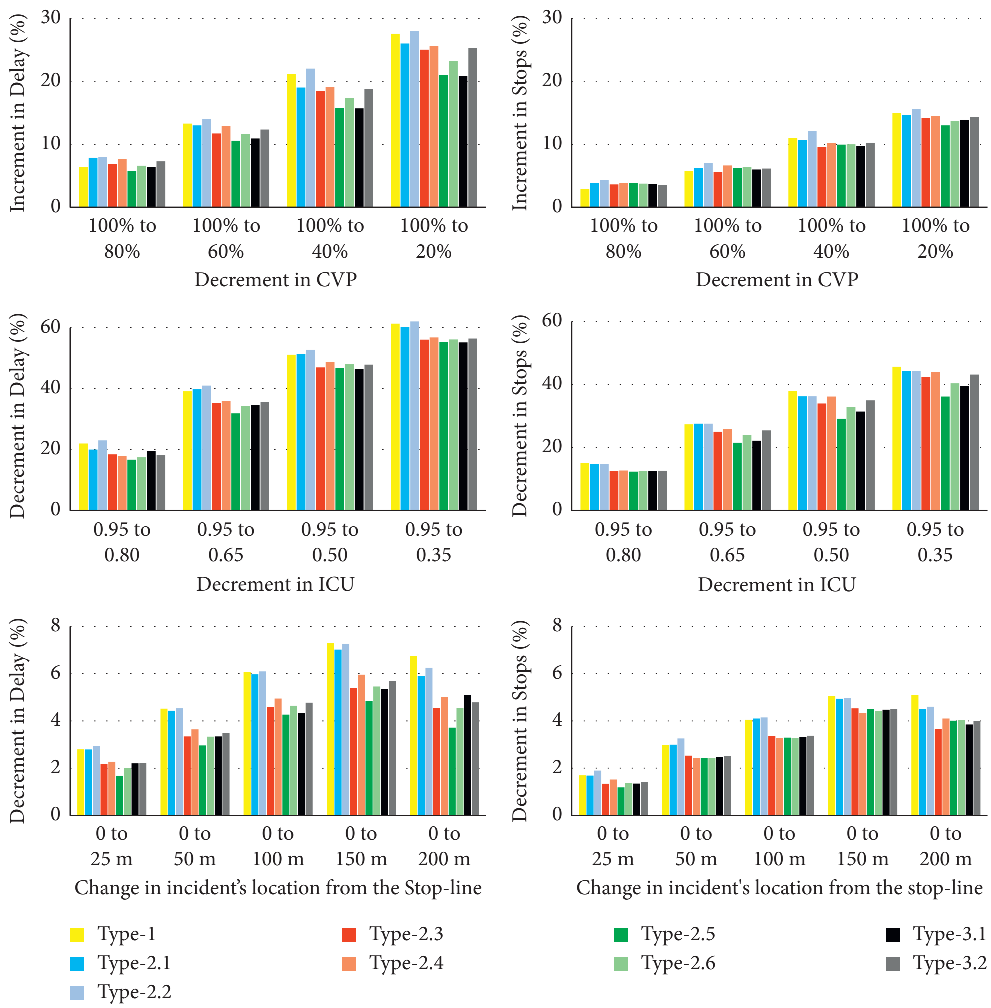


Figure 9: Percent change in IR-CVSC delays and stops with change in CVP, ICU, and incident's location from the stop-line.

Table 4: Signal control MOEs' evaluation at all CVPs, ICUs, and incident locations.

Incident	Type 1	Type 2.1	Type 2.2	Type 2.3	Type 2.4	Type 2.5	Type 2.6	Type 3.1	Type 3.2
Frequency	Once	2 min	2 min	5 min	5 min	10 min	10 min	10 min	10 min
Duration	20 min	20 s	40 s	20 s	40 s	20 s	40 s	60 s	120 s
Performance range of IR-CVSC over IA-CVSC at all CVPs, ICUs, and incident locations									
Delay (%)	13 to 26	10 to 24	8 to 27	7 to 17	9 to 21	6 to 24	8 to 21	5 to 20	6 to 16
Stops (%)	7 to 20	7 to 18	4 to 16	7 to 15	8 to 17	6 to 13	8 to 13	8 to 14	5 to 20
Performance range of IR-CVSC over EPICS at all CVPs, ICUs, and incident locations									
Delay (%)	−3 to 29	−8 to 34	−5 to 29	−6 to 25	−3 to 29	−7 to 25	−3 to 25	−3 to 22	−3 to 27
Stops (%)	−1 to 16	−2 to 19	−2 to 19	−5 to 17	−3 to 17	−1 to 16	−1 to 15	−2 to 16	−1 to 16

increased in all the signal control strategies, as expected.

(2) For a given duration, as the incidents' frequency increased (as in type 2), congestion increased, resulting in higher delays and stops.

(3) Delays and stops increased with the decrease in CVP and increase in ICU.

(4) As the incidents' location moved from 0m to 150m before the stop-line, delays and stops decreased. As expected, the closer the incidents' occurrence to the stop-line, the higher the delays and stops are.

(5) As the incidents' location moved from 150 m to 200 m before the stop-line, delays and stops increased (above 90% of the time) in all strategies. This is because the incidents' location at 200 m from the stop-line is far for the signal control strategy to serve the vehicles with lower MOEs compared with the location at 150 m. Changes in road geometry and the number of lanes might also be the influential factors for this pattern.

Conclusions on the performance of IR-CVSC strategy are as follows:

(1) IR-CVSC showed 5–27% lower delay and 4–20% lower stops compared with IA-CVSC strategy at all incident scenarios, thus, proving the necessity for an incident-responsive signal control strategy.

(2) At 40% and higher CVPs, at all types of incidents, IR-CVSC showed better performance over EPICS adaptive signal control, in reducing delays and stops by 1–34% and 1–19%, respectively.

(3) At 20% CVP, at all ICUs and incident locations, IR-CVSC showed 1–8% higher delays and 1–5% higher stops compared with EPICS.

(4) IR-CVSC strategy performed better with higher DR for incidents with longer duration. DR-IO for type-1 incidents was 21–36% and 12–19% higher than type-2 and type-3 incidents, respectively.

(5) For type-2 and type-3 incidents, as the frequency of incidents' occurrence is more than once and the incident duration is much shorter than type-1 incidents, IR-CVSC showed lower DR compared with type 1. This might be because the incident detection method was applied only during the green interval; thus, shorter duration incidents that might have occurred and cleared within a red interval remained undetected, or the incident might have occurred and cleared within the predefined threshold time ($T/3$ seconds).

(6) At higher ICUs, due to increased congestion with incidents' occurrence, IR-CVSC showed higher DRs and lower MTTDs. DR-IO and MTTD-IO at higher ICUs (0.95 and 0.80) were 17–25% higher and 40–66% lower than that of lower ICUs (0.50 and 0.35), respectively.

6. Conclusions and Future Work

This paper presented a novel algorithm that tackles incident-related traffic congestion problems for isolated intersections, by integrating 3 different strategies, namely, (1) a CV-based signal control strategy for normal traffic conditions without incidents, (2) an incident detection technique using CV/NCV information, and (3) a CV-based signal control strategy during the occurrence and dissipation of incidents. The integrated algorithm applies the corresponding strategy in real time, according to the incident/nonincident traffic conditions.

During nonincident conditions, the integrated algorithm applies the IA-CVSC strategy, where the speed and location information of CVs and NCVs at every time-step was obtained and green time was provided based on the ratio of space-mean speed to the desired speed of vehicles, as well as intersections' throughput maximization criteria. Incidents' occurrence is detected when a stopped vehicle during any green interval fails to move within a predefined threshold time. When an incident is detected, the integrated algorithm switches from IA-CVSC to IR-CVSC strategy, where green time is provided based on the space-mean speeds of vehicles on the nonincident lane, lane-changing pattern of the CVs behind the incident location, and throughput maximization criteria. Incidents' clearance is identified when the road portion between the stop-line and the location of the subject vehicle (which is responsible for the incidents' identification) on the incident lane is traversed. When the incident is cleared, IR-CVSC switches to the IA-CVSC strategy.

The incident detection accuracy and the signal control performance of the IR-CVSC strategy were evaluated by performing simulations on a real-field four-legged isolated intersection using the VISSIM software tool. Different incident scenarios were selected, with varied incident durations and frequencies of occurrence, and tested at different CVPs, ICUs, and incident locations. From the simulation results, the range of DR-IO and DR-IC (5th percentile), and MTTD-IO and MTTD-IC (95th percentile) for long-duration incidents (type 1) was 25–100%, 25–100%, 119–246 s, and 22–41 s, respectively, and for short-duration incidents with different frequencies of occurrence (type 2 and type 3) was 28–78%, 24–78%, 82–188 s, and 20–42 s, respectively. Higher DRs and lower MTTDs have resulted at higher CVPs, higher ICUs, and closer incident locations to the stop-line. In relation to the signal control strategy, at 40% and higher CVPs, at all types of incidents, IR-CVSC showed better performance over EPICS, in reducing delays and stops. Delays and stops of IR-CVSC strategy increased with a decrease in CVP and increase in ICU, and at incidents' locations nearer to the stop-line.

Findings from the results of incident detection and incident-responsive signal control strategies showed the modelling approach's potential in utilizing the emerging connected vehicle technology to mitigate the impact of incident-related traffic congestion significantly compared with an adaptive signal control solution. The integrated algorithm framework also provides more opportunities to study, build, and test several new heuristics to tackle incident-related traffic problems on both isolated intersections and intersection networks.

It is necessary to mention a few limitations related to the proposed algorithm. Currently, the algorithm is applicable for isolated intersections that have at least one adjacent lane available to serve the vehicles during the occurrence of incidents. IR-CVSC strategy must be improved for the situation where, if the incident occurs on a left-turning lane that does not belong to the phase of straight and right-turning movements, the phase plan must be altered in real time by including all the traffic movements on the incident-affected lanes under one phase, thus giving the possibility for the left-turning vehicles to use an adjacent lane during the occurrence of incidents. Future work should also focus on a method to estimate the speeds and positions of NCVs during a lane change and integrate it into the IR-CVSC strategy for more benefits.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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