A COOPERATIVE FRAMEWORK FOR URBAN SEMI-ACTUATED SIGNAL CONTROL AT SIGNALIZED T-INTERSECTIONS IN MIXED TRAFFIC FLOW

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ABSTRACT

Cities are suffering because of the rapid urbanization and population boom, which lead to increasing the load on the current traffic systems. Current traffic systems also suffer from several problems such as traffic congestion. Meanwhile, transportation engineering has rapidly evolved into a technical field, considerably induced by new technologies and algorithms to address today's challenges. The rise of connected and automated vehicle (CAV) emerging technology has brought new prospects to the automobile industry and transportation system during the past decade. This paper develops and evaluates a framework for CAVs to create additional suitable gaps to the minor road vehicles to reduce the interruption of the continuous flow on semi-actuated signalized intersections. A simulation platform was developed using VISSIM software to validate the effectiveness of the proposed framework. Simulation results show that the proposed algorithm improves the intersection performance where the major road delay decreases, and the intersection's capacity increases. The throughput of the targeted intersection increased up to 34% when the CAVs penetration reaches 70%.

Keywords: connected and automated vehicles, flow interruptions, mixed traffic, signalized intersection.

1 INTRODUCTION

Transportation engineering has rapidly evolved into a technical field, considerably induced by novel technologies and algorithms to address today's challenges. One important aspect of transportation is the growing need for mobility in urban areas. These high-traffic needs require sophisticated transportation networks, leading to major capacity limits and major problems such as congestions and accidents [1].

The rapid urbanization is causing an increase in the population of the cities, which is increasing the load on the current traffic systems, elevating traffic congestion. This is a serious concern as drivers have to spend a significant amount of time on the roads, leading to increased fuel consumption [2]. However, due to increasing population, urbanization, and motorization, current traffic management systems have become less effective in handling the increasing traffic demand. Thus, there is a need to handle the problem of traffic congestion primitively as it leads to other issues like inefficient transportation, air pollution, and higher fuel consumption.

Bottlenecks are another critical cause of traffic congestion that usually takes place in the case of road intersections. Intersections are two different roads that meet together with traffic flowing in opposite directions. The intersections are designed as a preventative measure from traffic congestion by facilitating the easy flow of vehicles. There are two types of intersections, signalized and unsignalized, based on the signs and signals they are designed to have. Signalized intersections have signals that help regulate traffic and assist drivers, whereas unsignalized intersections have only signs without any signals.

Traffic signal controlling devices have constantly been evolving to make green assignments more responsive to traffic. However, signalized intersections are the major sources of

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the increase in travel time for user mobility. Poorly timed and managed signal controls can introduce unnecessary and unwanted user delays. Signalized intersections can also be bottlenecks since their cyclic allocation of conflicting movements.

Traffic signals can be pre-timed or actuated or some combination of them. Pre-timed from its name involves fixed duration intervals. Green, yellow and red is done in a sequence fashion with a deterministic cycle length, whereas actuated control consists of intervals that are called and extended in response to vehicle detectors. The detection provides information about traffic demand to the controller. The detector input and corresponding controller parameters will determine each phase duration. Actuated control can be classified into fully actuated or semi-actuated, depending on the number of detected traffic movements.

The semi-actuated control is usually used when having a major-minor road situation. The detectors are placed only on the minor road. Green is allocated to the major road at all times unless there is a call from the minor road. It is used in the case of very light side-road traffic where it reduces the delay time for users incurred by the major road through movements [3]. The semi-actuated signal control can be suitable if a major road intersects with a low-volume road. The semi-actuated control can be the reason to cause an excessive delay to the major road if a consistent demand on the phases is presence on the minor road stream.

The rise of connected and automated vehicle (CAV) emerging technology has brought new prospects to the automobile industry and transportation system during the past decade. Notably, the rise has been observed considering vehicle connectivity levels that increased significantly, enabling these enhanced technologies to work cooperatively [4]. Moreover, recent technologies like Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications can mitigate present transportation issues and challenges. The deployment of these innovative V2I and V2V technologies can share traffic information and automated vehicles in a complete connected environment. Hence, the optimal route guidance proposed solution can be used for efficient traffic control and management, lessening the congestion and traffic accidents. In addition, efficient and green environment motion planning can be integrated with this proposed solution [4].

On a semi-actuated signal intersection where a major road intersects with a minor road, green light interruptions to the mainline traffic due to detection of individual vehicle arrivals at the minor approach often happen, causing significant stops and delays to the mainline vehicles. This problem can be tackled using the technology of CAVs. This work utilizes these technologies such as V2I and V2V to use the traffic information from CAVs to create suitable gaps to improve the flow. This work objective is to come up with a modified algorithm to the one proposed by [6] and evaluate it by applying it on signalized intersections to achieve less interruption on the mainline and increase the throughput of the intersection.

Finally, we can list the contributions of this paper as follows: (a) the introduction of a modified algorithm combined with the original algorithm that allows CAVs to create additional gaps at T-intersection; (b) investigating the proposed algorithm's performance by simulating the modified signal control in a microscopic environment (c) analyze the output of the simulation platform to evaluate the performance of this work. The structure of this paper is arranged as follows: Section 2 introduces the algorithm and how the modified algorithm applied to the original framework. Section 3 explains how the simulation platform was developed and the evaluations parameters. Section 4 provides the assessment performance of this method by analyzing the measures of effectiveness (MOE) results at the signalized intersection. Section 5 concludes the finding of this work and the future work.

2 LITERATURE REVIEW

Urban areas intersections, where conflicting traffic streams from different approaches connect, have been critical elements of transportation infrastructure. These intersections, if not managed properly, can lead to accidents. One study [7] showed that approximately 50% of all United States accidents occur at intersections. In order to enhance the safety measures at intersections, traffic lights and signal control systems, being the well-known traffic engineering methods, are most feasible solutions. Even though this engineering method introduces safer environment for all transportation means, it may be the reason of causing waiting (lost) time in the form of delays and restricting the transportation network.

Our focus on this study is signalized intersections with the presence of CAVs. Namazi et al. [2] conducted a systematic literature review about intelligent intersection management systems with the presence of CAVs. In the case of mixed traffic and signalized intersections, they have identified three different survey studies. This shows that mixed traffic signalized intersections are still a research topic that needs more investigation. Guo et al. [8] evaluated the intersection management systems based on urban signalized traffic flow in line with CAVs. The methods for the estimation of traffic flow and optimal traffic signal timing are the proposed methods existing in the literature.

Intersection traffic signal optimization has taken a wide part of research with great achievements in transportation field [8]. Normally, researchers and practitioners assume traffic signal controlling based on traffic models and consider it as an optimization problem [9], [10]. Researchers have main concerns about vehicle trajectory generation algorithms in terms of eco-driving at signalized intersections [11], [12].

The past decade has seen a boom in the research of using CAV information for optimizing signals and timing plans. The focus of these studies has been on different objectives—such as minimizing delays [13], [14], total queue length [15], [16] and green splits [17], [18], [19]. The literature review includes various studies that develop intersection management applications for CAV passing through signalized intersections. Optimizing signalized intersection has been one of the important research questions. The recent research about semi-actuated signal control system mainly focuses on conducting a variety of models to get the optimal semi-actuated signal control model and to optimize the system control parameters. By using the advantages of CAVs, it is possible to improve the traffic performance of signalized intersections.

Soleimaniamiri et al.[20] approached the problem by proposing an analytical joint optimization method using simplified approximation functions. Their experimental results showed substantial enhancements at a two-phase intersection. Liu et al. [21] proposed V2V communication based on a novel distributed conflict resolution methodology for safe and efficient navigation of CAVs at the signalized or unsignalized intersections. The proposed approaches used in these studies resulted in improvement in efficiency and accuracy by minimizing the average delay time. Zhao et al. [22] gave a cooperative speed advice and communication system called CoDrive to minimize fuel consumption at signalized intersections. Fayazi and Vahidi [23] proposed a controller-based modified mixed-integer linear programming at intersection for both autonomous and human-driven vehicles to improve signalized intersections time delay. In this work, we propose an algorithm and framework that guides CAVs on the mainline to create adequate gaps to the minor road that will eventually improve the flow of signalized intersections. The methodology works when vehicle arrivals on the main road permit the implementation of the control strategy to improve intersection efficiency in mixed traffic conditions. The contribution of this research is threefold: developing a framework that guides CAVs in creating gaps at signalized T-intersections while considering safety and efficiency under mixed traffic conditions, validating the proposed method by simulating the method in a microscopic environment, and evaluating the efficiency and safety of the intersection before and after the method.

3 MODIFIED SIGNAL CONTROL

In the secondary priority road at a semi-actuated signal control, the main road maintains the green time where the minor road maintains red time. When a vehicle is detected by the detector placed on the minor road and the green time on the main road reaches the minimum green time, the signal will switch to serve the minor road stream and obtain minimum green time (G_{min}). On the other hand, if no vehicle has been detected on the minor road approach, the main road will obtain the right of passage and maintain the green time. If a vehicle on the minor road is passing, the actual green time (G) will extend by a unit of extension time (G_0). Moreover, when vehicles on the minor road continue to arrive, the actual green time (G) will be extended until the maximum green time (G_{max}) [3].

The control strategy makes use of a modified algorithm at the minor road approach to allow longer vehicle waiting time so that an adequate gap to enter the intersection may be created by the CAVs without the need for a signal switch. The modified signal control operates a detection delay or a green-rest (GR) plan in the mainline directions and a flashing red (FR) for the minor road direction. In this way, a vehicle at the minor road approach can still enter the intersection during a FR since it functions as a stop sign. However, suppose the minor approach vehicle fails to find a long enough gap, and the waiting time is excessive. In that case, the new algorithm will expire to allow the provision of green light for the waiting vehicle on the minor road.

As the modified algorithm temporarily operates a FR for the minor road when a vehicle is waiting to enter the intersection, the CAVs in the mainline flow can execute the gap creation. If the minor approach vehicle cannot find a proper gap to use if there are no CAVs in the mainline traffic, the traffic signal resumes its semi-actuated operation. The effectiveness of the control algorithm will depend on how often the mainline signal is interrupted with and without CAVs to help create gaps. The flow chart for this situation is explained in Figure 4.

4 MODEL FORMULATION

In this study, we modify an algorithm that was proposed by [6] to control CAVs in semi-actuated signal intersection environments. This algorithm is designed to increase the throughput of the intersection and reduce delay on the mainline. The research's main objective is to utilize and develop a systematic framework and implementation plan that makes use of CAVs to create safe gaps in the mainline traffic stream for the minor road vehicles to utilize. The modified control logic of the semi-actuated signal is explained in the modified signal control section.

4.1 Intersection Assumptions

The main assumptions of this methods are as follows:

1. The intersection has a roadside unit (RSU) to receive and transmit information for all CAVs on a major road.

2. CAVs on the major road can obtain information within the range of communication to the RSU.
3. CAVs can detect the leading and following vehicles and calculate the distance along with the speeds of those vehicles.

4.2 The Safe Gap Front of CAVs Towards Intersection

The proposed control system can work in a mixed traffic environment since it considers both connected automated vehicles CAV and human vehicles HV. When a CAV is within the V2I communication range, and a vehicle is detected in the minor street by the Roadside Unit RSU, the CAV calculates whether the gap at the intersection is greater than the critical gap. However, suppose it is not more than the critical gap as explained in the previous section. In that case, CAV will reduce speed to help maintain a distance beyond the established critical gap if other conditions permit.

In this scenario, as shown in Figure 2, a CAV is following an HV and separated by an existing gap time T_1. T_1 is measured as the difference between the distance of CAV to the intersection L_{CAV} divided by the speed of CAV v subtracting from the distance of HV to intersection L_{HV} divided by the speed of HV:

$$T_1 = \frac{L_{CAV}}{v} - \frac{L_{HV}}{v} \quad (1)$$

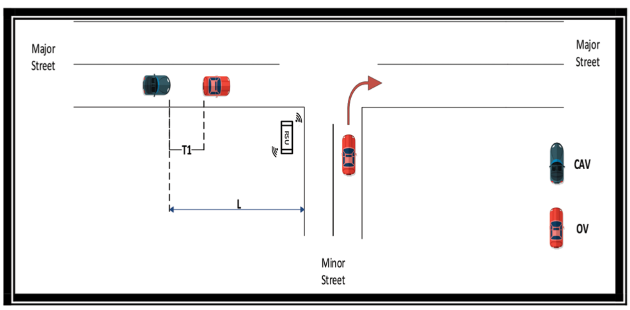


Figure 1: Distance between AV and the leading vehicle T1.

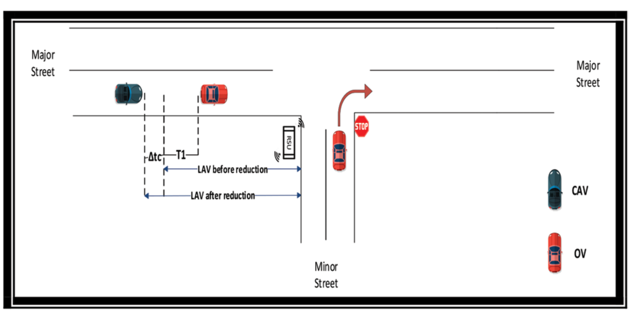


Figure 2: The extra time added to create the extra safe gap (Δt_c).

Where: v is the approaching speed in feet per second, L_{CAV} is the distance of the CAV towards the intersection in feet and L_{HV} is the distance of the HV to the intersection in feet. Since the distances are measured close to the intersection, speed variation before reaching the intersection is not considered.

The minor road vehicle looking for a safe gap to enter the intersection needs a gap equal to or greater than the critical gap called T_0. For a minor street vehicle to enter the intersection safely, T_1 must be greater than T_0. In the scenario where T_1 is less than T_0, CAV will be allowed to reduce speed in order to add an extra gap time, which is called Δt_c and it is defined as extra gap time added between two successive vehicles, as shown in Figure 2.

$$\Delta t_c = \frac{L_{CAV}}{v_c} - \frac{L_{CAV}}{v} \tag{2}$$

Where L_{CAV} is the distance of the connected automated vehicle to the intersection, and v_c is the speed of connected automated vehicles after reducing speed.

After the reduction of speed of CAV, extra gap time Δt_c will be added to T_1 to be greater than T_0. As a result, the equation to create a gap greater than T_0 is as follows:

$$\frac{L_{CAV}}{v} - \frac{L_{HV}}{v} + \Delta t_c \ \geq \ \mathrm{T}_0 \tag{3}$$

By substituting eqn (2) to (3), then:

$$\frac{L_{AV}}{v} - \frac{L_{OV}}{v} + \frac{L_{AV}}{v_c} - \frac{L_{AV}}{v} \ \geq \ T_0 \tag{4}$$

This results in:

$$\frac{L_{AV}}{v_c} - \frac{L_{OV}}{v} \ \geq \ T_0 \tag{5}$$

The parameter β is the amount of CAV speed reduction. This is used to determine the needed speed of CAVs to create an adequate gap. The reduced speed v_c will be calculated based on the original speed as follows to establish the gap greater than a critical gap $T_1 > T_0$:

$$v_c = \beta v \tag{6}$$

By substituting eqn (6) to (5), then, the equation will be as follows:

$$\frac{L_{AV}}{\beta v} - \frac{L_{OV}}{v} \ \geq \ \mathrm{T}_0 \tag{7}$$

The time for communication between CAVs and RSU through V2I is neglected compared with the speed of vehicles [25]. However, the time to reach the desired speed of CAV when creating an extra gap is called transition time Δt_{trans}. This transition time is when CAV receives the order and processes the reduction until it reaches the required speed. The formula for creating extra gaps by CAVs would be adding the Δt_{trans} to eqn (7) as follows:

$$\frac{L_{AV}}{\beta v} - \frac{L_{OV}}{v} \geq \mathrm{T}_0 + \Delta t_{trans} \tag{8}$$

4.3 The Safe Distance behind CAV Based on Safe Car-following Distance

Reducing speed on the main road to create additional gaps to the minor road vehicles can cause a significant impact on safety as well as on system performance. However, in preparation for the CAVs to reduce speed, the car-following safe distance needs to be considered to avoid rear-end crashes and delay of the major road stream. This section is to develop the distance that needs to be maintained before reducing the speed of CAVs on the main road. In the scenario, an HV is behind a CAV, as shown in Figure 3. Before CAV reduces speed to create the extra safe gap, CAV should check the distance of the following vehicle. This check ensures that the following vehicle would not be affected by the reduction of the CAV speed.

The gap between the subsequent vehicle to the CAV before the CAV reduces speed is called C-back. To ensure safety for the following vehicle, the C-back distance should be greater than the safe car-following distance (CFD) when CAV reduces speed to ensure the following vehicle's safety when CAV reduces speed.

$$C_{back} \geq CFD \tag{9}$$

Where C-back is the following vehicle distance to CAV before reducing speed; CFD can be determined as:

$$\mathrm{CFD} = v_o\, t_r + \frac{{v_o}^2 - {v_f}^2}{30\left(f \pm G\right)} \tag{10}$$

Where V_0 refers to the initial speed of the subsequent vehicle (feet per second); v_f represents the required reduced pace of CAV for creating an extra safe gap for the minor street approach (feet per second); t_r is the perception-brake reaction time (seconds); f is referred to as a coefficient of friction, and G is the grade level of the street.

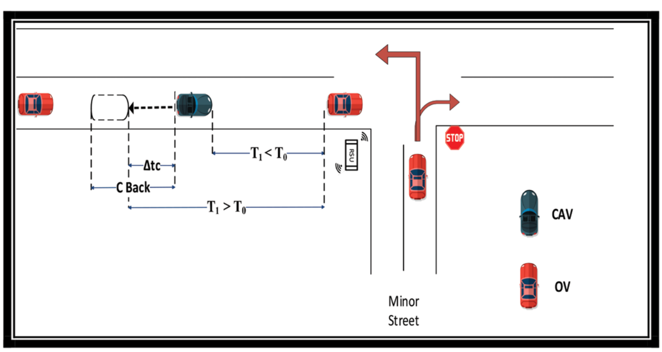


Figure 3: The additional time when CAV reduces speed.

As shown in Figure 3, when CAV reduces speed to create a gap that is more than the threshold distance, the gap between two automobiles will be subtracted by an amount of gap time, which is called Δt_c. Where CFD is a minimum safe CFD, to further enhance safety, the following equation is utilized:

$$C_{back} \text{ -}(\Delta t_c \ v) \geq \text{CFD} \tag{11}$$

The CAV scenario is coming towards the intersection between two vehicles, one vehicle behind and another vehicle in front of CAV is quite complex. In this scenario, the method starts with eqn (8) before eqn (11).

4.4 Signalized Scenario

In this section, for the signal control of this modified algorithm, assumptions are as follows:

1. The signal works as a semi-actuated signal control where there is a major road that has the right of way and has a GR.
2. The minor road signal has a FR where vehicles can accommodate gaps that are available or created by CAVs on the mainline.
3. A maximum waiting time is utilized for vehicles that cannot find suitable gaps, and then a green time is served for the minor road to clear queue.

The parameters of the semi-actuated signal control system include: (a) the minimum green time of the main road $G1_{min}$, (b) the maximum green time G_{max} and (c) the minimum green time of secondary road $G2_{min}$. On the other hand, signal timing parameters will be found according to the traffic flow at the specific intersection. This traffic flow will be classified into three levels: (a) low-, (b) medium- and (c) high-traffic volume. Each stream on the road will be classified as follows:

4.4.1 Main Road

1. When the major road has low, medium, and high volume, the maximum green time G_{max} for the major road is 50, 60 and 70 seconds, respectively.
2. The minimum green $G1_{min}$ for the major road is also varied with low, medium and high volumes as 10, 20 and 30 seconds, respectively.

4.4.2 Minor Road

1. When the major road has low, medium and high volume, the minimum green $G2_{min}$ time for the major road is 10, 15 and 20 seconds, respectively.
2. The maximum waiting time, W_{max}, is also classified into three levels based on the arrival rate on the minor road where low 10 seconds W_{max}, medium 20 seconds and high 30 seconds.

In this case, as shown in Figure 1, the major road traffic has the right of way, and the minor road users have to wait at the stop sign before merging. The minor road vehicles will enter

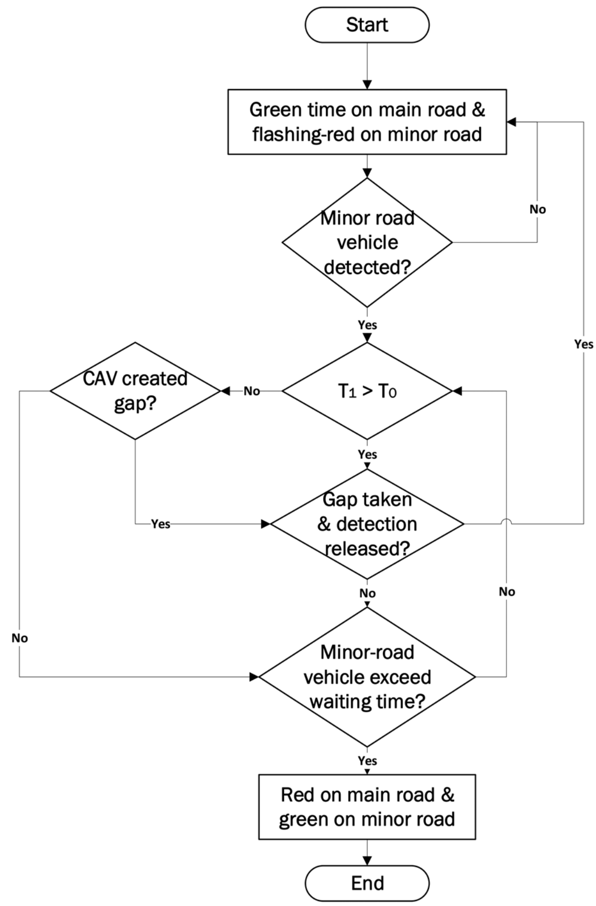


Figure 4: Control logic at semi-actuated signal.

only if there is a gap equal to or greater than the critical gap. If the RSU instructs the signal controller, there will be two phases, as explained below:

Phase 1: Green on the minor road and FR on minor road
This scenario is when CAVs on the major road can create additional gaps and minor vehicles can accommodate available gaps without the need of serving green to the minor road, only with the following possible conditions:

1. When minor road detectors detect the vehicle before the maximum waiting W_{max} time is reached.
2. When no vehicles are detected on the minor road or a gap found and the calls on the detection are released.
3. When the green time on the major road is less than the minimum green $G1_{min}$ even a vehicle is reached the maximum waiting time.

Phase 2: Red on the major road and green on the minor road:
This scenario is when either create gaps and couldn't accommodate all vehicles on the queue or cannot create additional gaps, which can be as follows:

1. When a vehicle is detected on the minor road and the maximum waiting time W_{max} is reached.
2. When vehicles place calls on minor road detectors and the maximum green G_{max} on the mainline is passed

5 SIMULATION APPROACH

To assess the planned model's effectiveness, the current research implements a simulation-based method using the software of PTV VISSIM. This software enables a microscopic traffic simulation for the examination of a stream of traffic flow operations under specific conditions such as certain flow, speed, and geometry. This software comes under the umbrella of Vision Traffic Suite software and is one of the leading tools for simulation programs based on multimodal traffic operations. The outcomes of the software have been observed to be realistic and almost accurate in every detail. This way, VISSIM is known to provide the ideal conditional for engineers to test various road traffic scenarios before their implementation. The software is also being used globally by various government-based and education institutes as well as consulting firms [21].

The first step was generating the overall traffic network through VISSIM, which includes designing the transport infrastructure such as route choices, priority rules, roads, and the frequency of vehicles along with their composition. The second step was creating CAV in VISSIM to add CAV as a new Vehicle Type and Vehicle Class. The dimension of CAV will remain in the same range as general passenger vehicles.

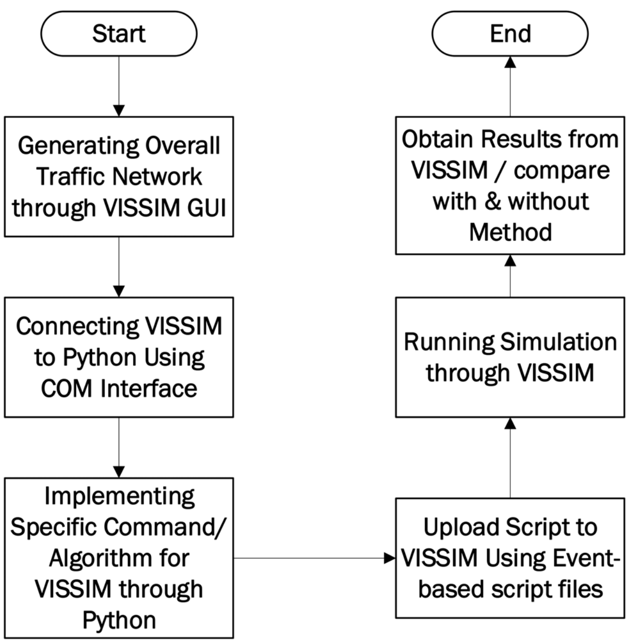


Figure 5: Flowchart of the VISSIM Implementation.

The controlled set of rules is put into use by incorporating VISSIM with Python through the interface of Object Model (COM). However, VISSIM-COM comes into handy when the model entails including custom algorithms that are not available on the version of VISSIM GUI [21]. Since the idea of controlling CAVs at the intersection is not in the GUI in VISSIM, the COM server was registered to be able to use the COM interface. This will allow VISSIM to be connected with the Python program to start writing the script through VISSIM. Then, the specific commands for our algorithm to control CAV's attributes are written through Python. After that, the Python script was uploaded to VISSIM through the Event-based Script files before running the simulation.

Once everything had been configured in VISSIM, the last remaining procedure is to simulate performance results. Based on the fact that VISSIM has a random nature of simulation model, the study performed a minimum of ten simulations with various arrangements of random seed numbers in order to ensure that the reported results and values give an accurate representation of the average. Nodes were placed at the intersection to evaluate the intersection's performance before and after implementing the connected automated vehicles strategy of creating gaps and the modified algorithm.

The measurable parameters reflecting effectiveness and performance of controlled intersections, average travel time, average delay time, queue length, and queue times for a simulated network, can be obtained using VISSIM simulation. The MOEs were used to test the proposed method, including the number of signal interruptions and control delay for the mainline stream beside the intersection's throughput. Different arrival rates on the major and minor roads, along with the different CAVs penetration rates (30%, 50% and 70%), were simulated via VISSIM. Simulations are conducted in two different vehicle compositions. The first vehicle composition is when we do not have any CAVs on the major road flow as the baseline, where the second composition is when we have mixed traffic conditions.

6 RESULTS

In this section, the results presented are from the output of VISSIM evaluation and the average of 10 simulations with different of 10 random seeds; each simulation is 3600-second (1-hour) period.

6.1 Number of Signal Interruptions

The signal interruptions are counted when the minor road vehicles are not able to find a safe gap in the mixed flow and the maximum waiting time is reached. The signal will switch to serve a minimum green to the minor road approach and stop the major road flow. Figure 6 illustrates the number of signals interrupted at different CAVs penetrations with a different allowable maximum waiting time on the minor approach. The number of signal interruptions is presented when the arrival rate of the minor road is 150 and 250 veh/hour, as shown in Figures 6 and 7.

Figure 6 shows the number of signal interruptions of the mainline at 150 veh/hour for different maximum allowable times for the minor road approach. As shown in Figure 6, the number of signal interruptions is inversely proportional and consistently decreases with the increase of penetration rate of CAVs. The number of signal interruptions reduced from 20 in 0 CAVs case to 10 when the penetration of CAVs 70%, which counts for 50% reduction at the maximum allowable time of 30 seconds when the major road volume is 1000 veh/hour. On the other hand, in the case of 30% and 50% CAVs, the number of signal interruptions is only

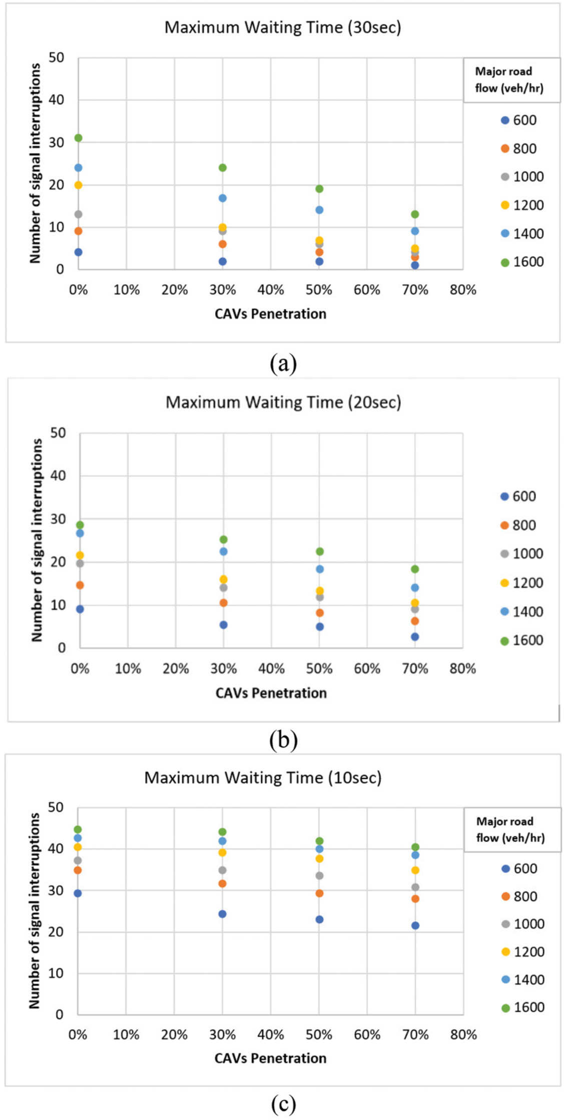
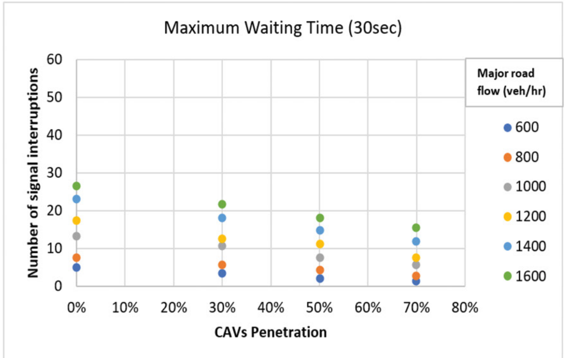


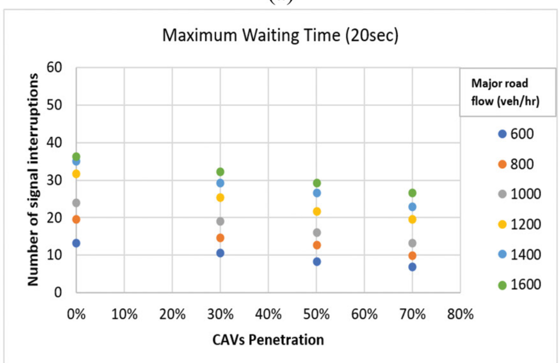
Figure 6: The number of signal interruptions of the mainline at different % of CAVs for 150 veh/hour on the minor road. (a) 30 seconds of maximum waiting time; (b) 20 seconds; (c) 10 seconds.

12, 14 compared to 20 at 100% HVs, which suggests that the additional suitable gaps created by CAVs on the mainline make a huge contribution to decreasing the need of serving green to the minor road which counts to reduce delay and increase the capacity of the intersection.

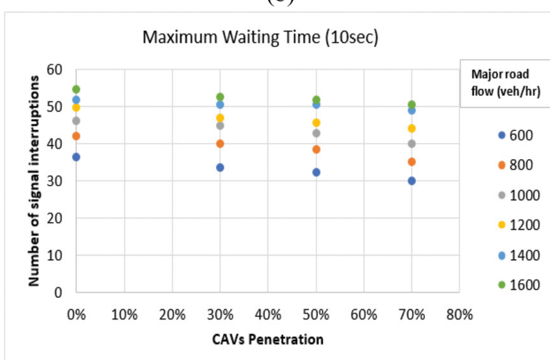
On the minor road, when we compare the three levels of waiting time, it can be seen that increasing the maximum allowable time of the minor road stream before switching the signal timing to serve the minor road would reduce the possibility of interrupting the mainline flow. In the case of a major road volume of 1200 veh/hour, the number of signal interruptions is



(a)



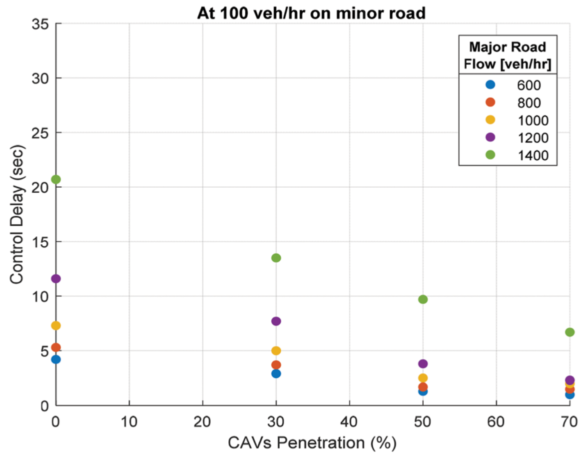
(b)



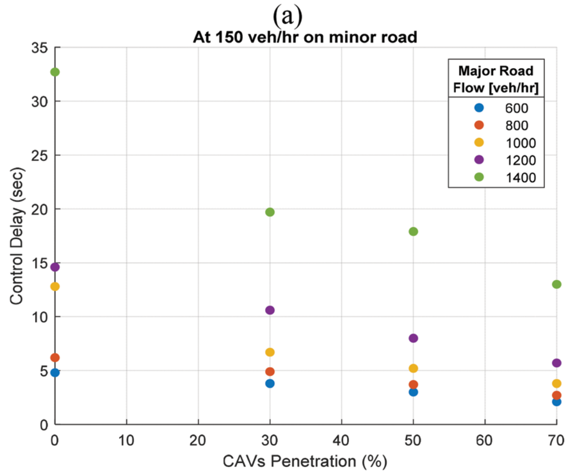
(c)

Figure 7: The number of signal interruptions of the mainline at different % of CAVs for 250 veh/hour on the minor road. (a) 30 seconds of maximum waiting time; (b) 20 seconds; (c) 10 seconds.

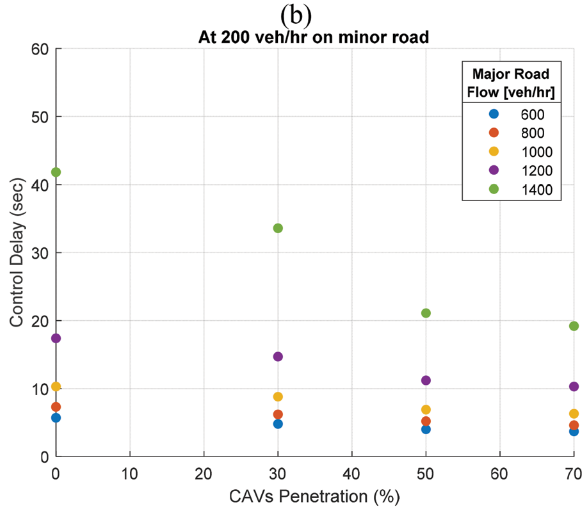
five times at 70% of CAVs penetration when the maximum waiting time is 30 seconds. On the other hand, when the maximum waiting time is only 10 seconds, the number of signal interruptions is 35 times per hour. This is because the more you make the minor road vehicles wait for available gaps before switching the signal, the more the probability of minor road vehicles finding available gaps before reaching the maximum waiting time.


At 100 veh/hr on minor road
Control Delay (sec)
CAVs Penetration (%)
Major Road Flow [veh/hr]
600
800
1000
1200
1400

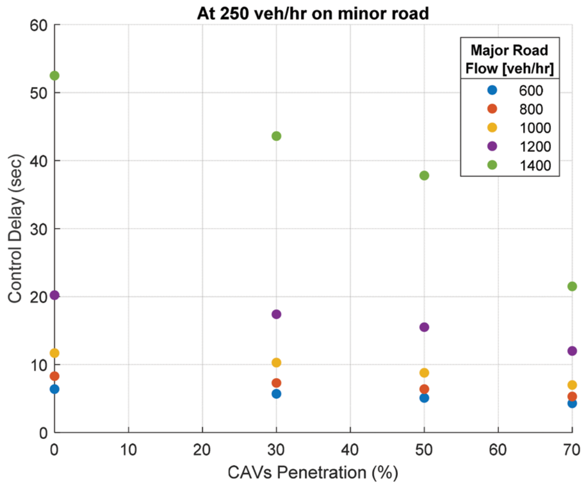
(a)


At 150 veh/hr on minor road
Control Delay (sec)
CAVs Penetration (%)
Major Road Flow [veh/hr]
600
800
1000
1200
1400

(b)


At 200 veh/hr on minor road
Control Delay (sec)
CAVs Penetration (%)
Major Road Flow [veh/hr]
600
800
1000
1200
1400

(c)



(d)

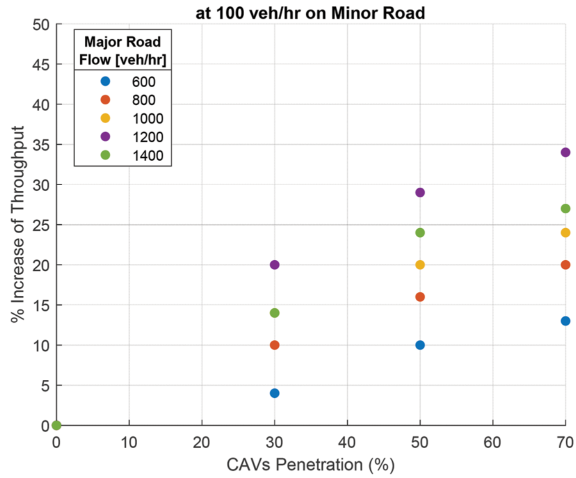
Figure 8: Control delay of the mainline approach at different % of CAVs and major road volumes. (a) 100 vehicles per hour on minor road; (b) 150 vehicles per hour; (c) 200 vehicles per hour; (d) 250 vehicles per hour.

Figure 7 shows the number of signal interruptions when the arrival rate of the minor road is 250 veh/hour. When the penetration rate is 70%, the number of signal interruptions on the mainline is reduced by 50% compared with the 0% CAVs penetration at a maximum waiting time of 20 seconds and major road volume of 800 veh/hour. Even with less percentage of CAVs, the number of signal interruptions is reduced at 30% and 50% CAVs on the major road where the number of signal interruptions is 13 and 15, respectively. It reveals that the interruption of the major road is more possible to happen when the CAVs penetration is 0% compared with when CAVs penetration increases.

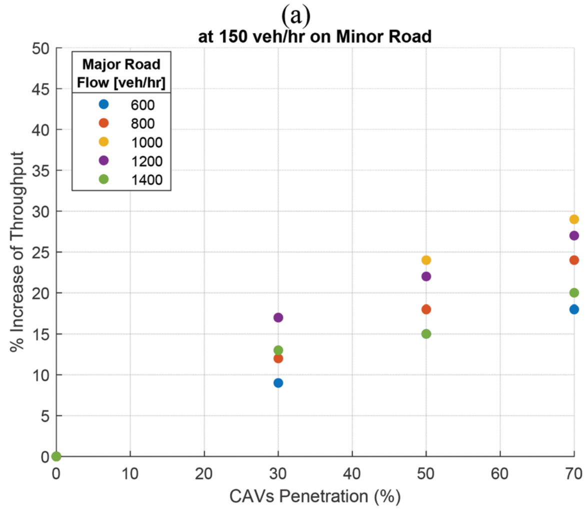
With the increase in the CAVs penetration on the mainline, the number of signal interruptions of the mainline reduces. That is because when there are more CAVs, the probability of creating additional safe gaps increases, which reduces the queue of the minor road approach. The reduction of the queue of the minor road approach would result in reducing the need to serve the minor approach signal. It can be found that at a low volume of the major road, the number of mainline interruptions is less than when the major road volume increases. Also, when the minor road volume increases, the possibility of interrupting the mainline increase.

6.2 Control Delay

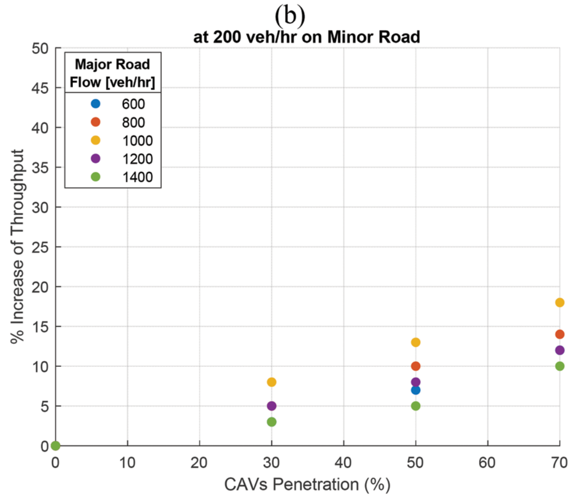
Control delay is the portion of the total delay attributed to traffic signal operation where it is defined as the primary performance measure for the signalized intersections. HCM defines the LOS of signalized intersections based on control delay. Figure 8 presents the control delay of the targeted intersection at different vehicle volumes on the major and minor roads along with a different percentage of CAVs. For all levels of minor road volumes, with the increase of major road volume along with the increase of CAVs penetration, the mainline delay reduces due to reduced interruptions on the major road approach.


at 100 veh/hr on Minor Road
Major Road Flow [veh/hr]
600
800
1000
1200
1400
% Increase of Throughput
CAVs Penetration (%)

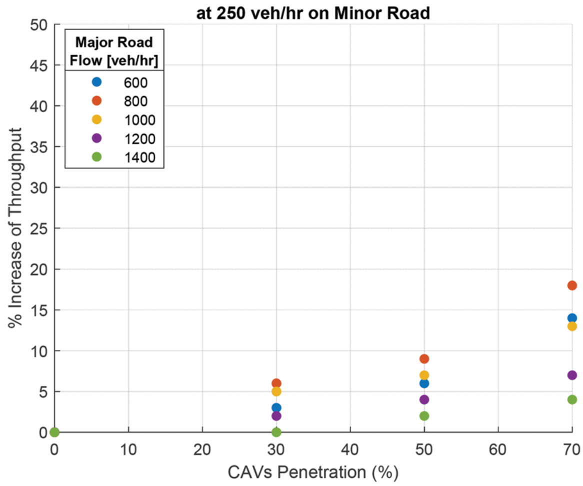
(a)


at 150 veh/hr on Minor Road
Major Road Flow [veh/hr]
600
800
1000
1200
1400
% Increase of Throughput
CAVs Penetration (%)

(b)


at 200 veh/hr on Minor Road
Major Road Flow [veh/hr]
600
800
1000
1200
1400
% Increase of Throughput
CAVs Penetration (%)

(c)



(d)

Figure 9: The increase of intersection's Throughput due to the additional gaps created by CAVs at different major and minor road volumes and CAVs penetration.

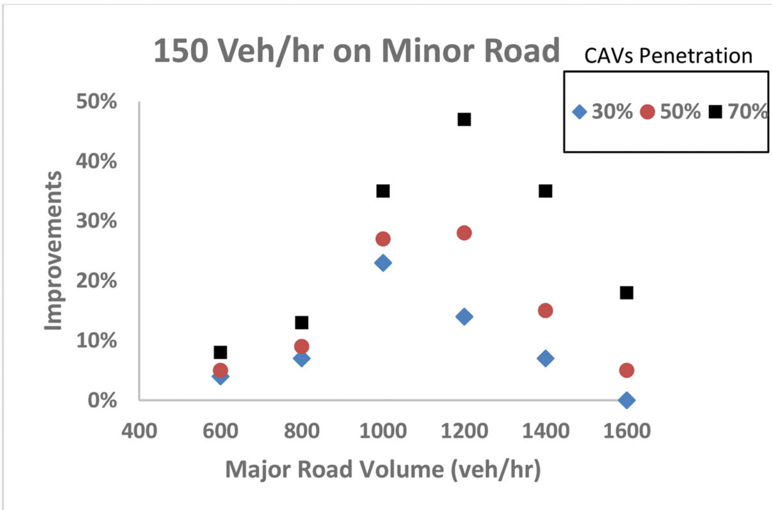
As shown in Figure 8, the control delay of the mainline is 13 seconds when the major road volume is 1400 veh/hour, and CAVs penetration is 70%, compared with 32 seconds when the CAVs penetration is 0% at 150 veh/hour on the minor road. For lower flow values on the major road such as 600 and 800 veh/hour, the improvements on the control delay are less than when the major road increases, and it is due to the increase of the major road volumes, the number of CAVs creating gaps increased. When comparing the minor road volumes with the result of the control delay, it can be seen that with the increase of the minor road volumes, the need for signal switching increases resulting in increasing the control delay of the mainline.

6.3 Throughput

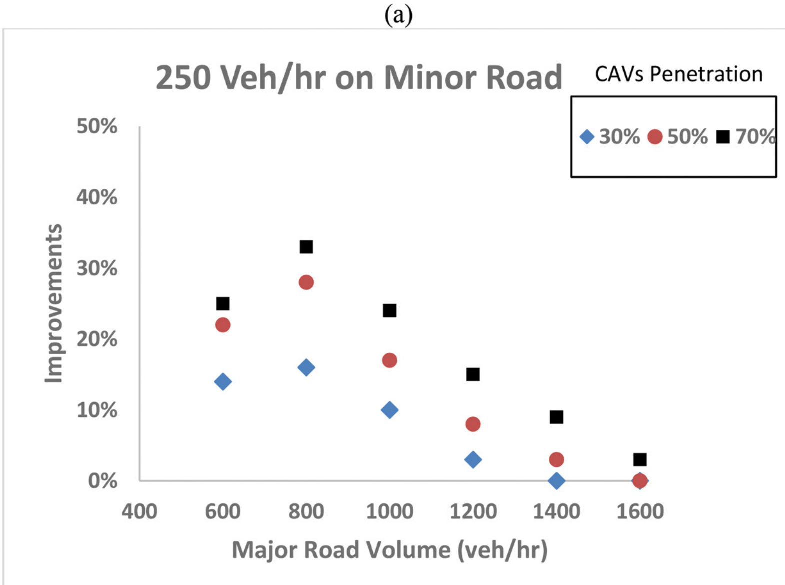
Since CAVs help creates additional gaps for the minor road vehicles, the number of vehicles on the minor road approach that needs signal accommodations decreases, and the intersection's throughput is expected to increase. The results of the increase in the intersection's throughput are observed and analyzed. Figure 9 presents the increase in the intersection's throughput of the targeted intersection at different vehicle inputs on the major and minor roads along with a different percentage of CAVs. Figure 9 presents the impact of the modified algorithm on the intersection's throughput for three levels of CAVs penetration. The increase in the intersection's throughput results in Figure 9 indicates that when the minor road is at low volume (100 veh/hour), the throughput will increase until the volume of the major road (1000 veh/hour). Once the major road increase above 1000 veh/hour, the intersection's throughput will decrease due to the increase of signal interruption of the mainline, as explained in Figure 6. However, the intersection throughput improvements will decrease when the minor road volume increases and the major road volume increases simultaneously. This is because the increase of the major and minor volumes would make the number of additional gaps created by CAVs limited due to the capacity of the mainline and results in reducing the capability of increasing the throughput of the intersection.

6.4 Fuel Consumption

With the rapid increase in the number of vehicles worldwide, traffic congestion has been a problem in the field of transportation engineering that caused huge fuel consumption and traffic emissions [23]. It is known that delays caused by waiting at the stop-line of a signalized intersection may increase vehicles' fuel consumption and emissions. In this study, the fuel consumption of the minor and major road vehicles was obtained from VISSIM to



(a)



(b)

Figure 10: The improvement of fuel consumption due to the additional gaps created by CAVs at different major and minor road volumes and CAVs penetration.

evaluate further the proposed algorithm based on environmental impact. Figure 10 presents the improvement in fuel consumption at different CAVs penetration along with different major and minor road volumes.

Figure 10 shows that with the increase of major road volume and the increase of CAV's penetration, the fuel consumption can be reduced up to 48% compared with the case of no CAVs at 70% CAVs penetration, and the minor road volume is 150 veh/hour. Notably, the highest benefit of the control algorithm for the fuel-saving (48%) is achieved at the highest CAVs penetration and medium to the high-traffic volume of both streams. Therefore, the proposed method reduced fuel consumption and reduced traffic emissions.

7 CONCLUSION

The rapid development of CAVs in the last decade brought high achievement to the transportation system. Additionally, traffic signals have become more advanced and more efficient with the advantage of CAVs. This paper proposed a framework for CAVs to create additional adequate gaps on the major road to the minor road vehicles to reduce the interruption of the continuous flow on semi-actuated signalized intersections. The algorithm was based on a framework developed for unsignalized T-intersection, and this study developed the algorithm to be suitable for semi-actuated signalized T-intersections. The main objective was to reduce the interruption of the major road while increasing the total throughput of the intersection.

The modified algorithm presented in this work significantly improves the total intersection performance since the interruption of the continuous flow is reduced at different percentages of CAVs. As the penetration of CAVs increases, the throughput of the intersection improves with a sharp increase at around 30% when the CAV's penetration is 70%. Results of the simulation showed that the number of signal interruptions of the major road stream reduces when the number of CAVs increases. This was achieved by increasing the number of suitable gaps to the minor road vehicles when the algorithm was applied to reduce the need for signals to the minor road stream.

In this research, reducing fuel consumption is achieved by reducing the waiting time of major and minor road vehicles when applying the modified signal control and the algorithm. The proposed method decreased the fuel consumption by reducing the possibility of major and minor vehicles stopping at the signal. Such results indicate the importance of the proposed algorithm on protecting the environment by saving fuel at intersections.

The results of this study can improve such T-intersections where it reduces the need for signalization; the modified algorithm can be applied on intersections where the minor road stream arrival rate fluctuates from one time to another. Further studies can focus on four-leg intersections to further improve the algorithm applied on such intersections and more lanes on each direction to study the lane changing on creating gaps.

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