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IMPROVING THE PERFORMANCE OF UNSIGNALIZED T-INTERSECTIONS WITHIN CAVS MIXED TRAFFIC

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The rapid growth in population and the increase in the number of vehicles on the road have resulted in severe traffic congestion over the last two decades. However, intersections, where different flows intersect, are among the major cause of traffic congestion besides bottlenecks. Past decades have seen major technological advancements in road vehicles aimed at making vehicles traveling securely and comfortably. Current connected and automated vehicles (CAV) are packed with lane-keeping assistance and adaptive cruise control to ensure that vehicles do not collide and reduce traffic congestion. In this research, we developed a control algorithm that utilizes CAVs to help generate additional usable gaps for the minor road vehicles to enter the intersection without affecting the mainline traffic flow. Simulation results showed that the delay and queue length of the minor road approach is minimized without causing a significant delay to the mainline. The minor road delay was reduced by 72% when the percentage of CAVs on the major road is 70% compared to the benchmark with no CAVs on the major road.

Key words: CAVs, connected and automated vehicles, unsignalized intersections, gap acceptance, intersection priority, merging capacity

INTRODUCTION

The rapid population growth and the attendant increase in vehicle numbers over the last few decades have caused widespread travel problems, with traffic congestion forecast to increase by 60% by 2030 [1]. Those problems lead to inefficient use of the transportation network, forcing drivers to spend more time commuting and increasing the overall fuel consumption. Among the major bottlenecks that cause traffic congestion are road intersections with different flow conflicts [2]. Low congested intersections are less critical to be managed than high congested intersections. The decision made in the Latter case is fundamentally important to avoid increasing congestions [3]. Most intersections in urban areas are signalized to regulate the movement of traffic flows. The unsignalized intersections are typically found in suburban areas where low and high traffic flows meet. There is a higher chance of collision at an unsignalized intersection than signalized intersection due to the driver's indecision or wrong decision to enter the intersection from the unsignalized approach. One report of the National Highway Traffic Safety Administration (NHTSA) in 2011 indicates that 40% of car collisions in the U.S. happen at intersections, and 60% of them are related to unsignalized intersections [4]. Accidents occur at unsignalized intersections not only because of a lack of traffic control devices but also often due to geometric condition constraints or inappropriate speed control [5]. With such limitations, drivers from the minor road often face the challenge of selecting a proper vehicular gap to enter the intersection, as any mistake could lead to a safety hazard, in addition to a negative effect on efficient inter-

section operations. At major-minor intersections, traffic control for vehicles on the major road generally has a priority over the minor road. With low traffic on the major road, larger gaps may be found in the traffic stream; on the other hand, with high traffic on the major road, it is more likely to have smaller and less safe gaps for the minor road drivers to choose from [6]. A longer waiting time experienced by the driver while waiting can result in losing patience to accept a shorter critical gap [7]. Moreover, additional factors may also influence the gap selection behavior of the driver, including age group, time of the day, and trip purpose. However, the biggest influencing factors are the presence of a queue behind the driver, the number of gaps rejected, as well as the wait time [8]. The potential capacity of the major-minor unsignalized intersections depends on gaps available for the minor road vehicles that are larger than the critical gap. The safety of such intersections is affected by the gap acceptance of the minor road vehicles. In 2008, fatal angle collisions at unsignalized intersections were likely the results of minor road vehicles taking smaller gaps. This is evidence that with the increase of the available gaps on the main road, the frequency of theses crashes will be reduced [11]. Additionally, the major road vehicles experience interruption from the minor road vehicles when taking smaller gaps due to the limitation of the available safe gaps [12]. It can be affirmed that the increase of available suitable gaps on the mainline will not only help the minor road stream but also will reduce the interruption of the major road. Such additional gaps can be countered with the help of new technologies such as connected automated vehicles (CAVs). 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 [11]. 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 completely 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 [12]. This research aims to enhance the performance of unsignalized intersections with the help of connected automated vehicles in creating extra adequate gaps to the minor road vehicles when needed at a mixed traffic condition. 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 such 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.

LITERATURE REVIEW

Transportation is being transformed by connected and automated vehicles (CAVs). Connected and automated vehicles (CAVs) use advanced wireless technologies like Cellular V2X (C-V2X) or Dedicated Short-Range Communication (DSRC). These wireless technologies would create a link between vehicles to form a network of shared information such as speed, location and traffic control, etc. [13]. This shared link includes "Vehicle to Infrastructure" (V2I), "Vehicle to Vehicle" (V2V), and "Vehicle to X (other connected devices)" (V2X), which enables data communications among them [14]. According to the simulation and field test phases that CAVs have passed, the vehicles are beneficial to the road system due to their automated features and other configured communication sensors such as V2V and vehicle to everything (V2X). When it is combined with the wireless communication systems, the automated driving and data processing technology empower the connected and automated vehicles (CAV) to be a potential solution to the safety and congestion problems [15]. These features and configurations are considered an advantage because they help improve traffic flow and reduce traffic flow interruption, thereby enhancing safety and fuel consumption, and emission [16]. Existing studies, including limited field tests, have shown the benefits of CAVs in re-

ducing traffic flow interruptions and improving traffic flow dynamics, thereby enhancing safety and efficiency and reducing fuel consumption and emission [16]. It is also well understood that, before CAVs become a dominant, frequently used technology, a mixed form of vehicles, human-driven vehicles (HV) along with CAVs, will be driving simultaneously on the road [17]. Automated Traffic Control has gotten a lot of attention lately due to the rise of autonomous ground vehicles and recent advances in Intelligent Transportation Systems. Autonomous Intersection Management (AIM) is also called Cooperative Intersection Management (CIM). It is one of the more difficult traffic challenges, raising serious concerns about safety and efficiency in terms of delayed, fuel usage, pollution, and durability [18]. In the intersection, the management of CAVs is divided into centralized and decentralized techniques where the centralized technique contains a management unit coordinating CAV rights-of-way, with the management unit attempting to improve efficiency after receiving data from all associated CAVs [19]. In contrast, the decentralized technique CAV decides its own control strategy depending on the data got from other CAVs and side of the road foundation [20]. Dresner and Stone presented the first study that developed Autonomous Intersection Management (AIM) [21]. It was followed by a number of research that conducted similar concepts and most of these approaches used First-come, first-serve (FCFS) [22]. Multiple models were used to develop AIM, including linear programming [23], mixed-integer linear programming [24], and mixed-integer nonlinear programming [25]. AIM was also formulated in different models to be a control framework [26], or as optimization problem [27]. Furthermore, there are researches focused on this issue in terms of model predictive control framework [28] or as a dynamic optimization issue [29]. Multiple AIM models presented different findings. Of which, vehicle arrival time at the departing time or conflicting points was discussed by some models along with the calculation of the intersection exit time [30]. On the contrary, other models focused on the total vehicle number which was permitted to move [24]. The ultimate goal of these varying models was focused on maximizing the overall throughput [31], limiting the total travel time period [32], reducing the consumption of the fuel [33], and diminishing the potential threat [26]. The main purpose of developing AIM is to compromise autonomous or connected automated vehicle (AVs/CAVs) so that the controller can be followed by all the vehicles. Limited studies exist in when it comes to the interaction of AIM with human vehicles which are not partially or not equipped with the V2I and V2V communication facilities neither possess an autonomous driving module [34]. Most of research used traffic lights as a medium of communication with human vehicles and others consider only autonomous and automated vehicles without considering mixed traffic. Many CAV application studies on unsignalized intersections have been reported, and most of them are conducted under the assumption of a

100% CAV environment to explore potential benefits of CAVs; only a few studies have focused on unsignalized intersections in mixed traffic conditions [35]. Zhong, et al. [36] studied a priority unsignalized intersection management to ensure vehicle crossing while considering the efficiency and safety of both approaches. The vehicles on the major road will have priority while creating gaps for the minor road. Similarly, a gap-based eco-driving speed control algorithm for unsignalized intersections was studied by considering the realistic traffic conditions. The proposed algorithm incorporates information about the gaps, initial speed, and vehicular position as control variables while performing optimizations to develop the acceleration/deceleration profiles; hence, guiding vehicles at the stop line [37]. Although the proposed method was found to improve efficiency while considering safety, the study considers only fully automated vehicles at the intersection. All the above studies have treated the traffic coming to the intersection at an equal level of importance. Additionally, most of intersection are signalized and few authors focused on unsignalized intersection considering the human behavior. More studies are needed at a major-minor intersection with priority set for the major road under mixed traffic conditions. This research aims to enhance the performance of unsignalized intersections with the help of connected automated vehicles in creating extra adequate gaps to the minor road vehicles when needed at a mixed traffic condition. 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 rest of the paper is organized as follows: Section 3 introduces the framework that guides CAVs in creating gaps, including the formulation, communication, and simulation. Section 4 reviews the results of the simulation to validate the effectiveness of the proposed framework. Section 5 provides the conclusions of this work and some future research directions.

METHODOLOGY

The research's main objective is to 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 method takes into consideration safety as the priority as well as efficiency, and its main benefit is to minimize interruptions to the mainline traffic flow due to minor road vehicles.

Intersection Layout

This study focuses on T-intersections for simplicity, where a minor road approach interests a major road. The minor road approach is controlled by either an actuated signal or a stop sign where the major road approach has the right of way. The minor road approaches have one lane, but the major road may have one or more lanes in each direction, as shown in Fig. 1. CAVs are operated only in major street flow with different percentage penetrations

where a minor street has only human vehicles HVs. The main assumptions of this method 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.
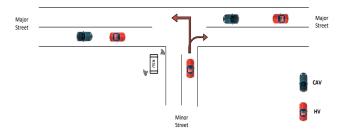

Figure 1: Geometric configuration of the intersection studied

The Safe Gap 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 road 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.
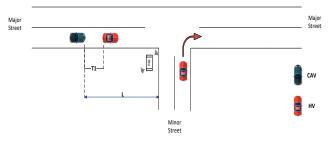

Figure 2: Distance between CAV and the leading vehicle (T_1)

In this scenario shown in Fig. 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 LAV divided by the speed of CAV v subtracting from distance of HV to intersection LHV divided by the speed of HV v:

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

Where: v is the approaching speed in ft/sec, L_{CAV} is the distance of the CAV towards the intersection in ft, and L_{HV} is the distance of the HV to the intersection in ft. 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 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 Fig. 3.

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

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.
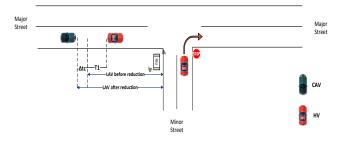

Figure 3: The extra time added to create the extra safe gap (Δt_c)

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:

$$\frac{L_{CAV}}{v} - \frac{L_{HV}}{v} + \Delta t_c \geq T_0 \tag{3}$$

By substituting Equation 2 to 3, then:

$$\frac{L_{CAV}}{v} - \frac{L_{HV}}{v} + \frac{L_{CAV}}{v_c} - \frac{L_{CAV}}{v} \geq T_0 \tag{4}$$

This results in:

$$\frac{L_{CAV}}{v_c} - \frac{L_{HV}}{v} \geq T_0 \tag{5}$$

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 Equation 6 to 5, then, the equation will be as follows:

$$\frac{L_{CAV}}{\beta v} - \frac{L_{HV}}{v} \geq T_0 \tag{7}$$

The time for communication between CAVs and RSU through V2I is neglected compared with the speed of vehicles [38]. 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 Eq. (7), as follows:

$$\frac{L_{CAV}}{\beta v} - \frac{L_{HV}}{v} \geq T_0 + \Delta t_{trans} \tag{8}$$

The Safe Distance Based on Safe Car-following Distance (CFD)

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 speed of CAVs on the main road. In the scenario, an HV is behind a CAV, as shown in Fig. 4. 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. CFD is calculated based on Stopping Sight Distance (SSD).

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

Where C_{back} is the following vehicle distance to CAV before reducing speed; CFD can be determined as:

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

Where V_o refers to the initial speed of the subsequent vehicle (ft/sec) ; v_f represents the required reduced pace of CAV for creating an extra safe gap for the minor street

approach (ft/sec); t_r is the perception-brake reaction time (sec); f is referred to as a coefficient of friction, and G is the grade level of the street. As shown in Fig. 4, 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 car-following distance, to further enhance safety, the following equation is utilized:

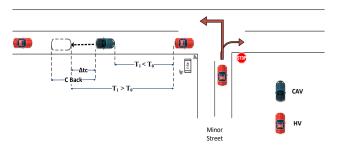$$C_{back} - (\Delta t_c\ v) \geq CFD \qquad (11)$$

Figure 4: The added time when CAV reduces speed

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 Equation 9 before Equation 11. In this model, V2V and V2I communication were also used to make decisions when CAVs can reduce speed to create extra safe gaps. Detailed information regarding nearby vehicles' movement to calculate the gaps could be provided through V2V communications or the CAV sensors. V2I communication could inform the targeted CAV when a vehicle is in the minor street approach looking for a gap to slow down through the roadside unit (RSU). The range of communication by V2I is assumed to be the current effective DSRC communication range or 5G (300 m).The communication process starts when a detector detects a
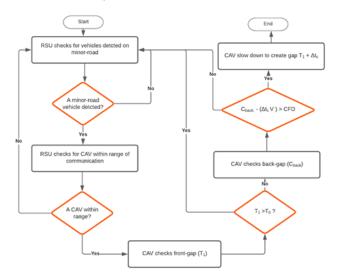

Figure 5:CAVs communication process of the proposed CAV framework

vehicle in the minor street approach, and RSU obtains it. Then, RSU feeds CAV, which are within the range of communication, information regarding incoming vehicles from the minor street approach. Once a CAV received information from RSU, it would check the gap towards the intersection to check it with the critical gap. If the gap is less than the critical gap, the CAV will start to check for the safe distance, the distance of the following vehicle to CAV to ensure it is safe. The process of the connected automated vehicles in creating gaps is shown in Fig. 5.

Unsignalized Intersection Scenarios

In this section, two scenarios of CAVs on the major road stream are presented and analyzed. In this case, the major road traffic has the right of way, and the minor road users have to wait at the stop sign before merging as shown in Fig. 1. The minor road vehicles will enter only if there is a gap equal to or greater than the critical gap. In a mixed traffic flow, if the RSU instructs a CAV to check if it can help create a usable gap, it will have two options to take, as explained below:

• Option 1: Do nothing: This scenario is when a CAV is within the range of communication but cannot create a needed gap due to the following possible conditions:

1. The front gap time of the CAV from the leading vehicle HV is greater than the critical gap, so there is no need for gap creation, or:

$$T_1 \geq T_0$$

2. The front gap time of the CAV is less than the critical gap, but the CAV cannot help to create a usable gap. This happens when a CAV is too close to the leading HV and not enough time can be saved by slowing down, that is:

$$T_1 + \Delta t_c < T_0$$

3. The back gap of the CAV to the following HV is less than the safe distance required. This scenario is when the following HV is close to the CAV, and it is unsafe for the CAV to reduce speed, or:

$$C_{back} - (\Delta t_c\ V) < CFD$$

• Option 2: Reduce Speed: This scenario is when a CAV can reduce speed to help create a long enough gap for the minor road vehicle, and it can satisfy both of the following conditions:

1. The front gap time is less than the critical gap, and CAV can help to create a gap not less than the critical gap by reducing speed, that is:

$$T_1 + \Delta t_c \geq T_0$$

2. The back gap of the CAV from the following HV is greater than the safe distance:

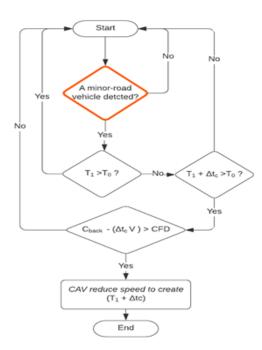$$C_{back} - (\Delta t_c\ V) \geq CFD$$

Figure 6: Flow chart of the process of CAVs scenarios

Left Turn Scenario

The above discussion has considered only one direction traffic on the major road, with minor road vehicles turning right. However, for minor road vehicles turning left, safety considerations must be given to both directions on the major road because of the potential conflicts. Fig. 7 shows a minor road vehicle waiting to find a gap to turn left and join the mainline traffic.
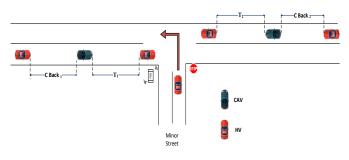

Figure 7: Road entry through a left turn

In this case, the CAV will check if, in each direction, the condition $T_i < T_0$, exists and the CAV can slow down to create a gap value of Δt_c to satisfy the condition $T_i + \Delta t_c \geq T_0$. The algorithm will not let the CAV participate before making sure that CAVs in both directions can help create the needed ng safe gaps. If the back gap of either direction on the major road is less than the car-following distance CFD, the algorithm will select option 1 (do nothing). The control algorithm for minor road vehicles turning left is shown in Fig. 8.
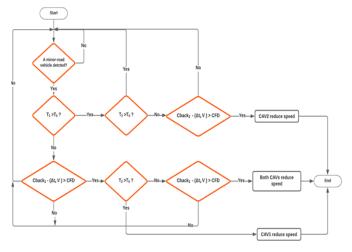

Figure 8: Control logic for left turns with CAVs in both directions

SIMULATION & RESULTS

In this section, the control algorithm is simulated using PTV VISSIM platform and the accompanying code is written in Python. The section discusses in detail the experimental and simulation setup along with the results. The results implications are also discussed at the end of this section.

Simulation Setup

The most useful tool for traffic engineers to measure the effectiveness of a method is to simulate the method through traffic simulation software. To test the concept and estimate the potential effectiveness of the proposed method, a simulation was performed using the VISSIM platform. VISSIM simulates in every detail realistically and accurately the traffic condition designed where VISSIM creates better conditions than many other software tools to test different traffic scenarios before implementation. VISSIM is chosen because it is now being used widely by the public sector, consulting firms, and universities [10]. The controlled set of rules are put into use by incorporating VISSIM with Python through the interface of Object Model (COM). VISSIM-COM comes into handy when the model entails including custom algorithms that are not available on the version of VISSIM GUI. This will allow VISSIM to control the attribute of CAVs on the network to apply the control algorithm. Due to the stochastic nature of traffic arrivals, a minimum of 10 simulation runs were performed with different random seed numbers to ensure that the values reported incorporating the stochastic changes in traffic flow. Since the car-following behavior has a direct impact on creating gaps by reducing speed and traffic flow, the Wiedemann 99 model has been chosen in this work because it is more advanced and flexible than Wiedemann 74 [40]. the Wiedemann 74 is recommended by the VISSIM user manual to be used in urban areas where Wiedemann 99 can be used on freeways and multilane highways [41]. This paper used the default values of the Wiedemann 99 car-following

model and it has ten essential parameters that can be found on PTV VISSIM's user manual [42]. The critical gap is the minimum gap needed by a driver to enter the intersection from a minor road stream. The critical gap value differs from one intersection to another, but HCM states that the average of these values based on many experiments can be used in experiments. In this study, the critical gap value used in this study is based on Highway Capacity Manual (HCM) [39]. The test plan includes comparisons to evaluate intersection performance before and after implementing the CAV utilization strategy to create gaps. The vehicle setting was standardized for both human-driven vehicles HVs and connected and automated vehicles CAVs. This includes the vehicle size of passenger vehicles and their attributes, and the speed used in this simulation platform is 35 mph on the major road and 25 mph on the minor road. Two types of vehicle compositions are specified. The first is when there are no CAVs on the major road, which is the benchmark for comparison, the second includes a mixed traffic condition with CAVs and HVs. Different traffic demand levels are considered on the major and minor roads along with different penetration of CAVs on the major road. The measures of effectiveness (MOEs) were used to evaluate the proposed method, including delay, queue length, and fuel consumption.

Results

The stopped delay occurs when a vehicle is waiting for a safe gap at the minor road approach. The average stopped delay, grouped by different penetrations of CAVs, is shown in Fig. 9, where three different CAVs percentages are presented as 30%, 50%, and 70%. Fig. 9-a, b, c, and d represent the minor road volumes as 100, 150, 200, and 250 veh/hr.
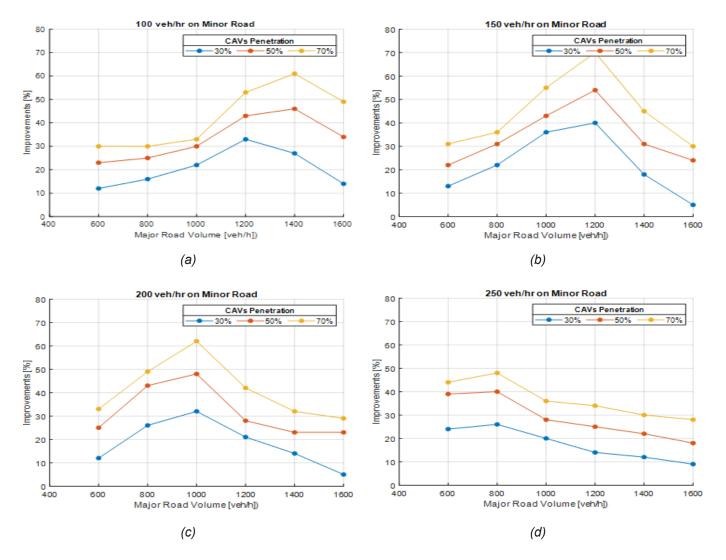

(a)

(b)

(c)

(d)

Figure 9: Improvement in waiting time of the minor road queue at different major and minor road volumes along with different CAVs penetration

The waiting time on the minor road stream improved at all levels of traffic on the minor road. As shown in Fig. 9, 70% of CAVs on the major road from the total volume is the highest improvements on all traffic levels of the minor road. When the volume on the minor road is low, 100 veh/hr, the improvements on the waiting time of the minor road approach increases until the volume of the major road reaches 1400 veh/hr. Once the major road increase above 1400 veh/hr, the improvements decrease as shown in Fig. 9-a. When the minor road volume increases to 250 veh/hr, as shown in Fig. 9-d, the improvements on the waiting time increases until the major road volume reaches 800 veh/hr, then, the improvements decrease. The highest point of improvement on the waiting time of the minor road depends on the major road volumes. When the minor road volume increases, the highest point of the improvements shifts to the left due to fewer gaps available on the major road and an increase in the demand on the minor road stream As shown in Fig. 9, when CAV's penetration to the total volume on the major road increases, the stopped delay of the minor road approach decreases to a certain level. This is primarily because the increase of flow in the major road and the increase of CAVs' can help create more safe gaps. Therefore, the increase in the number of safe gaps would lead to less waiting time on the minor road approach, resulting in improved stopped delay compared with no CAVs on the major road. However, once the major road vol-ume reached a certain level, the improvements start to decrease because more vehicles on the major road will result in shorter headways between vehicles. The reduction of the headway reduces the possibility for CAVs to create safe gaps in the minor road vehicles. The waiting time of the minor road vehicles increases and cause a bottleneck at the unsignalized intersection when the major and minor road volumes increase due to the limitation of the throughput when the capacity is reached. However, the results indicate that the control logic can increase the throughput of the intersection from both directions when CAVs create gaps. This shows that the proposed algorithm achieved its objective and the created gaps are accepted.The impact on the major road traffic flow is also studied by obtaining the average delay on the major road approaches before and after the proposed method, and it is calculated as: Table 1 shows a comparison between the delay added to the major road with the improvement in reducing delay on the minor road. The result shows that the delay caused to the major road at low volumes is almost zero while on the minor approach is 23% & 30%. The added delay to the major stream reaches 11% at 1000 veh/hr of traffic on the major road, whereas the improvement in the minor road approaches increases to 62%. Therefore, the proposed method at unsignalized intersections is mainly helping the minor-road approach without affecting the major road efficiency and safety.
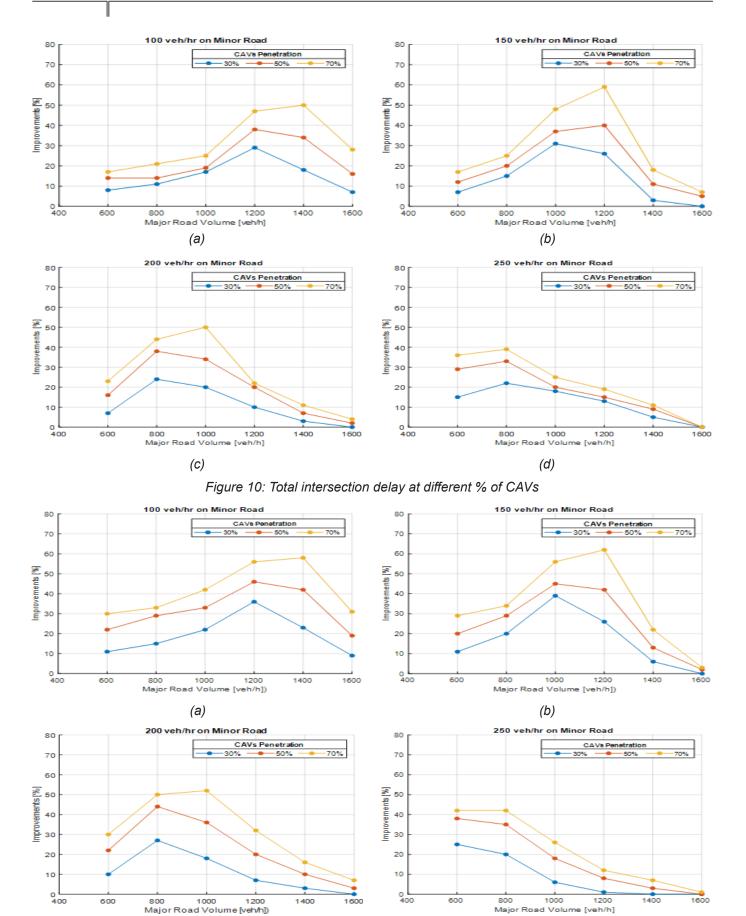
$$Additional\ Average\ Delay = delay\ with\ CAVs - delay\ without\ CAVs \tag{12}$$

Table 1: Comparison between delays added to the major road with improvements in the delay at the minor road

Minor Road Volume (vph)	Major Road Volume (vph)	% of CAV	% of Delay added (major road)	% of Improvements in Delay (minor road)
100	600	50%	1%	23%
	1000	50%	2%	30%
150	800	30%	3%	15%
	1200	30%	6%	40%
200	600	70%	4%	23%
	1000	70%	11%	62%
250	800	30%	6%	22%
	1200	50%	20%	25%

To understand and investigate the average additional delay caused by CAVs reducing speed to create additional gaps to the minor road and compare it with the improvements on the minor road approach, the intersection delay is presented and analyzed. The intersection delay measurement can evaluate the minor road approach delay improvements and the average additional delay on the major road combined. Compared with the benchmark, the intersection delay has improved up to 60% when the CAVs penetration is 70%. This is due to the number of gaps created on the mainline to the minor road vehicles increased resulted in reducing the delay of the minor road stream. As shown in Fig. 10, the improvements in the intersection's average total delay increase when the number of CAVs increases on the major road. This is because with the increase of the number of CAVs on the major road, the probability of creating additional gaps to the minor road approach increases, which reduces the delay of the intersection delay. Since there is an improvement in the total intersection delay at all CAVs penetration levels, the control logic showed its effectiveness as one measurement of effectiveness (MOE) is improved. However, with the increase of the major and minor road volume, improvements of the intersection

Figure 10: Total intersection delay at different % of CAVs

Figure 11: Improvement in the queue length of the minor road at different major and minor road volumes along with different CAVs penetration

delay decrease due to the limitations of the intersection capacity. The queue length is defined as the distance of the rear end of the furthest stopped vehicle from the stop line. In VISSIM, the queue length at intersections is defined from the queue counter location on the last vehicle's entry link in the queuing state. This section observes the field measured the average queuing length of the minor road approach at different major and minor road volumes and different CAVs' penetration with the corresponding simulation outputs for the target intersections. Fig. 11 shows the improvement in the queue length of the minor road approach at different CAVs penetration. Each figure represents a different minor road volume where the volumes of the minor road volumes are 100, 150, 200, 250 veh/hr. The minor street approach's improvement in queue length was also examined with different major road volumes: 600, 800, 1000, 1200 1400, and 1600 vehicles per hour. The queue length and the waiting time on the minor road approach are related since with the increase of the waiting time, the queue length will increase. As a result, the queue length improvements will follow the pattern of the waiting time results. The increase in the number of CAVs on the major road helps to reduce the queue length on the minor road

approach. The increase of the minor road will increase the need for gap creation on the mainline, which increases the queue length when the major road flow increases. This is due to the limitation in the intersection capacity. It can be seen from the graphs above that the queue length of the minor road approach reduced with the increase of the number of CAVs on the major road. The result shows that the queue length was reduced by about 62% when CAV's penetration reached 70% at 150 veh/hr on the minor road approach, and the major road volume was 1200 veh/hr. Even with the 50% and 30% of CAVs on the major road, the results show a decrease in the queue length due to an increase in the number of gaps created when the number of CAVs increases. The decrease in queue length for the minor road stream can further improve driving behavior since the waiting time and queue length affects the gap acceptance behavior for drivers waiting for a gap at the minor road, as stated in the literature. This shows that the control logic of this study improves not only the performance but also the safety of unsignalized intersections since the behavior of the drivers at unsignalized intersections depends on the number of gaps available on the major road stream. From Fig. 9 and Fig. 11, we can observe that deploying
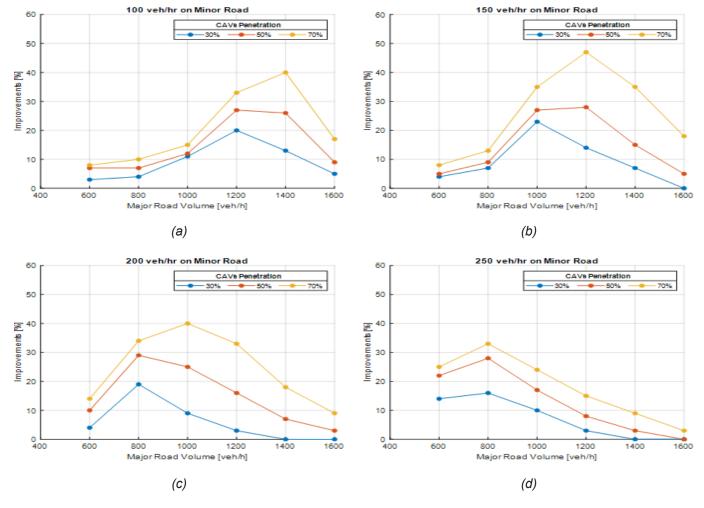

(a)

(b)

(c)

(d)

Figure 12: Fuel consumption improvements at different major and minor road volumes along with different CAVs penetration

CAVs in the road network with the proposed strategy can positively impact traffic efficiency. The is because the minor road approach waiting time and queue length was reduced at all traffic levels. Based on the analysis above in terms of the effectiveness of CAVs creating usable gaps to the minor road approach, it was concluded that the strategy of controlling such an unsignalized intersection with the help of CAVs would help reduce the congestion on the queue of the minor approach. It can also be concluded that the implementation of the control algorithm will positively impact the operation of the unsignalized intersection and drivers' behaviors. The waiting time that a driver uses at intersections increases overall fuel consumption, which also increases emissions. Fig. 12 that with the increase of major road volume and the increase of CAV's penetration, the fuel consumption can be reduced up to 48% when the level of CAVs penetration is 70%. Fig. 12 shows that the proposed method in creating additional usable gaps to the minor road approach effectively reduces fuel consumption compared with no CAVs creating additional safe gaps. With the increase of CAV's penetration, the reduction of fuel consumption is more significant. This is mainly due to the decrease in waiting time at the intersection since there are more safe gaps available, reducing fuel consumption. Fig. 12 indicates that an increase in CAVs penetration on the major road would reduce fuel consumption for all penetration levels. The result indicates that an increase in CAV's penetration of 70% at 200 veh/hr on the minor road approach would improve fuel consumption by more than 40%. Besides, at a high level of traffic on the minor road approach, the fuel consumption was reduced by 32% when CAV penetration is high. Notably, the highest benefit of the control algorithm for the fuel saving (48%) are achieved at the highest CAVs perntration and medium to high traffic volume of both streams. The significant reduction in fuel consumption is achieved by creating usable gaps in the mainline for the minor road drivers when needed. Therefore, the proposed method reduced the average waiting time delay and queue length for the minor road approach, effectively reducing fuel consumption. The main aim of this study is to improve the operation of unsignalized intersections. Utilizing the right amount of gaps, calibrating drivers' behavior, and optimizing delays will ultimately enhance the overall performance of unsignalized intersections. It can also be concluded that the implementation of the control algorithm will positively impact the operation of the unsignalized intersection. One of the goals is also to ease the operation of the minor road approach while not causing a significant delay to the continuous flow of the major road. This study improves the operation of major-minor unsignalized intersections in terms of efficiency and safety. These results will aid practitioners in better design and operating unsignalized intersections.

CONCLUSION

This research developed and evaluated a systemic framework that guides CAVs to create additional safe gaps in the mainline traffic stream for the minor road vehicles to reduce extended queueing of the minor road approach. Since a mixed traffic condition in the next twenty to thirty years is the scenario, the proposed system considered a mixed traffic environment; it considers both connected automated vehicles (CAV) and human vehicles (HV). Bottlenecking in the minor stream is mainly due to the extended queueing, specifically due to minimal gaps as the intersection's high priority exists with the major stream. Using technology such as connected and automated vehicles (CAVs) to create extra safe gaps to the minor stream is needed for drivers' efficiency and safety. The method proposed in this research effectively minimizes the delay and queue of the minor road approach while not causing a significant delay on the major road at unsignalized intersections. We can observe that deploying CAVs in the road network with the proposed method can positively impact traffic efficiency, as the waiting time and queue length is reduced for the minor road approach. The ability of connected and automated vehicles to improve traffic operation and safety is wide and can be suitable for research. This study improves the operation of major-minor unsignalized intersections in terms of efficiency and safety. However, there are several important aspects of future work that can be investigated. The method can be expanded to be suitable for a signalized intersection where it can be beneficial to reduce the mainline interruption. This work will be a good contribution since it will draw a broad of the original method. Further investigation is needed to conduct a field investigation to study the feasibility of the control algorithm. It can be beneficial to help agencies, cities, and governments to draw an environmental and comfortable urban transportation system.

REFERENCES

1. Namazi, E., Li, J., & Lu, C. (2019). Intelligent intersection management systems considering autonomous vehicles: A systematic literature review. IEEE Access, vol. 7, 91946-91965.

2. Deng, Z., Shi, Y., Han, Q., Lv, L., & Shen, W. (2020). A Conflict Duration Graph-Based Coordination Method for Connected and Automated Vehicles at Signal-Free Intersections. Applied Sciences, vol. 10, no. 18, 6223.

3. Filocamo, B., Ruiz, J. A., & Sotelo, M. A. (2020). Efficient management of road intersections for automated vehicles—The FRFP system applied to the various types of intersections and roundabouts. Applied Sciences, vol. 10, no. 1, 316.

4. Pruekprasert, S., Zhang, X., Dubut, J., Huang, C., & Kishida, M. (2019). Decision making for autonomous vehicles at unsignalized intersection in presence of malicious vehicles. In 2019 IEEE Intelligent Transportation Systems Conference (ITSC), 2019, pp. 2299-2304. IEEE.

5. Ahmed, A., Sadullah, A. F. M., & Yahya, A. S. (2016). Field study on the behavior of right-turning vehicles in Malaysia and their contribution on the safety of unsignalized intersections. Transportation research part F: traffic psychology and behaviour, vol. 42, 433-446.

6. Dissanayake, S., Lu, J. J., & Ping, Y. I. (2002). Driver age differences in day and night gap acceptance capabilities. Iatss research, vol. 26, no. 1, 71-79.

7. Datta, S. (2014). Modelling critical gaps for U-turn vehicles at median openings under Indian mixed traffic conditions (Doctoral dissertation).

8. Tupper, S. M., Knodler Jr, M. A., & Hurwitz, D. S. (2011). Connecting gap acceptance behavior with crash experience. In 3rd International Conference on Road Safety and Simulation Purdue University Transportation Research Board.

9. McGowen, P., & Stanley, L. (2012). Alternative methodology for determining gap acceptance for two-way stop-controlled intersections. Journal of transportation engineering, vol. 138, no. 5, 495-501.

10. Boon, M. A. A., Mandjes, M. R. H., & Núñez Queija, R. (2016). Congestion analysis of unsignalized intersections.

11. Wang, Y., Cai, P., & Lu, G. (2020). Cooperative autonomous traffic organization method for connected automated vehicles in multi-intersection road networks. Transportation research part C: emerging technologies, vol. 111, 458-476.

12. Zhou, M., Qu, X., & Qi, W. (2021). Improving efficiency at highway T-junctions with connected and automated vehicles. Transportmetrica A: transport science, vol. 17, no. 1, 107-123.

13. Gao, K., Huang, S., Han, F., Li, S., Wu, W., & Du, R. (2020). An integrated algorithm for intersection queue length estimation based on IoT in a mixed traffic scenario. Applied Sciences, vol. 10, no. 6, 2078.

14. Naumann, R., Rasche, R., Tacken, J., & Tahedi, C. (1997). Validation and simulation of a decentralized intersection collision avoidance algorithm. Proceedings of Conference on Intelligent Transportation Systems, pp. 818-823. IEEE.

15. Pan, T., Guo, R., Lam, W. H., Zhong, R., Wang, W., & He, B. (2021). Integrated optimal control strategies for freeway traffic mixed with connected automated vehicles: A model-based reinforcement learning approach. Transportation research part C: emerging technologies, vol. 123, 102987.

16. Bashiri, M., Jafarzadeh, H., & Fleming, C. H. (2018). Paim: Platoon-based autonomous intersection management. 21st International Conference on Intelligent Transportation Systems (ITSC), 2018. pp. 374-380. IEEE.

17. Niels, T., Mitrovic, N., Dobrota, N., Bogenberger, K., Stevanovic, A., & Bertini, R. (2020). Simulation-based evaluation of a new integrated intersection control scheme for connected automated vehicles and pedestrians. Transportation research record, vol. 2674, no. 11, 779-793.

18. Zhang, H., Zhang, R., Chen, C., Duan, D., Cheng, X., & Yang, L. (2021). A Priority-Based Autonomous Intersection Management (AIM) Scheme for Connected Automated Vehicles (CAVs). Vehicles, vol. 3, no. 3, 533-544.

19. Dresner, K., & Stone, P. (2008). A multiagent approach to autonomous intersection management. Journal of artificial intelligence research, vol. 31, 591-656.

20. Lee, J., & Park, B. (2012). Development and evaluation of a cooperative vehicle intersection control algorithm under the connected vehicles environment. IEEE Transactions on Intelligent Transportation Systems, vol. 13, no. 1, 81-90.

21. Jin, Q., Wu, G., Boriboonsomsin, K., & Barth, M. (2012, December). Multi-agent intersection management for connected vehicles using an optimal scheduling approach. International Conference on Connected Vehicles and Expo (ICCVE 2012), pp. 185-190. IEEE.

22. Zhu, F., & Ukkusuri, S. V. (2015). A linear programming formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment. Transportation Research Part C: Emerging Technologies, vol. 55, 363-378

23. Sun, W., Zheng, J., & Liu, H. X. (2017). A capacity maximization scheme for intersection management with automated vehicles. Transportation research procedia, vol. 23, 121-136.

24. Kamal, M. A. S., Imura, J. I., Hayakawa, T., Ohata, A., & Aihara, K. (2014). A vehicle-intersection coordination scheme for smooth flows of traffic without using traffic lights. IEEE Transactions on Intelligent Transportation Systems, vol. 16, no. 3, 1136-1147.

25. Mirheli, A., Hajibabai, L., & Hajbabaie, A. (2018). Development of a signal-head-free intersection control logic in a fully connected and autonomous vehicle environment. Transportation Research Part C: Emerging Technologies, vol. 92, 412-425.

26. Kamal, M. A. S., Imura, J. I., Ohata, A., Hayakawa, T., & Aihara, K. (2013). Coordination of automated vehicles at a traffic-lightless intersection. 16th International IEEE Conference on Intelligent Transportation Systems (ITSC) 2013, pp. 922-927. IEEE.

27. Wuthishuwong, C., & Traechtler, A. (2013). Vehicle to infrastructure based safe trajectory planning for Autonomous Intersection Management. 13th international conference on ITS telecommunications (ITST) 2013. pp. 175-180. IEEE.

28. Levin, M. W., & Rey, D. (2017). Conflict-point formulation of intersection control for autonomous vehicles. Transportation Research Part C: Emerging Technologies, vol. 85, 528-547.

29. Fayazi, S. A., Vahidi, A., & Luckow, A. (2017). Optimal scheduling of autonomous vehicle arrivals at intelligent intersections via MILP. American control conference (ACC) 2017. pp. 4920-4925. IEEE.

30. Jin, Q., Wu, G., Boriboonsomsin, K., & Barth, M. (2012, December). Multi-agent intersection management for connected vehicles using an optimal scheduling approach. International Conference on Connected Vehicles and Expo (ICCVE) 2012, pp. 185-190. IEEE

31. Zhang, Y. J., Malikopoulos, A. A., & Cassandras, C. G. (2016). Optimal control and coordination of connected and automated vehicles at urban traffic intersections. American Control Conference (ACC) 2016, pp. 6227-6232. IEEE.

32. Ma, Q., Zhang, S., & Zhou, Q. (2021). Development of a conflict-free unsignalized intersection organization method for multiple connected and autonomous vehicles. Plos one, vol. 16, no. 3, e0249170.

33. Zhong, G., Zhang, J., Yin, T., & Nie, J. (2015). A Cooperative Management Strategy Designed for Unsignalized Intersections Under a Connected Vehicle Environment. CICTP 2015, pp. 233-245.

34. Chen, W., & Liu, Y. (2017). Gap-based automated vehicular speed guidance towards eco-driving at an unsignalized intersection. Transportmetrica B: Transport Dynamics.

35. Weyland, C. M., Baumann, M. V., Buck, H. S., & Vortisch, P. (2021). Parameters Influencing Lane Flow Distribution on Multilane Freeways in PTV Vissim. Procedia Computer Science, vol. 184, 453-460.

36. Chen, C., Zhao, X., Liu, H., Ren, G., Zhang, Y., & Liu, X. (2019). Assessing the influence of adverse weather on traffic flow characteristics using a driving simulator and VISSIM. Sustainability, vol. 11, no. 3, 830.

37. PTV AG. (2018). PTV Vissim 10 user manual. PTV AG: Karlsruhe, Germany.

38. Shaaban, K., & Hamad, H. (2020). Critical gap comparison between one-, two-, and three-lane roundabouts in Qatar. Sustainability, vol. 12, no. 10, 4232.

39. Čelar, N., Stanković, S., Kajalić, J., & Stepanović, N. (2018). Methodology for control delay estimation using new algorithm for critical points identification. Journal of Transportation Engineering, Part A: Systems, vol. 144, no. 2, 04017073.

40. Yu, H., Kong, J., Ren, Y., & Yin, C. (2020). On the Urban Link Fundamental Diagram Based on Velocity-Weighted Flow and Queue Length. Symmetry, vol. 12, no. 11, 1852.

41. Narayanan, S., Chaniotakis, E., & Antoniou, C. (2020). Factors affecting traffic flow efficiency implications of connected and autonomous vehicles: A review and policy recommendations. Advances in Transport Policy and Planning, vol. 5, 1-50.

42. Calle-Laguna, A. J., Du, J., & Rakha, H. A. (2019). Computing optimum traffic signal cycle length considering vehicle delay and fuel consumption. Transportation Research Interdisciplinary Perspectives, vol. 3, 100021.