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Access Control at Major/Minor Road Intersection through CAV in Mixed Traffic

Dr. Ping Yi, PE

The University of Akron

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

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Access Control at Major/Minor Road Intersection through CAV in Mixed Traffic

by

Ping Yi, Ph.D., Professor

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Contacts

For more information:

Department of Civil Engineering
The University of Akron
Phone: 440=972-7294
Email: pyi@uakron.edu

CCAT
University of Michigan Transportation Research Institute
2901 Baxter Road
Ann Arbor, MI 48152
uumtri-ccat@umich.edu
(734) 763-2498

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16. Abstract

Roadway intersections are among the major causes of traffic congestion besides lane reduction bottlenecks. When a major road intersects a minor road at an unsignalized intersection without the control of a traffic signal, the mainline vehicles are given priority over the minor road vehicles to go through the intersection, and the latter can only enter or cross the intersection when there is a sufficient gap between successive vehicles on the major road.

Connected and automated vehicles (CAV) are packed with tracking and lane-keeping assistance and adaptive speed control to ensure that vehicles do not collide while reducing traffic congestion. This research aims to utilize CAVs to help generate usable gaps for minor road vehicles to enter the intersection without interrupting the mainline traffic flow. A probability function is developed to study the probability in which CAVs can create additional usable gaps for the minor road vehicles based on the headway distribution of the mainline vehicles.

The control logic algorithm is utilized when vehicle arrivals on the main road permit implementing the control strategy to improve intersection efficiency in mixed traffic conditions. The proposed control logic is simulated under two traffic scenarios, unsignalized and semi-actuated signal control, to study the effectiveness of the proposed method. Additionally, a field investigation is conducted at two intersections to verify the feasibility of the control logic implementation in real traffic conditions.

Simulation results of the unsignalized intersection scenario show 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 is reduced by as much as 90% when the percentage of CAVs on the major road is 70% compared with the benchmark of no CAVs on the major road. The modified algorithm of semi-actuated signal control reduces the major road interruptions with the increase of CAVs penetration. Additionally, the intersection capacity increases with the increase of the number of gaps created on the major road. The minor road drivers are mostly willing to accept gaps created when CAVs reduce speed, where more than 60% of gaps created were accepted. This research has shown that deploying CAVs in the road network with the proposed method can positively impact the traffic efficiency while maintaining safety of the intersection.

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Gap Creation, Connected and Automated Vehicles, T-intersections, Probability, Simulation	No restrictions.

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A. Traffic problems

The rapid growth in population and the increase in the number of vehicles have resulted in additional traffic congestion over the last two decades. It has been projected that worldwide traffic congestion is to increase 60% by the year 2030 (Namazi, Li, & Lu, 2019). Traffic congestion leads to inefficient utilization of the transport infrastructure, overconsumption of fuel, and forcing drivers to travel more. Intersections, where different flows intersect, are among the major reasons for congestion besides bottlenecks (Hadjigeorgiou, & Timotheou, 2019).

Intersections are designed as a preventative measure to enhance safety by facilitating orderly flow of vehicle streams. An intersection is characterized into two categories: signalized intersection – control of intersection using traffic signals – and unsignalized intersection – intersection without traffic signals but stop signs.

In this research, an intersection where a major road meets a minor road is referred to as a major/minor road intersection. In urban areas, most intersections are signalized to regulate the movement of high traffic volumes. However, in suburban or rural areas, major/minor road intersections are commonly unsignalized 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 (Pruekprasert, et al, 2019).

Unsignalized intersections generally lack more rigorous traffic controls. Some of those intersections are constrained by poor geometric conditions or under inappropriate speed control (Ahmed, et al, 2016). With such limitations, drivers from the minor road often face the challenge of selecting a proper vehicular gap in the traffic flow to enter the major road, as any mistake could lead to a safety hazard, in addition the impact on efficient intersection operations.

B. Gap Acceptance and Critical Gap at Unsignalized Intersections

At a major/minor road unsignalized intersection, vehicles on the major road have the right-of-way priority over those on the minor road. Vehicles on the minor road can only enter the intersection when there is a sufficient gap between the approaching vehicles.

The safety and performance of unsignalized intersections are largely influenced by the driver's gap acceptance behavior. Gap acceptance behavior represents the choice to accept or reject a gap of a specific size (Nagalla et al., 2017). Different scholars have provided several ways to define this gap, called critical gap, which is considered as the time interval between two succeeding major road vehicles, generally accepted by the minor road vehicle (Lord-Attivor & Jha, 2012).

With light traffic on the major road, there is a good probability that more larger gaps exist in the traffic stream; on the other hand, with heavy traffic on the major road, it is more likely to have smaller and less safe gaps for the minor street drivers to select (Naumann, Rasche, & Tacken, 1997). This gap is called an acceptable gap, and it should be greater than the critical gap to be safe. However, the decision to take a gap or not is up to the driver on the minor street.

1. Critical Gap at Major/Minor Road Unsignalized Intersections

A critical gap is the most common metric of driver's gap acceptance behavior and is mainly defined by the smallest gap that a driver accepts at intersections (Troutbeck, 2014). Lord-Attivor and Jha (2012) defined the critical gap as the time interval between two succeeding major road vehicles, required to be maintained by the driver of a minor road vehicle for taking the desired turn safely. According to the Highway Capacity Manual (HCM), the gap is "the time, in seconds, for the front bumper of the second of two vehicles to reach the starting point of the front bumper of the first." Arrival at a full stop is required for the drivers who have reached the major/minor road intersection from a controlled approach.

At major/minor road unsignalized intersections, The minor road driver's behavior is highly affected by the number of available gaps on the major road. In such cases where there is light traffic on the major road, there is a higher probability that there will be large gaps; thus, providing ease to the minor road drivers to witness an acceptable gap. On the other hand, with higher traffic on the major road, there is a higher possibility of smaller and less safe gaps to the minor road drivers. The vehicle delay for the minor road vehicle influences the critical gap selection. A longer waiting time experienced by the driver while waiting can result in losing patience to accept a shorter critical gap (Dissanayake, Lu, and Yi, 2002).

While additional factors may also influence the gap selection behavior of the driver, including driver age, time of the day, and trip purpose, it is evident that the critical gap also differs with the traffic flow conditions (Tian, 2000).The increase in the number of rejected gaps also affects the gap selection of a driver. When more gaps are rejected, the minor road driver becomes impatient and would accept smaller gaps (Tupper & Hurwitz, 2011). As far as driver's gender is concerned, Tupper, Knodler, and Hurwitz (2011) found that the average critical gap of male drivers is shorter than for female drivers.

2. The Danger of Taking a Bad Gap

NHTSA claims that over 8500 vehicle crashes in the US occurred at intersections (Fatality Analysis Reporting System, 2015). According to the study conducted by Rusch et al (2014), a stop-sign control intersection that involves left-turns is especially dangerous. The study further found that just by taking a bad gap, around 700,000 vehicles become the victim of collisions, annually. Intersections are a dangerous and complex part of the road transportation system where most of the road accidents, approximately 50% in Australia, occur at an intersection. This can either be due to taking a wrong left or right turn or moving from minor to major or major to minor streams with gap level less than the critical gap (Cornelissen, et al., 2015).

It has been shown that driving at an intersection is the most complex and dynamic task of drivers. Lack of attention can result in taking a bad gap decision; hence, endangering the driver as well as interrupting the traffic flow. Bad gap decisions often lead to high speeds at the intersection due to the driver's intention of moving through the small gap.

C. Connected and Automated Vehicles (CAVs)

Connected and automated vehicles (CAVs) are gradually becoming a reality after it was a dream. CAVs are expected to change the dimension of the transportation industry, by allowing technology to make decisions on roads and intersections. CAVs can perceive their navigation and environment without any form of human input (Birdsall's, 2014). See Figure 1.

The rise of connected and automated vehicle (CAV) technology has brought new prospects to the automobile industry and transportation system since the past decade. Notably, the rise has been observed considering the connectivity levels in vehicles that have increased significantly, enabling these enhanced technologies to work in a cooperative way (Wang, Han, and Han, 2021). Automated vehicles (AVs) have a certain automation level to replace or support human control. The Society of Automotive Engineers defines the different levels of automation, comprised from level (0) of automation to level (5). These levels constitute different functions of the vehicle, i.e., level (0) is completely under human control, while level (5) is fully autonomous (Narayanan, Chaniotakis, and Antoniou, 2020).

CAVs are equipped with multiple sensors along with wireless communication technology that allows them to communicate with each other and infrastructure, as shown in Figure 2. CAVs can communicate with each other through vehicle to vehicle technology and communicate with other infrastructure such as traffic signals through the vehicle to infrastructure technology. These wireless technologies create a link between vehicles to inform a network of shared information such as speed, location and traffic control, etc. 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 (Caldwell, 2016).

Figure 1 - Example of Connected and Automated Vehicles (CAV).

When it is combined with wireless communication systems, automated driving and data processing technology empowers CAVs to be a potential solution to the safety and congestion problems. CAVs are projected to limit the need for human input that will result in drastically reducing human errors such as aggressive driving, rubbernecking, tailgating, and delayed reaction time. This would enhance travel time, reduce labor costs, and inspire high-speed limits.

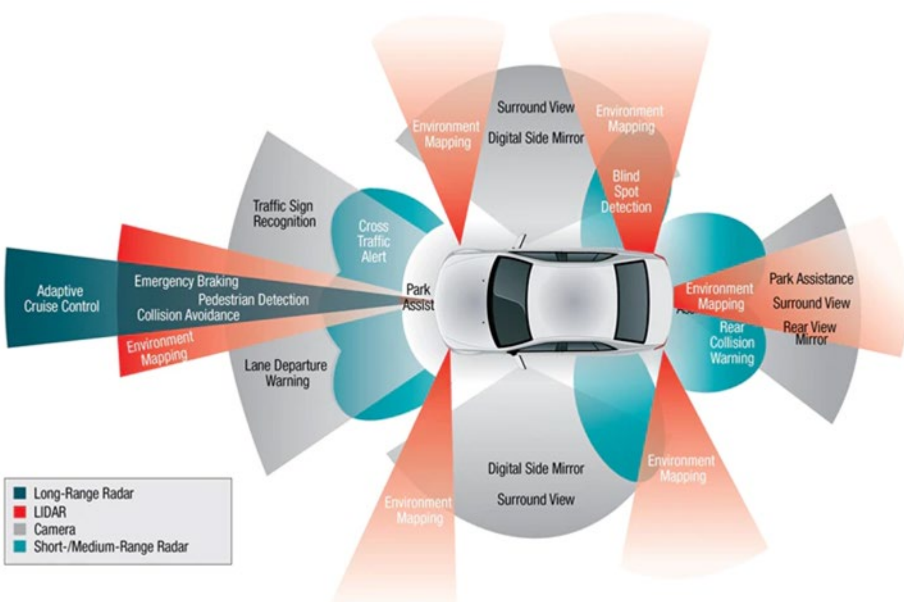

Figure 2 - CAV sensors.

Since CAVs are equipped with multiple sensors along with wireless communication technology that allows CAVs to communicate with each other and infrastructure, CAVs understand the gap pattern of different vehicles and act based on this information. CAVs can calculate whether the gap at the intersection is greater than the critical gap. However, if it is not more than the critical gap, CAV may help maintain a distance beyond the established critical gap if other conditions permit.

For simplicity, a T-intersection where CAVs may help create usable gaps is demonstrated for the minor road vehicles to enter the intersection, as shown in Figure 3.

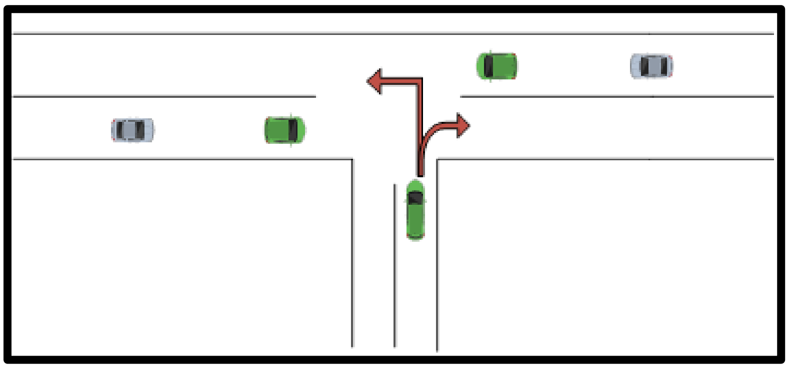

Figure 3 - Basic T – Intersection.

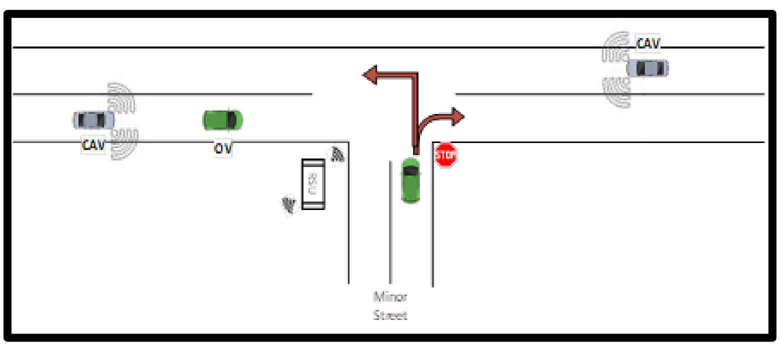

Figure 4 - RSU communication with CAV through V2I.

D. Problem Statement

This study utilizes the concept of V2I technology to cooperate between a Roadside Unit (RSU) and the approaching CAV on the main road, as shown in Figure 4. Once the CAV enters the range of RSU, if a minor road vehicle is detected, the RSU informs the CAV to adjust its speed so that a gap greater than the critical gap may be created. This helps create a sense of relief for drivers on the minor road since they can merge safely into the main road with less waiting time.

If the signal is signalized, a semi-actuated signal control is commonly used to serve the minor road vehicles based on detection. In such an operation, green light interruptions to the mainline traffic frequently happen due to detection of individual vehicle arrivals at the minor approach, causing significant stops and delay to the mainline vehicles. The V2I technology with CAVs can also help ease this problem

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by further communicating with the signal system to manage data detection and traffic lights accordingly, allowing usable gaps to be created and selected by the minor road vehicles. This control strategy is expected to improve the performance of the intersection in terms of reducing delay and increasing capacity.

E. Objective of Study

The objectives of this research are as follow:

- To increase gap acceptance by creating extra safe gaps.
- To improve the capacity of the intersection by providing extra gaps to the minor road vehicles.
- To enhance the safety and efficiency of the mainline traffic flow by reducing interruptions from the minor road vehicles

F. Scope of Research

The primary aim of this research is to enhance the overall performance of intersections by using CAV technology. Since CAVs are equipped with multiple sensors and have V2V and V2I capabilities, they can be used to create additional safe gaps to the minor road vehicles without affecting the operation.

This research will develop a systematic framework and implementation plan that uses 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 the benefit of minimizing interruptions to the mainline traffic flow. The algorithm and framework are then implemented and studied via simulations to estimate the potential improvements.

The algorithm is studied in two different scenarios involving an unsignalized intersection and a signalized intersection, each at different vehicle compositions between CAVs and the ordinary cehicles (Ovs).

The last part of the research field testing to study the feasibility of the control logic implementation in real traffic conditions.

II. LITERATURE REVIEW

A. Introduction

Rapid population growth and the associated increase in the number of vehicles have caused worldwide traffic congestion, thereby transportation systems have gained increased attention. However, the upcoming wave of advancements in wireless communication and processing power technology has made connected and automated vehicles a potential solution to the congestion problem (Namazi, Li, and Lu, 2019). In this account, Sezer et al. (2015) state that the assistive technologies, including brake assist, collision avoidance (CA), collision warning (CW), and adaptive cruise control (ACC) in CAVs, aim to make the roads safer for human drivers. Moreover, due to its ability to establish communication over the V2I or V2V network, CAVs can improve safety and traffic throughput.

This section discusses the effect of traffic congestion issues and gap acceptance behavior at major/minor road intersections. In addition, the section discusses the effects of CAVs on the overall traffic system and the impacts they will make on the safety and efficiency of intersections.

B. Traffic Congestion

As Mandjes, Boon, and Núnez-Queija (2016) discussed, when managing unsignalized intersections, the major road approach is given a higher-level priority over the minor road approach. However, in traditional management strategies, the gaps are determined visually by the drivers in lower-level streams. Zhong et al. (2015) affirm that unsignalized intersections might become the source of traffic congestion if poorly managed in moderate traffic flows.

According to Pasco Country MPO (2016), as shown in Figure 5 and 6, maximum traffic congestion at a local intersection in the USA is due to the traffic flow's bottleneck. The vehicles having a low priority stream can only be allowed to cross when an acceptable gap exceeds that of the critical gap. The performance of the intersections, according to Prasad et al. (2014), is evaluated by vehicles' queue characteristics in a minor stream.

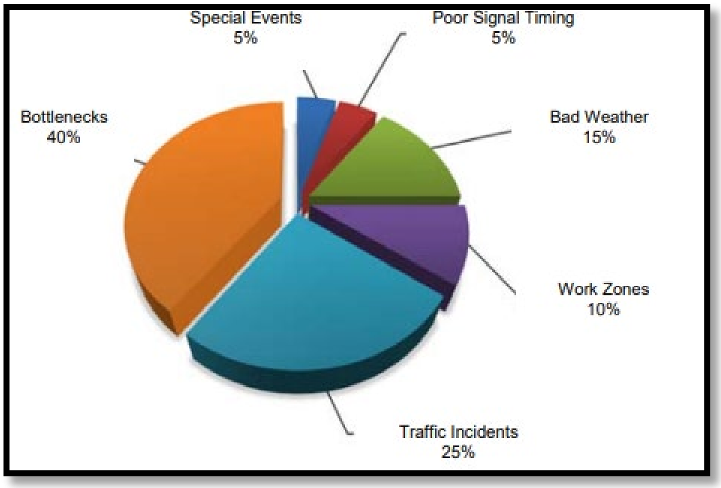

Figure 5 - Congestion causes at a local intersection (Pasco County MPO, 2016).

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Figure 6 - Minor road queueing due to minimal gaps on a major road.

C. Gap Acceptance at Unsignalized Intersections

Unsignalized intersections are often places where accidents occur because of a lack of traffic control devices, inadequate sight distance, and generally poor visibility (Ahmed et al., 2016, Wu et al., 2013, Dutta & Ahmed, 2018). Nagalla et al. (2017) argued that the driver's gap acceptance behavior influences the safety and performance of unsignalized intersections. According to Sangole et al. (2011), this gap acceptance behavior implies the choice to accept or reject a gap of a specific size. It is the outcome of the decision process of the human brain that evaluates a set of explanatory variables. The HCM has named critical gap as "Critical Headway" where the discussion on the gap acceptance theory has involved mainly three aspects, i.e., size of the gaps, distribution of the gaps to the drivers, and their usefulness to the drivers along with the priority considerations.

Tupper and Hurwitz (2011) have mentioned different factors that influence the crash behavior of the driver. For example, the time of the day affects the decision of gap acceptance of the driver. The biggest influence was the presence of queue behind the driver, the number of gaps rejected, as well as the wait time, as shown in Figure 7.

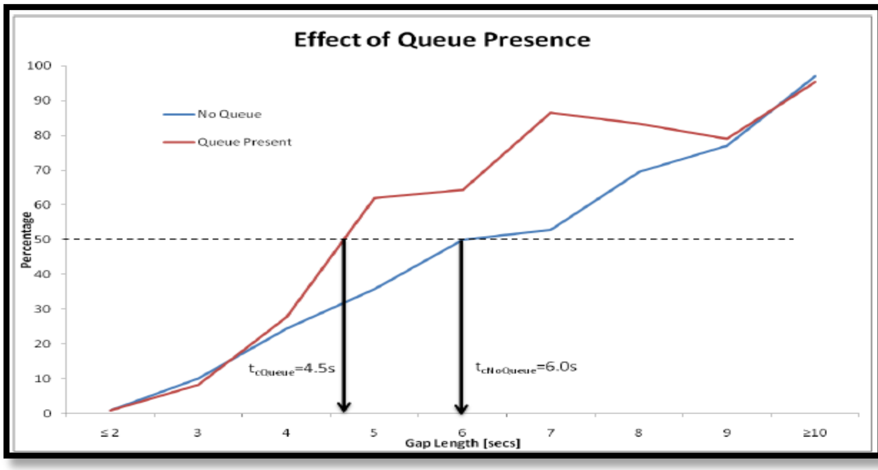

Figure 7 - Queue presence effect on gap acceptance of a driver (Tupper, & Hurwitz, 2011).

D. The Interruption of Continuous Flow at Signalized Intersections

Signalized intersections may be controlled with pre-timed signal control, semi-actuated, and fully actuated plans. The pre-timed signal timing is programmed in a fixed time for all phases. The semi-actuated signal timing is found where a major road intersects with a minor road, and the detections are placed only on the minor road approach. The main idea of semi-actuated signals control is to prioritize the continuous flow of the major road and reduce interruptions if no calls are placed on the minor road detectors.

Detectors are placed on all approaches to serve the demand properly at the fully actuated signal timing without causing delay to the high demand. Fully actuated signals are found where the random fluctuations in traffic flow happen, and the main concept of the fully actuated signals are first come, first serve (FCFS).

At a major/minor road intersection, a semi-actuated signal control is commonly used where a minimum green (Gmin) is served to the mainline even when a call is placed on the minor road approach. However, if a minimum green is served to the major road and no calls are placed on the minor road, the green will be extended to serve the maximum green (Gmax) to the major road or even set on green rest (GR) until a vehicle on the minor road is detected.

Signal interruptions to the mainline traffic due to the detection of individual vehicle at the minor road approach often happen, causing significant stops and delays to the mainline vehicles. In this research, the control strategy of creating additional usable gaps for the minor road users uses a modified algorithm that operates a detection delay or an extended green-rest (GR) plan in the mainline directions. More details are discussed later in the report.

E. CAVs

CAVs use advanced wireless technologies like C-V2X or Dedicated Short-Range Communication (DSRC). These wireless technologies create a link between vehicles to inform a network of shared information such as speed, location, and traffic control, etc. This shared link includes V2I, V2V, and V2X, which enables data communications among them (Caldwell, 2016).

The Investor Service of Moody forecasts that a significant number of vehicles will become autonomous by 2040 and that CAVs will become universal by 2050 (Zushi, 2017). 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 configurated communication sensors such as V2V and vehicle to everything (V2X). These features and configurations are considered a benefit because they help improve traffic flow and reduce traffic flow interruption, thereby enhancing safety, fuel consumption, and emissions (Naumann, et al., 1997). Furthermore, the penetration rate of AVs and CAVs will rely on various determinants like the level of awareness among the public, environmental concerns, driving-related seeking scale, relative advantage, trust of strangers, subjective norms, safety, and self-efficacy (Gkartzonikas and Gkritza, 2019).

When it is combined with the wireless communication systems, automated driving and data processing technology empowers CAVs to be a potential solution to the safety and congestion problems. Existing studies, including limited field tests, have shown the benefits of CAVs in reducing traffic flow interruptions and improving traffic flow dynamics, thereby enhancing safety and efficiency. It is also well understood that, before CAVs become a dominant, frequently used technology, a mix of human-driven vehicles along with CAVs will be driving simultaneously on the road.

1. Levels of Automation

According to Talebpour and Mahmassani (2016), Mahmassani (2016) and Bagloee et al. (2016), six different incremental levels of technology for automated vehicles have been defined by the NHTSA. These levels are discussed as follows and are also shown in Figure 8:

No Automation (Level 0): This automation, as mentioned by Bagloee et al. (2016), refers to vehicles fully controlled by the driver, and the driver is the only decision-maker. According to Mahmassani (2016), all the vehicle's commands and control, including braking, steering, motive power, and throttle, all reside with the driver. The monitoring and execution of commands are considered the responsibility of the driver.

Function Specific Automation (Level 1): This is the type of automation level where at least one control function of the vehicle is automated. In this automation, as discussed by Bierstedt et al. (2014), the driver is assisted with a medium level of automation with braking or stability control. Lane adjustment and electronic stability are the main highlights of this type of automation. Function-specific automation is already present in standard higher-end cars, and it is also known as a driver-assistant function.

Combined-Function Automation (Level 2): Combined-function automation is the type of automation consisting of at least two vehicle functions. According to Talebpour and Mahmassani (2016), these functions work side by side with each other and provide help to the driver. The prominent capabilities include assistance in traffic jams; in a congested environment, the vehicle would maintain lane position and speed. This automation aims to provide better convenience and overall safety while posing the least impact to the mobility systems and traffic.

Restricted Self-Driving Automation (Level 3): According to Bagloee et al. (2016), in this type of automation, although the driver has control over the vehicle, it is not expected that the driver will monitor and take actions when required. In this type of automation, as mentioned by Mahmassani (2016), vehicles can take control of safety-critical functions. However, the control is limited to certain traffic, roadway, and weather conditions. Furthermore, if necessary and enough time is provided for the transition, the driver can take over. Although it is a handy feature, it comes with different problems. For instance, the driver does not check the performance of a self-driving vehicle, and sometimes, overreliance becomes an issue. Apart from this, it is the job of automation to decrease the workload in normal driving conditions, but with this new system, adapting to it requires a huge amount of mental workload.

Complete Self-Driving Automation (Level 4): Caldwell (2016) discussed that complete self-driving automation refers to autonomous vehicles that do not require any kind of human interaction. In this type of automation, it is the responsibility of the vehicle to take care of entire driving functions in any road, traffic conditions, or weather. Moreover, according to Yeomans (2014), the driver is only required to put in the destination; the self-driving vehicle will find the best possible route to reach that destination while considering different weather, traffic, and road conditions. Furthermore, it not only optimizes the best possible route and avoids traffic congestion, but it also prevents accidents.

Automated Taxis (Level 5): This is the type of automation where vehicles communicate with each other and based on communication, traffic congestion and accidents can be avoided (Talebpour & Mahmassani, 2016). Since each vehicle has the information of the other vehicle, communication takes place, and optimum traffic conditions are created that are devoid of any risk or safety issue.

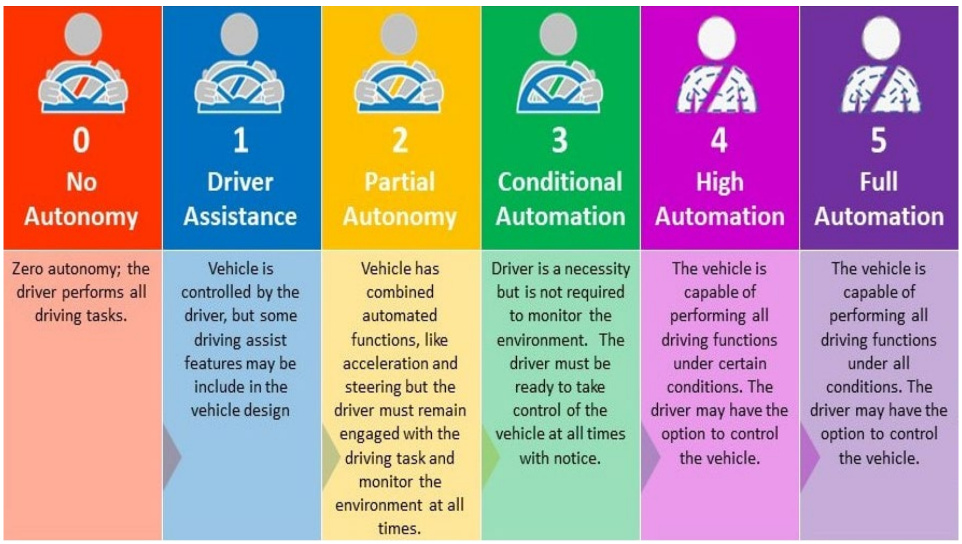

Figure 8 - Level of Automation (Source: https://www.sae.org/blog/sae-j3016-update)

F. Connected and Automated Vehicles a T-intersection

Unsignalized intersections considerably affect the efficacy of the traffic system in many cities, and therefore many studies have been conducted to improve the traffic management at such intersections. In the past few decades, only limited efforts have been made where autonomous and connected vehicle technologies were considered to help traffic management at T-intersections (Namazi & Lu, 2019).

Naumann, Rasche, and Tacken (1997) designed a strategic management approach to enable a vehicle to cross a road intersection automatically, in a self-organized manner, well aligned and coordinated with other vehicles overlapping the intersection. This approach is a calculated method of identifying priority for each vehicle among a list of weighted factors like idling time, velocity, speed, etc. This priority of a connected automated vehicle is then sent to other automated vehicles through a sensory motion which enhances its self-organizing features. Accordingly, the engineers presented a driving schedule to determine an optimal driving plan with the least evacuation time. The study proposed to do this by examining, assessing, and considering all probable arrangements of vehicles.

In a similar context, Ahmane, Abbas, and Perronnet (2013) also introduced a new model referred to as Time Petri Net with Multipliers (TPNM) Approach. This particular model stems from the theoretical framework of self-organization and is based on a control strategy of an isolated intersection. Subsequently, the strategy is proposed to reduce the waiting time of vehicles at an intersection, thereby minimizing the queue length.

Wu, Abbas, and Moudni (2009) have also put forward a control approach for an unsignalized intersection founded on a dynamic programming system and considers new information and communication algorithms for autonomous vehicles. The researchers adopted a comparative approach to equate V2V communication, center controller, and global solution. These were compared using simulations, and the outcome indicated that as compared to the other two methods of V2V communication and center controller, the global solution possesses a higher ability to minimize the average time taken by vehicles and thereby reduce the queue length.

In order to guide connected automated vehicles to pass through signalized or unsignalized intersection automatically in a safe and efficient manner, Liu et al., (2018) advanced a new model via V2V communication named the distributed conflict resolution mechanism. The proposition of this mechanism determined that intersection efficiency has the potential to improve by minimizing the average vehicle delay. In this context, Zhao et al. (2018) also proposed another coordination scheme referred to as a multi-objective optimization model so that crossing an intersection from a connected automated vehicle can reduce fuel consumption, improve traffic flow, and provide greater comfort in driving. The results of testing this approach indicated that perhaps a multi-objective optimization model is able to provide higher fuel consumption efficiency, avoid traffic jams and offer ride comfort with an assurance of safety and minimum computational cost in a connected automated vehicle (Zhao, Wang, Chen, and Yin, 2018).

A proposition of an optimization-based centralized intersection controller was used to find the optimal velocity of each vehicle and increase the vehicle throughput. Chai, Cai, Shang, & Wang (2017) proposed a method of preassigned slots for enhancing the coordination of CAVs at the intersection. By setting up the status adjusting area, the method works to let vehicles easily pass through the intersection without any stops and collisions.

Even though all the proposed methods outlined above are reported to improve traffic flow at signalized or unsignalized intersections in some way, these studies were done in a fully automated vehicle environment. It has been discussed earlier that there will be a long transition time where roads will have mixed traffic conditions.

This research aims to enhance the performance of unsignalized intersections with autonomous vehicles to create additional adequate gaps when needed in mixed traffic conditions. Through the extra gaps provided by AVs it is expected that the proposed control strategy will improve the intersection's performance in terms of delay, capacity, gaps, and safety.

III. METHODOLOGY

A. Expected Probability Headway Distribution

The gap acceptance that happens at unsignalized intersections is the minor road driver's choice to accept or reject a perceived headway. Delay at the minor road before merging into the major roads depends on the frequency of headways equal to or greater than the critical headway. The arrival of vehicles on the major road relies on the distribution pattern at the intersection point.

At a major/minor road intersection in a suburban area, the major road arrival is often not affected by the upstream signals, which means vehicle arrivals are stochastic. In this case, for light to medium traffic flow, it is assumed that the vehicle arrival follows the Poisson distribution (Garber & Hoel, 2014; Cowan, 1975).

1. Headway Distribution of Major Road Traffic Flow

Headway is the time interval between two successive vehicle arrivals at the same roadway point. A waiting vehicle on the minor road approach will merge into the major road only if a proper headway (or gap) is available on the major road. The Poisson distribution describes the probability of having a certain number of vehicles arriving at a given time unit, and it is calculated as follows:

$$P(X = x) = \frac{e^{-m}\ m^{x}}{x!} \qquad 0 \leq x \leq \infty \qquad (1)$$

Where m is the average arrival rate and x is the number of vehicles. Since m is dependent on the duration of time t, it can be written as vt, where v is the traffic volume expressed in a unit time.

The probability of having zero vehicles coming in an interval time can be interpreted as the probability of having headway equal or greater than t. The headway is generally defined as the time difference between two successive vehicles crossing the same roadway point. The probability of having zero vehicle arrive within an interval t is estimated as:

$$P(X = x) = \frac{e^{-m}\ m^{0}}{0!} \qquad 0 \leq x \leq \infty \qquad (2)$$

Thus, the probability of having headway greater or equal to the headway t is estimated as:

$$P(T \geq t) = e^{-vt} \qquad 0 \leq t \leq \infty \qquad (3)$$

Since the probability of having no vehicles arriving during time t can be interpreted as the probability of having a headway t or longer, the headway distribution of vehicles for those at lease the size of the critical headway, t_{cr}, on the major road can be estimated by modifying Equation 1. The cumulative distribution function for all headways not less than t_{cr} can be obtained through using an adjusted probability density function which ensures the cumulative distribution function gradually approaches to unity when t keeps increasing, as:

$$\mathbf{P}(t) = \int_0^t v\, e^{-vt}\ dt \tag{4}$$

2. Critical Headway (t_{cr}) and Minimum Headway (t_{min})

The critical headway, t_{cr}, is the minimum headway between two successive vehicles on the major road that is needed by a vehicle on the minor road in order to enter the major road. The minimum headway, t_{min}, is the shortest time headway between the vehicles. The minimum headway is considered in this research because its duration may be increased by a CAV through reducing speed, so that the extended headway could be at least the length of the critical headway. The minimum headway used in this model is based on field observation which is discussed more in-depth in Chapter VI.

To find how much help CAVs can provide to increase the number of headways usable for the minor road vehicles, the probability of having headways less than the critical headway but larger than the minimum headway must be considered. Since headways greater than the critical headway do not need modification, they are not included in the consideration. The above two probabilities can be respectively obtained through the following equations:

$$\mathbf{P}_{min}(t \le t_{min}) = \int_0^{t_{min}} v\, e^{-vt}\, dt \tag{5}$$

$$\mathbf{P}_0(t \ge t_{cr}) = \int_{tcr}^{\infty} v\, e^{-vt}\, dt \tag{6}$$

3. Probability of Gaps Creation by CAVs

To determine the probability of CAV assistance in gap creation, the difference between the headways less than the critical headway and greater than the minimum headway are considered:

$$\mathbf{P}_{cav} = (1 - \mathbf{P_0} - \mathbf{P}_{min}) \tag{7}$$

Where $\mathbf{P}_{cav}$ is the probability that additional gap times may be created for those headways between the critical headway and the minimum headway by CAVs, so that the extended headways could become usable for vehicles on the minor road to enter the major road. The total number of additional usable headways that CAVs may be able to create, N_{cav}, can be determined by using the number of CAVs in the traffic volume on the major road, as

$$N_{cav} = \mathbf{P}_{cav}\, q_{cav} \tag{8}$$

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Where q_{cav} is the number of connected automated vehicles on the major road in ideal conditions that are evenly distributed in the traffic stream.

Equations 1 through 8 have considered only one direction of the mainline traffic, and they can only be applied to the right-turning vehicles from the minor road. More commonly, a two-way traffic condition should be considered for left-turn vehicles from the minor road. Therefore, the number of gaps that can be created in both directions on a major road needs to be estimated. The conditional probability of having headways less than the critical gap and greater than the minimum headway on both directions of the major road is calculated as follows:

$$\mathbf{P}_{cav(L)} = \mathbf{P}_{cav(E)} \ \mathbf{P}_{cav(W)} \quad (9)$$

Where, $\mathbf{P}_{cav(E)}$ and $\mathbf{P}_{cav(W)}$ are the probability of potential gap creation to extend the headways by CAVs in the eastbound and westbound traffic, respectively. $\mathbf{P}_{cav(L)}$ is the resultant probability for the left-turning vehicles on the minor road to enter the major road.

B. Gap Creation Modeling

After analyzing the possibility of creating additional gaps by CAVs for the minor road vehicles, this section discusses the gap creation modeling in detail. The framework takes into consideration safety as the priority as well as efficiency, together with its main benefit to reduce interruptions to the mainline traffic flow.

Vehicles waiting at the minor road entrance require a safe gap in the major road traffic stream to enter the major road. This gap can be found easily when the mainline traffic volume is low. However, when traffic volume increases, such as in rush hours, the long gaps between vehicles change into shorter gaps in the mainline traffic flow and the minor road vehicles must wait at the stop for a much longer time until a long enough gap becomes available. This commonly observed problem leads to a long delay for the vehicles on the minor road, which, as discussed before, may prompt frustrated drivers on the minor road to take unsafe shorter gaps.

Since CAVs can communicate through V2V and V2I technologies, an approaching CAV can be made aware of the presence of waiting vehicles on the minor road through the Roadside Unit (RSU). Depending on the presence and location of other vehicles in front and behind the CAV, the system can instruct the CAV to reduce its speed as to increase the gap time to the level of the critical gap for a minor road vehicle to merge into the mainline traffic flow.

1. Type of Intersection

In this research, we focus on T-intersections, where a minor road intercepts a major road. The minor road approach is controlled by either a stop sign or an actuated signal where the major road has the right of way. For simplicity in developing the control algorithm, both the major and minor road are assumed to include only one lane in each direction, as shown in Figure 9. CAVs are operated only in major street flow with different percentage penetrations where a minor street has only ordinary vehicles (OVs).

In addition, the following conditions are used in the modeling:

1) A roadside unit (RSU) is installed at the intersection to receive and transmit information with 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 determine the spacing along with the speeds of those vehicles.

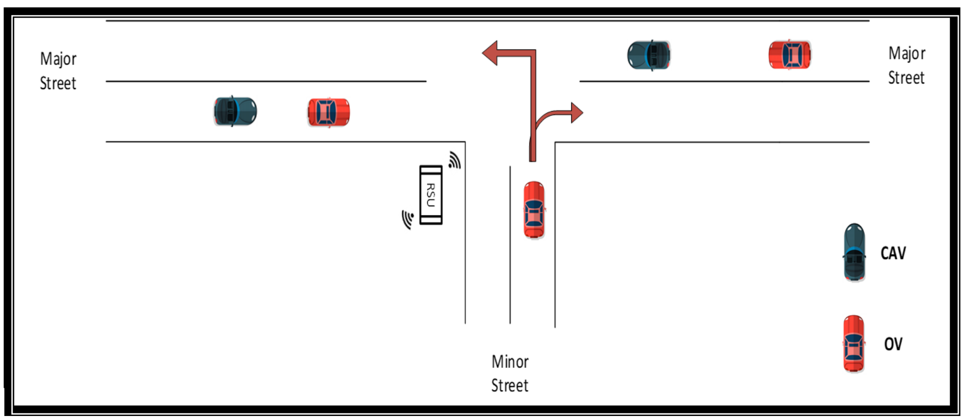

Figure 9 - Study Scenario at T-Intersection.

2. Safe Gap in Front of CAV

The proposed control system is intended to work in a mixed traffic environment since it considers both CAVs and OVs. When a CAV is within the V2I communication range, and a vehicle is detected in the minor road by the RSU, The CAV calculates whether the gap to the vehicle in front of the CAV is greater than the critical gap when it passes the intersection; if it is less than the critical gap as explained in the previous section, the system will decide if the CAV can reduce speed to prolong the gap beyond the established critical gap if other conditions permit.

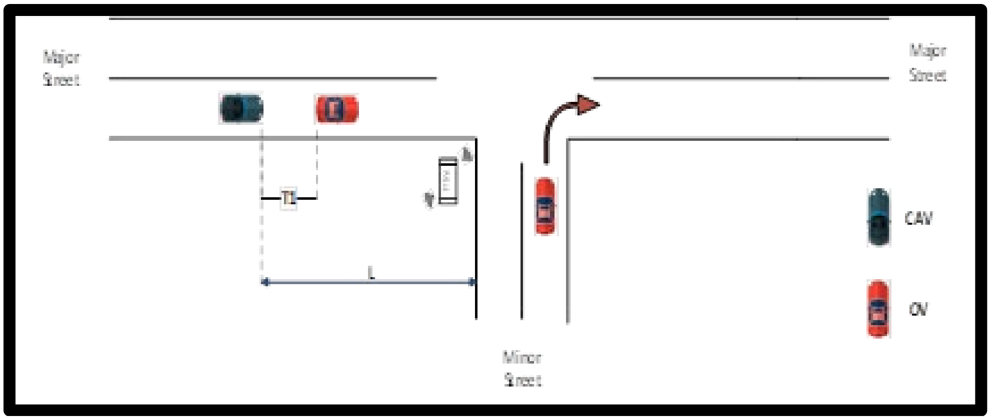

Figure 10 - Distance between CAV and the leading vehicle T_1.

In the scenario shown in Figure 10, a CAV follows an OV and is separated by an existing gap time, T_1, which is measured as the time difference between the CAV and the OV going to the intersection:

$$T_1 = \frac{L_{CAV}}{v} - \frac{L_{OV}}{v} \quad (11)$$

Where, v is the approaching speed of vehicles in ft/sec, L_{CAV} is the distance of the CAV to the intersection in feet, and L_{OV} is the distance of the OV to the intersection in feet. Since the distances are measured near the intersection, speed variations by the vehicles are 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 this 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 may reduce speed to add an extra gap time, Δt_c, to the existing gap between the two successive vehicles, as shown in Figure 11.

$$\Delta t_c = \frac{L_{CAV}}{v_c} - \frac{L_{CAV}}{v} \quad (12)$$

Where v_c is the CAV speed after reducing speed.

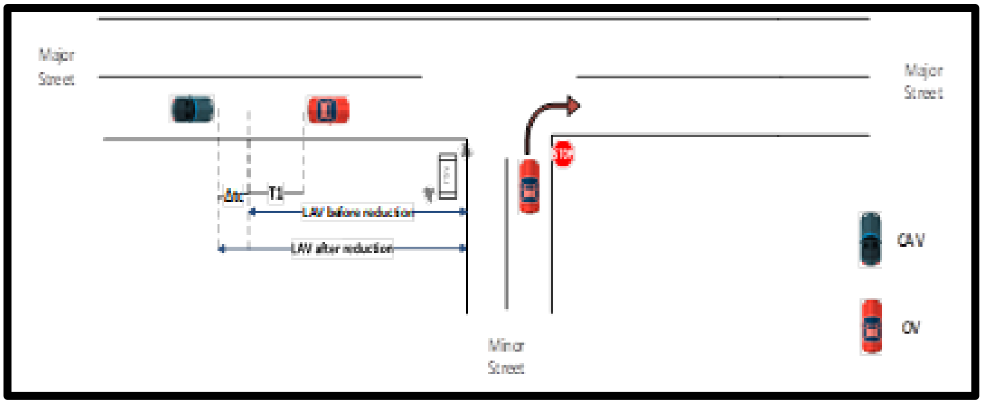

Figure 11 - Creation of extra gap time Δt_c.

The extra gap time should be large enough so that Δt_c plus T_1 is at least equal to T_0. As a result,

$$\frac{L_{CAV}}{v} - \frac{L_{OV}}{v} + \Delta t_c \geq T_0 \quad (13)$$

Substituting Equation 12 to 13, then:

$$\frac{L_{CAV}}{v} - \frac{L_{OV}}{v} + \frac{L_{CAV}}{v_c} - \frac{L_{CAV}}{v} \geq T_0 \quad (14)$$

or

$$\frac{L_{CAV}}{v_c} - \frac{L_{OV}}{v} \geq T_0 \quad (15)$$

If the extent of speed reduction for CAV is denoted as $\boldsymbol{\beta}$, as

$$v_c = \boldsymbol{\beta} v \quad (16)$$

then combining Equations 16 to 15 we get:

$$\frac{L_{CAV}}{\boldsymbol{\beta} v} - \frac{L_{OV}}{v} \geq T_0 \quad (17)$$

The time for communication between CAVs and RSU through V2I is neglected when it is compared with the speed of vehicles (Zhong et al.,2015). However, the time to reach the desired speed of CAV, called transition time Δt_{trans}, should be considered. This transition time is measured when CAV receives the instruction of gap time adjustment until it reaches the required speed. The formula for gap creation by a CAV should include Δt_{trans}, as follows:

$$\frac{L_{AV}}{\boldsymbol{\beta} v} - \frac{L_{OV}}{v} \geq T_0 + \Delta t_{trans} \quad (18)$$

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This equation can be rewritten by rearranging the terms to show the relationship between the different distances, as

$$\frac{L_{AV}}{\beta} - L_{OV} - (v\ \Delta t_{trans}) \geq (v\ T_0) \tag{19}$$

3. Safety Gap Behind the CAV

In this scenario, an OV is behind a CAV, as shown in Figure 12. Before CAV reduces speed to create the needed safe gap, it should check the distance of the vehicle behind. This ensures that the safety of the following vehicle would not be compromised by the reduction of the CAV speed. The distance gap between the CAV and the vehicle behind before the speed reduction is denoted as C_{back}. To ensure safety for the following vehicle, C_{back} should be at least greater than the safe car-following distance (CFD) when CAV reduces speed, or

$$C_{back} \geq CFD \tag{20}$$

Where CFD can be determined as:

$$\text{CFD} = v_i\, t_r + \frac{v_i^2 - v_f^2}{30(f \pm G)} \tag{21}$$

In the above equation, v_i refers to the initial speed of the following vehicle (ft/sec); v_f represents the required speed of CAV for creating the safe gap (ft/sec); t_r is the perception-reaction time (sec); f is referred to the coefficient of friction, and G is the slope of the roadway.

As shown in Figure 12, when the CAV reduces speed to create a gap, Δt_c, this gap time is added to the required existing gap between the CAV and the following vehicle so that the potential of speed impedance on the following vehicle is kept low. Thus, this safety measure can be written as:

$$C_{back} - (\Delta t_c\ v) \geq \text{CFD} \tag{22}$$

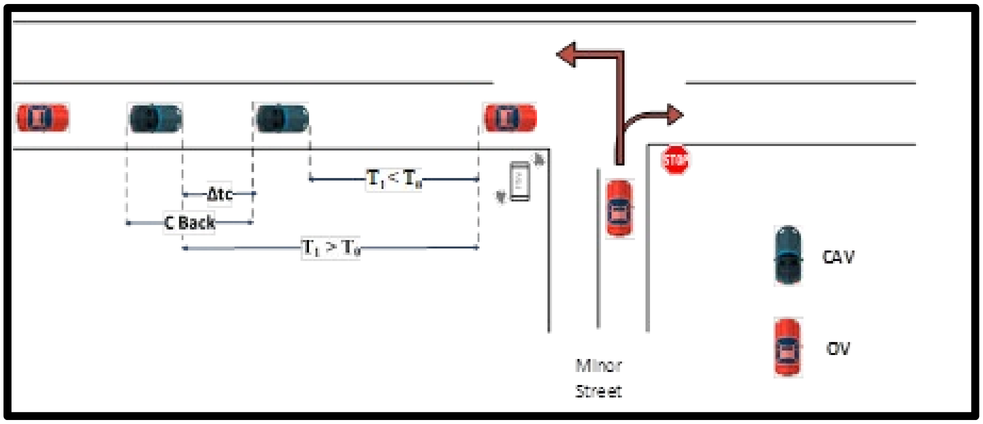

Figure 12 - Added gap time when CAV reduces speed.

C. Communication

In this model, the control strategies are built on V2V and V2I communications in data flow and decision making. Detailed data about approaching vehicles are collected by the CAV sensors and the V2I communication between the on-board unit and the roadside unit works to inform the targeted CAV if and by how much to adjust its speed. The range of communication by V2I is limited to the current effective DSRC communication range of 300 meters, approximately.

The communication process starts when a detector detects a vehicle in the minor street approach. The RSU informs the CAVs within the range of communication to check the vehicular gaps towards the intersection. If a gap less than the critical gap is found in front of the CAV, it will start to check for the safe distance as well as the distance of any vehicle following the CAV to ensure it will be safe to reduce speed. This process is shown in Figure 13.

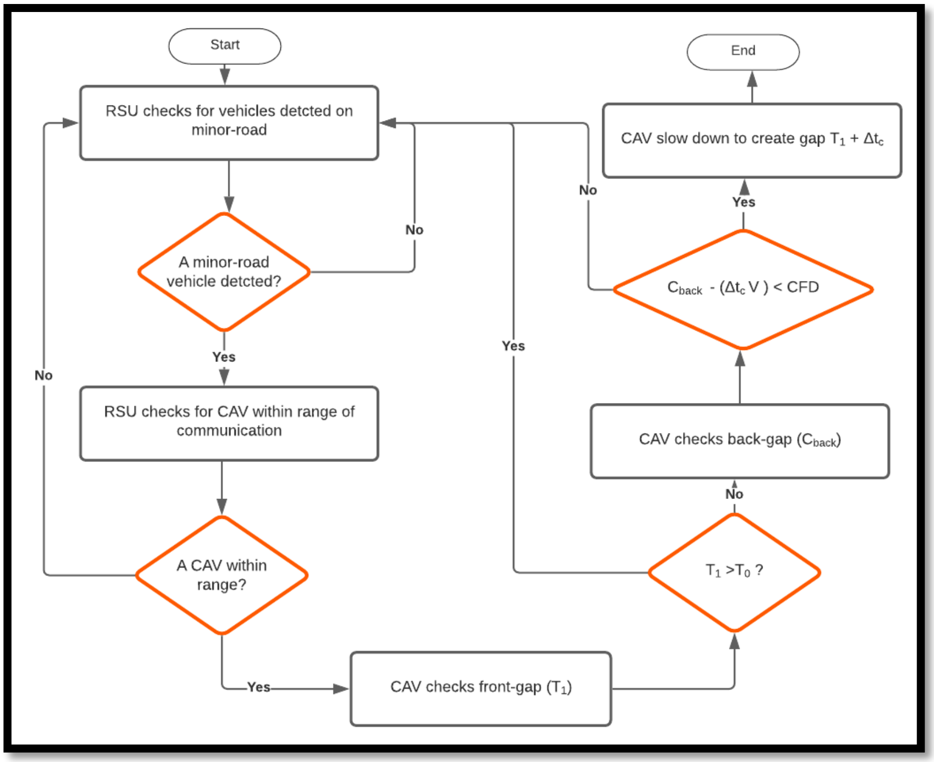

Figure 13 - Communication process and control strategy framework.

D. Minor Road Approach Maneuvers

There are two types of maneuvers for the minor road vehicle to join the mainline traffic. The first is when the minor road vehicle is taking a right turn where it needs to interact with eastbound traffic and find a safe gap to enter the intersection. The second type of maneuver is when a minor road approach vehicle is taking a left turn to join the westbound traffic. The minor road vehicle in this scenario will need to interact with both the eastbound and westbound traffic streams on the mainline road, as shown in Figure 14.

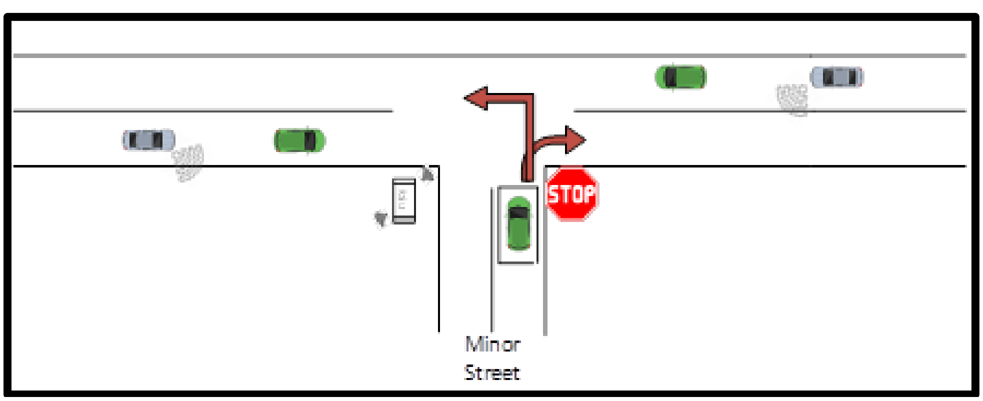

Figure 14 - T-intersection Movements (Right and Left).

1. Interaction of Right Turning Vehicle

Vehicles turning right from the minor road approach are less complex than vehicles turning left because they only need to interact with the eastbound traffic. The gap finding and creation concept has been discussed in the previous sections and the control logic in this scenario is more clearly described in the flow chart shown in Figure 15.

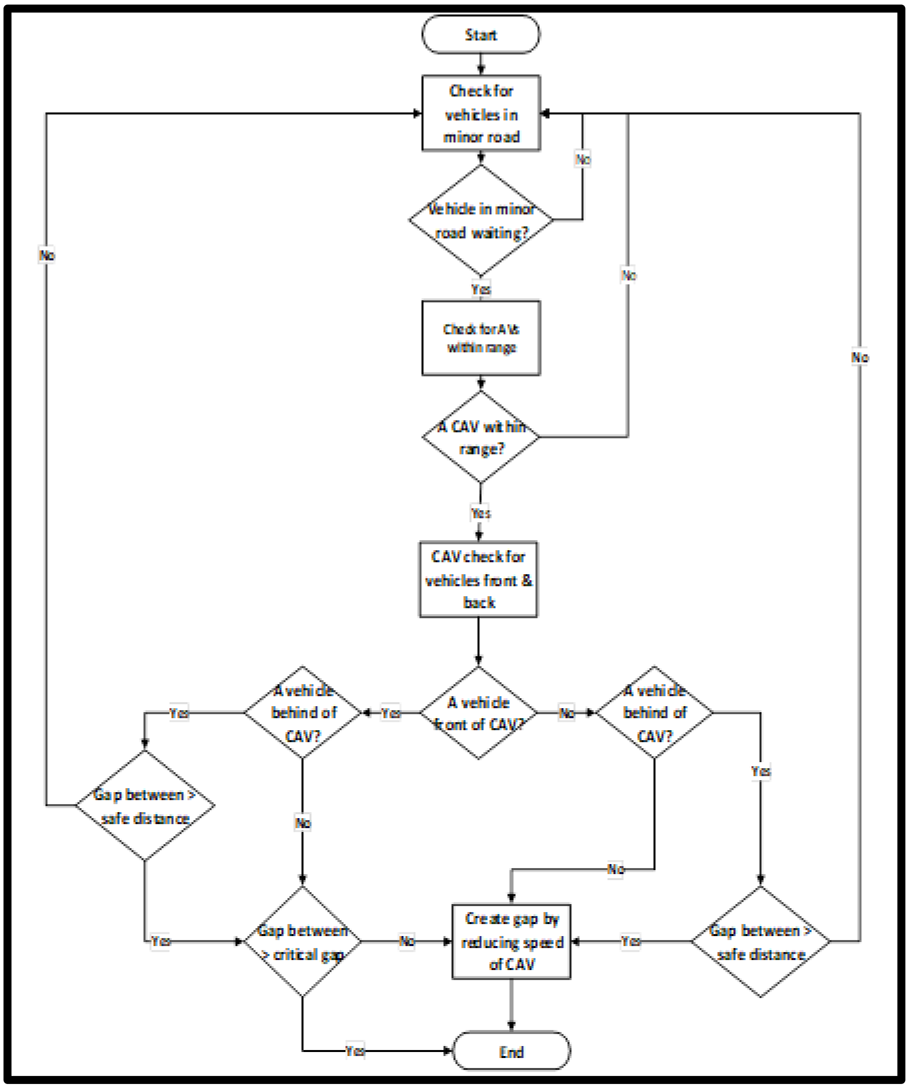

Figure 15 - Control logic for vehicles turning right from the minor road.

2. Interaction of Left Turning Vehicles

The minor road vehicles turning left present a more complex situation than turning right because they will need to intersect with both the eastbound and westbound traffic flows on the mainline. In this case, the control logic is built on the previous (right-turning) scenario and expanded to consider the joint effect of gap existence and creation from the westbound traffic flow as shown in Figure 16. The flow chart of control algorithm for this scenario explained in detail in Figure 17 when a general condition is considered.

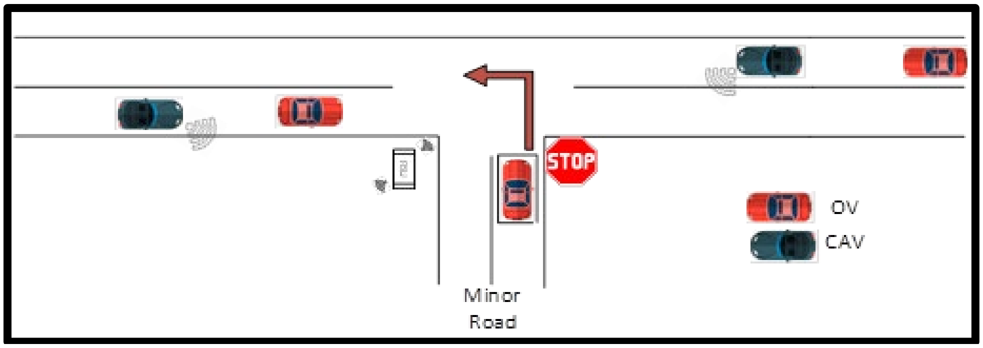

Figure 16 - Interactions with mainline traffic by left-turning vehicles.

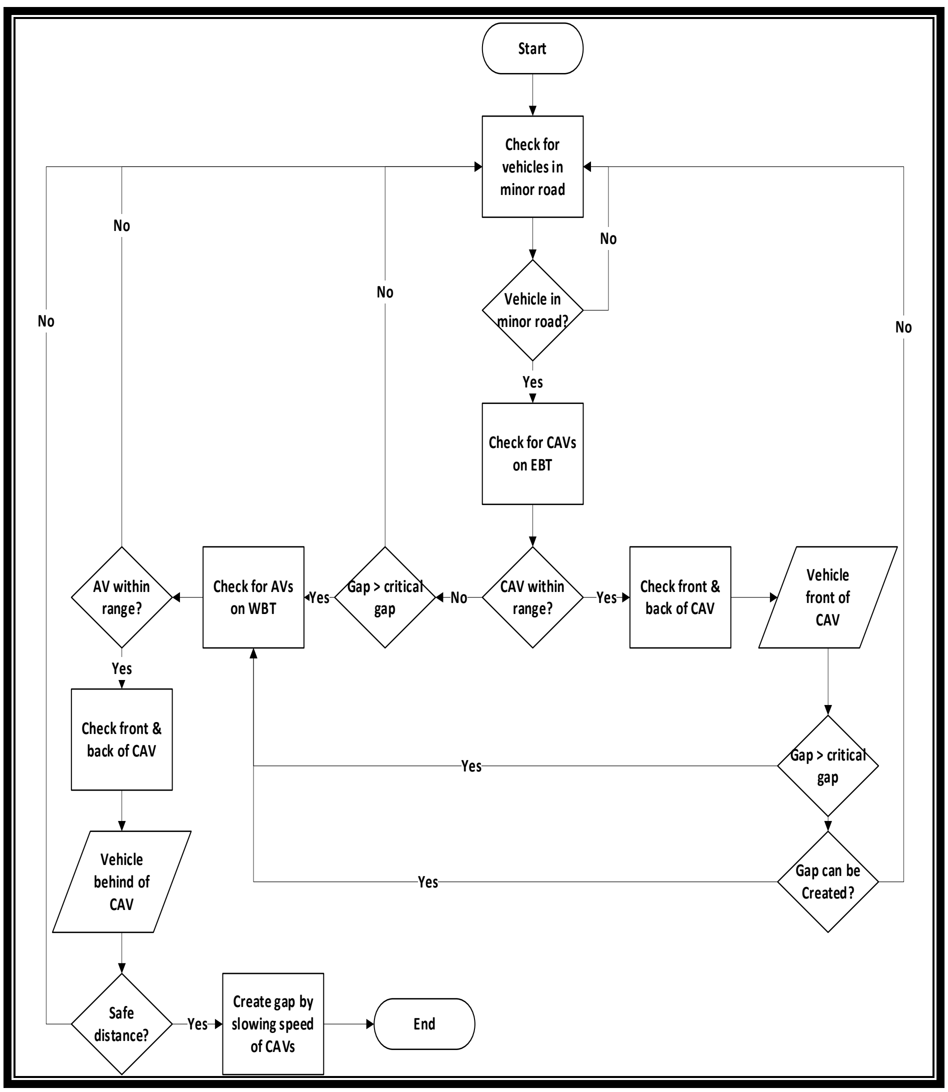

Figure 17 - Control logic for left-turning vehicles from minor road in general traffic conditions.

The control logic shown above is for general traffic conditions. Often, the case may be simplified if some situations exist. For example, if there are no vehicles either leading or following the CAV, as shown in Figure 18. The flow chart for the changed condition is shown in Figure 19.

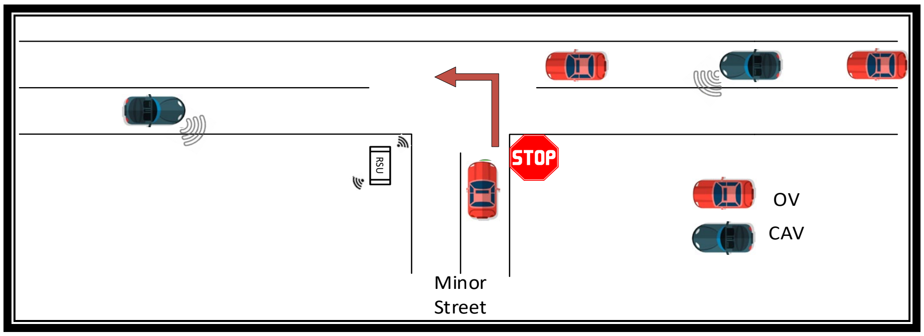

Figure 18 - No vehicles leading or following CAV.

In an extreme situation, when there are no vehicles (CAV or OV) approaching the intersection from one direction, the control algorithm for the remaining direction will be used, where the CAV may reduce speed to create a gap without considering the traffic flow in the other direction.

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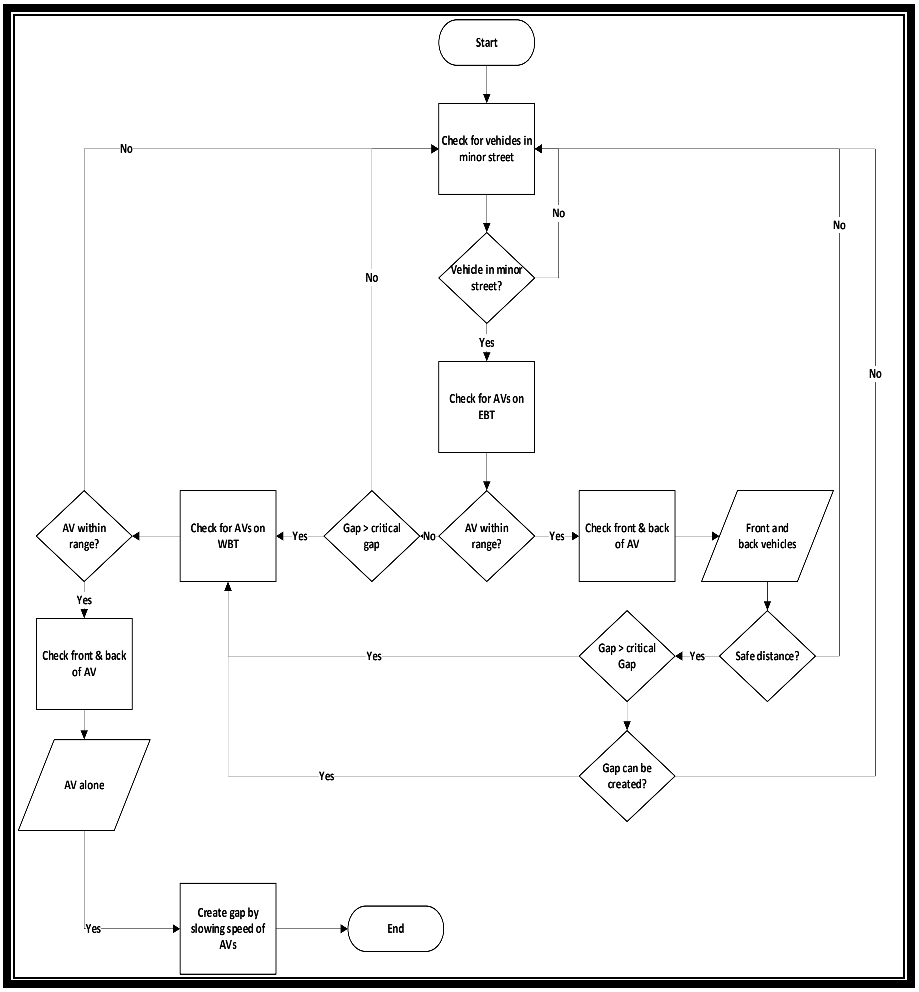

Figure 19 - Control logic for left-turning vehicles with no vehicles leading or following the CAV in one direction.

The proposed algorithm and the framework explained above are suitable only for a major road with one lane in each direction, which is common in suburban areas. More discussion on how CAVs are controlled for multilane situations will need to be made in the future. It is expected, however, that most of the control logic details will remain valid, with extra effort only to focus on gap distribution on multilane highways.

IV. CONTROL LOGIC AND SIMULATION

A. Introduction

One of the most useful tools for traffic engineers to estimate the effectiveness of an engineering solution is to conduct a simulation through traffic simulation software. In this research, simulation work was performed on the VISSIM platform. The VISSIM simulation software is commonly used in traffic analysis today, which in every detail is capable of realistically setting up the geometric and traffic conditions in the simulation environment. VISSIM has been used worldwide by public, governments, and universities (Mandjes, et. al, 2016).

B. Software Selection

VISSIM enables a microscopic traffic simulation to study traffic flows under specific conditions involving flow level, speed, and turning movement in addition to the geometry. This software comes under the umbrella of Vision Traffic Suite software and is one of the leading tools for simulation based on multimodal traffic operations. The outcomes of the software have been reported realistic and flexible in describing the practical applications. VISSIM is known to provide the ideal means for engineers to test various road traffic scenarios before implementation. The software has been used globally by various government-sponsored organizations and education institutes, in addition to the vast consulting industry (Ramadhan, Joelianto, and Sutarto, 2019).

Since this research involves CAVs in the traffic flow and the control logic relies on data communications between the vehicles and with the roadside units, the VISSIM software is the best simulation tool chosen to model vehicular interactions in the proposed intersection control method. By integrating with the control algorithm through external programming, the software is capable of simulating V2V and V2I applications.

C. Case Studies

Two types of intersection control are considered to demonstrate how the proposed algorithm works, including stop-controlled and semi-actuated control at a T-intersection. The mainline road at the three-legged intersection includes one lane in each direction, and at the minor road approach, enough lateral spacing is provided so that vehicles can turn left or right to join the major road from a designated turning lane. In both cases, the mainline has a priority over the minor approach.

1. Unsignalized Intersection

In this case study, an intersection with the same layout showed in Figure 20 is utilized where vehicles on the major road always have the right of way over those on the minor road, and the latter would have to wait at the stop sign before merging. For safe operation, minor road vehicles can enter the intersection only if there is a gap greater or equal to the critical gap. In the case of semi-actuated signal, however, if a vehicle at the minor road approach has waited excessively long, the detected presence by this vehicle may trigger the signal to change resulting in an interruption to the mainline traffic stream.

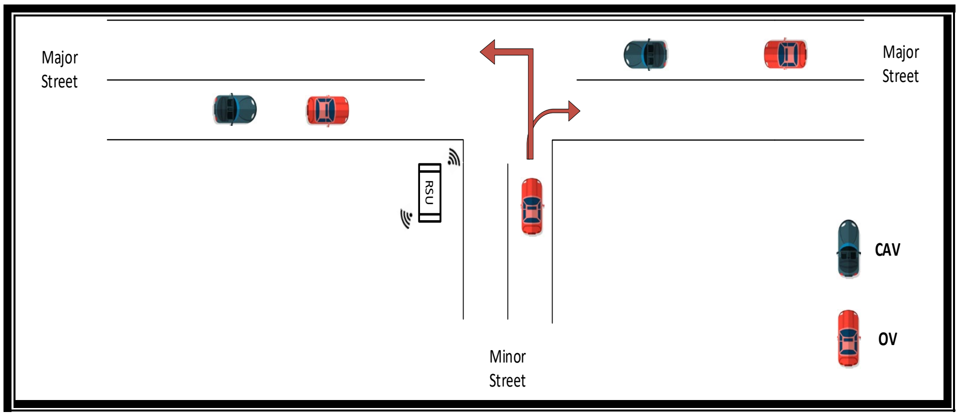

Figure 20 - Intersection layout of unsignalized intersection.

During simulation, if a CAV in a traffic flow mixed with ordinary vehicles receives speed reduction instruction from the RSU to create a usable gap for the minor road vehicle, 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 gap of needed size due to the following possible scenarios:

1) The front gap time of the CAV from the leading OV is greater than the critical gap, so there is no need for gap creation. This scenario happens when,

$$T_1 \geq T_0$$

2) The front gap time of the CAV is less than the critical gap, but the CAV cannot make the gap equal to or greater than the critical gap. This happens when a CAV is close to the leading OV and not enough time can be saved by slowing down; that is,

$$T_1 + \Delta t_c < T_0$$

3) The back gap distance of the CAV from the following OV is less than the safe distance required. This scenario is when the following OV 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 help create a long enough gap for the minor road vehicle, when the following conditions are satisfied:

1) The front gap time is less than the critical gap, and a CAV can help make the 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 OV is greater than the safe distance.

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

The control logic flow for the above two options is shown in Figure 21.

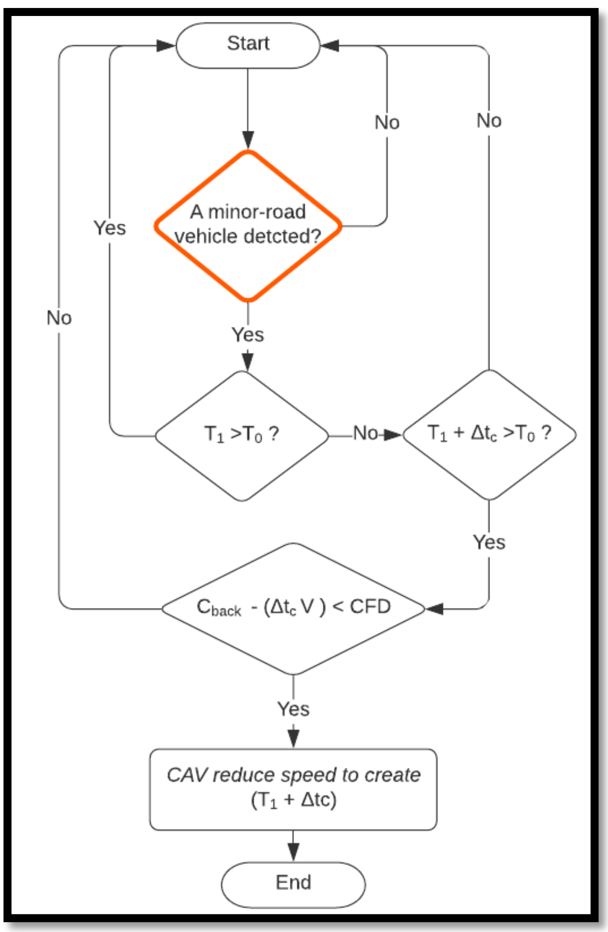

Figure 21 - Logic flow of gap creation for different cases.

The above discussion has considered only one direction on the major road, presenting the condition for minor road vehicles to make right turns. However, for minor road vehicles turning left, safety considerations must be given to both directions on the major road because of the potential conflicts between the available gaps. In this case, both directions on the major road should satisfy the safety conditions before any CAV reduces speed. Figure 22 shows the scenario where a minor road vehicle is waiting for a gap in the mainline traffic flow in both directions to make a left turn.

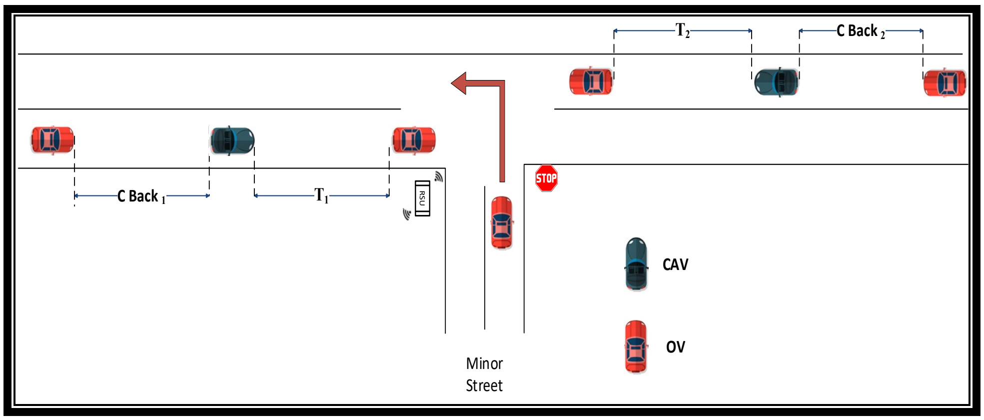

Figure 22 - Minor road vehicle turning left and two CAVs coming towards intersection from both directions.

When traffic flow in both directions is considered, the algorithm will not let the CAV in one direction to slow down to create the extra gap Δt_c before making sure that an adequate gap in the other direction is available or can be created at the same time. If either scenario 2 or scenario 3 in Option 1 above applies to any traffic direction, the algorithm will not be executed; similarly, if condition 1 or condition 2 in Option 2 is not met the procedure will not be carried out. As discussed in the Methodology section, it is more difficult to make left turns at unsignalized intersections due to a conditional probability. The control algorithm for left turns is shown in Figure 23.

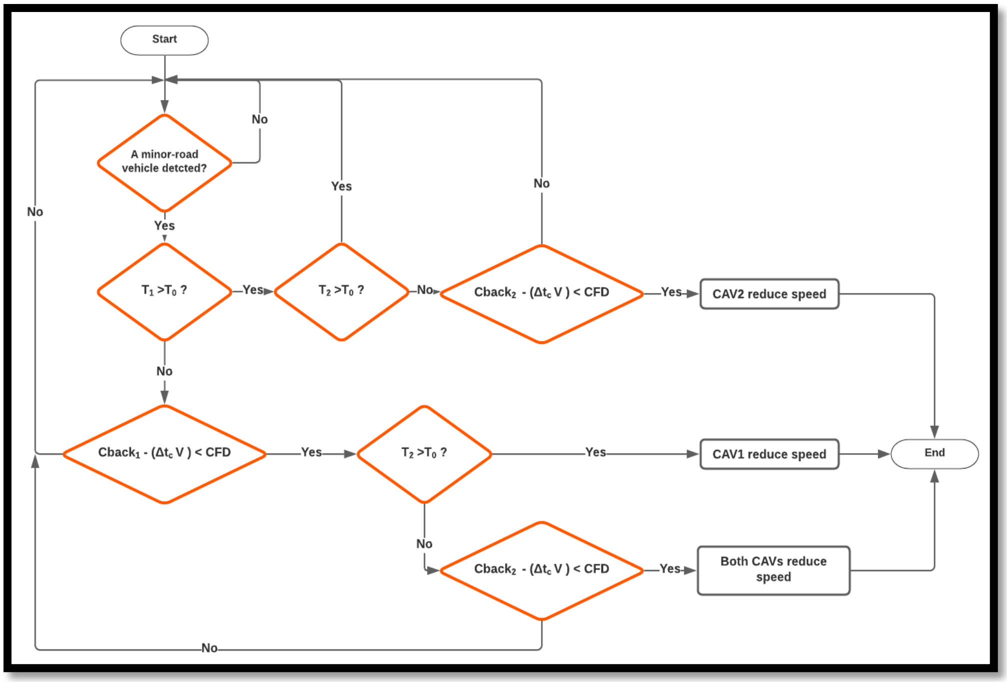

Figure 23 - Logic flow for left turning vehicles at minor road to merging into the major road with two directional traffic flows.

2. Semi-actuated Signal Control

Another application of the proposed control strategy to take advantage of CAVs is at a signalized intersection under semi-actuated control. By helping create gaps in the mainline traffic flow for the minor road vehicles to enter the intersection, signal interruptions to the mainline traffic flow due to detection of the waiting vehicles at the minor approach may be reduced. The signal system at the intersection will be working as in normal conditions, except that the detection and signal operation is changed to allow longer vehicle waiting time in order to allow gap creations by CAVs. If successful, the minor road vehicle can enter the intersection without the need for a designated green time phase.

The modified signal operation algorithm uses a green-rest (GR) plan in the mainline The GR plan kicks in if a gap can be created near the end of green for the mainline. Instead of switching the green time to the minor road, the mainline green is extended to allow the execution of the gap creation procedure. If successful, a vehicle at the minor road approach can still enter the intersection without the need of a green light. However, if conditions do not support gap creation or no CAVs are found in the approaching traffic, the normal operation of the semi-actuated signal will not be affected, and the minor road vehicle can enter the intersection after receiving a green light.

In practice, traffic signals at most T-intersections of a major road with a minor road operate on two-timing phases, where Φ1 serves the major road phase and

Φ2 serves the minor road. Another method to facilitate gap creation on the mainline traffic is by temporarily changing the two-phase operation to a flashing-red for the minor approach and yellow flashing for the major road. This also avoids signal interruptions, and it gives a chance for CAVs in the mainline traffic to execute the gap creation algorithm. With a flashing red signal, the minor road operates as if it was controlled by a stop sign. If the minor approach vehicle failed to find a gap and excessive waiting time is reached, the flashing-red algorithm will expire to allow the signal switch to green for the waiting vehicle.

In either case of the modified signal operation plan, the effectiveness of this control algorithm can be evaluated by how often the signal interruption is reduced with and without CAVs to help create gaps. The flow chart of this scenario is explained in Figure 24.

During simulation, a minimum green and a maximum green time are used for the semi-actuated signal. The traffic volume is classified into three levels: low, medium, and high, and the corresponding maximum green time used is 50, 60, and 70 seconds, together with a minimum green of 10, 20, and 30 seconds, respectively. Similarly, the minor-road green time for the low, medium, and high traffic volumes is set as 10, 15, and 20 seconds, respectively.

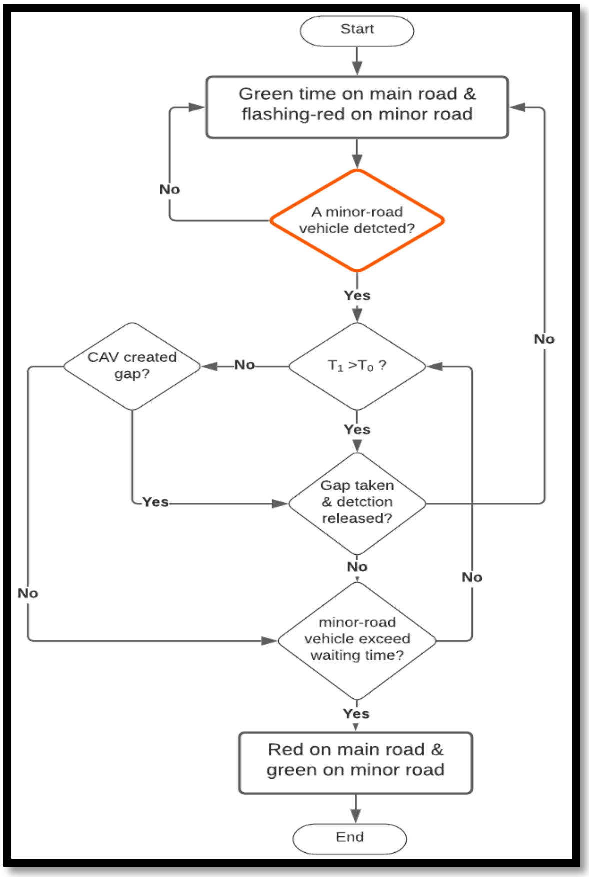

Figure 24 - Control logic for semi-actuated signals.

D. VISSIM Simulation

The proposed algorithm of using CAVs to create additional usable gaps for the minor road vehicle to enter the major road is simulated under different traffic conditions. The major road volumes selected are 600, 800, 1000, 1200, 1400, and 1600 vehicles per hour, where the percentage of CAVs on the major road is assumed at three levels, 30%, 50%, and 70%. The minor road volume is set as100, 150, 200, and 250 vehicles per hour, as shown in Table 1. Two types of traffic compositions are considered, in which the first is when there are no CAVs on the major road (the benchmark for comparison) and the second includes a mixed traffic condition with both CAVs and OVs.

While the critical gap values recommended by HCM have been commonly used in many traffic analyses, a more accurate estimation of the critical gaps is obtained by using field observations in real traffic conditions. Additionally, a utilization factor was applied on the number of gaps accepted by the minor road vehicles based on the field observation. The acceptance rate on the results found in the field test section is obtained and applied in the simulation to evaluate the gap acceptance more practically, as discussed further later.

1. Data Input

The first step of simulation to test the control logic algorithm in VISSIM is to set up the traffic network, including building roadway links, specifying route choices, and setting up the priority rules, as shown in Figure 25. The second step is to define vehicle compositions and add CAVs as a new vehicle type/class. The physical dimensions of the CAVs will remain in the same range as general passenger vehicles.

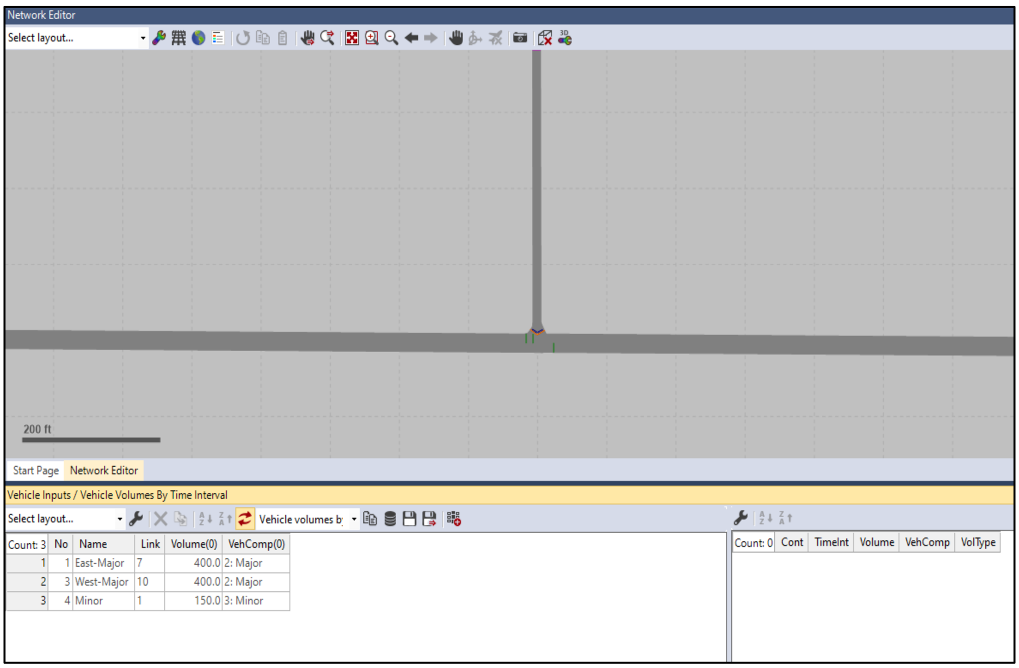

Figure 25 - Traffic network generated in VISSIM.

The simulation will be performed to verify the feasibility of the proposed control logic under different traffic conditions as shown in Table 1. The major road volume includes both CAVs and OVs.

Table 1 - Traffic volumes for both the major and minor roads.

% of Connected and Automated Vehicles	Major Street Volume	Minor Street Volume
%	vehicles per hour	vehicles per hour
No CAV	600-800	100
30%	900-1100	150
50%	1200-1400	200

70%	1500-1600	250

2. Coding in VISSIM

The control logic developed must be incorporated in VISSIM when CAVs are introduced to create additional usable gaps. For this purpose, the Python programming language is used through the interface of Object Model (COM). VISSIM-COM comes in handy when the model entails custom algorithms that are not available on the version of VISSIM GUI (Ramadhan, Joelianto, and Sutarto, 2019). Since the idea of controlling CAVs at the intersection is not in the GUI functions in VISSIM, the COM server is registered to be able to use the COM interface. This allows integration of VISSIM with the Python program and execution of scripts through VISSIM. Thus, the specific commands for our algorithm to control CAVs in gap creation are written in Python and uploaded to VISSIM through the Event-based Script file in the simulation. Figure 26 shows the implementation of this method in the VISSIM software.

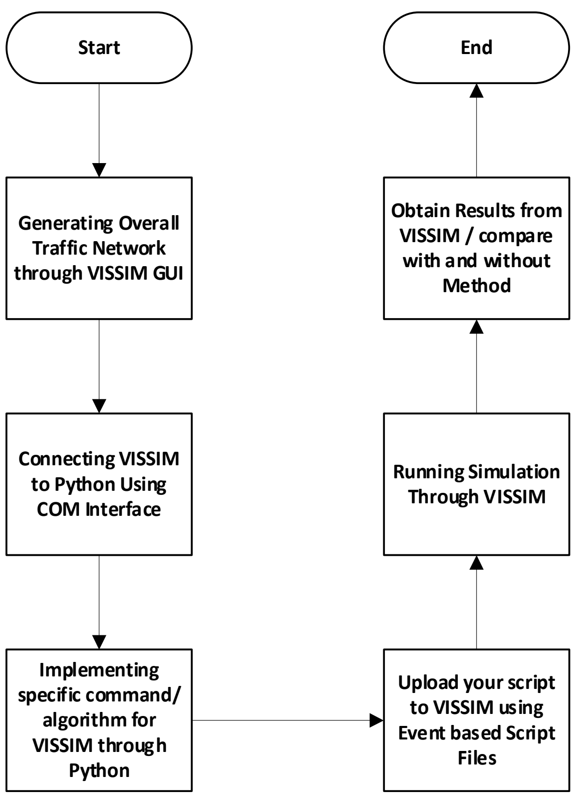

Figure 26 - Process of implementing Python scripts in VISSIM.

3. Simulation preparation

Since VISSIM has built in a random nature in its simulation model, the study has been performed in ten simulation runs for each scenario with various arrangements of random seed numbers to ensure that the reported results give an accurate representation of the average. The intersection (represented by the node in the network) performance was summarized before and after implementing the strategy of using CAVs to create gaps.

The simulations are conducted in two different vehicle compositions to test the objective of the research. The first vehicle composition is when there are no CAVs on the mainline flow and the second composition refers to the mixed traffic conditions by CAVs and OVs.

VISSIM results include the average vehicle delays and stopped delays of the vehicles on the major road as well as minor road approach. The average queue length before and after CAV applications is also obtained from VISSIM. The delay measures the additional time experienced due to speed reduction by CAVs to ensure safety and efficiency of the continuous flow. More detailed discussions and results of the simulations are provided in the next section.

V. SIMULATION RESULTS AND DISCUSSION

A. Introduction

Different measurements of effectiveness (MOEs) have been used in the simulation study, including waiting time, queue length, average delay, control delay, signal interruption, and capacity for both approaches. In addition, an analytical study of the gap characteristics was also performed to estimate the available gaps in the traffic flow and help define the range of CAV percentages to be used. The simulation results have included both cases, unsignalized and semi-actuated intersections.

B. Analytical Study of Gap Distribution

For a normal suburban roadway, it is assumed that CAVs are present in both directions of the traffic flow. The opportunities for CAVs to create additional safe gaps for the minor road vehicles depend mainly on the number of vehicles and percentage of CAVs on the major road. Following the discussions in Section III, Equations 4 through 9 are used to estimate the availability of gaps in the traffic mixed with CAVs. Figure 27 shows the number of gaps that CAVs may possibly create to help right turns from the minor road approach at different major road volumes and CAV penetrations.

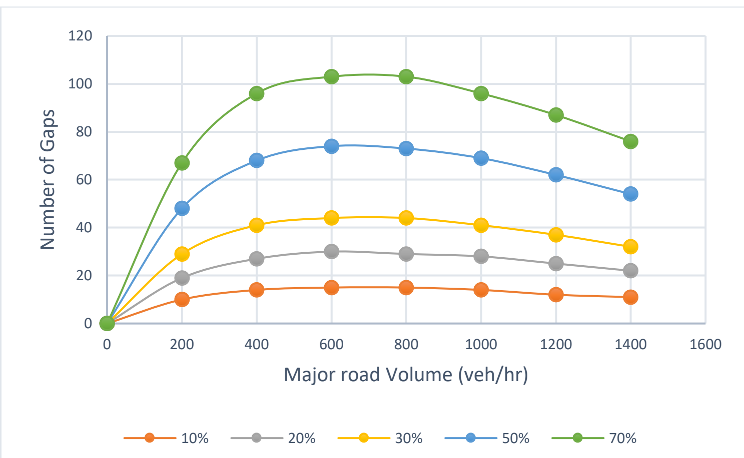

Figure 27 - Number of gaps CAVs may possibly create to help right turns.

As shown in Figure 27, the case of 70% of CAVs on the major road leads to the highest number of gap creations and the 10% case yields the lowest number of gaps. The results show that the number of possible gaps created increases with the increase of CAV penetrations and the increase of major road volume. However, when the major road volume continues to increase, as shown in Figure 27, the number of gaps decreases because, with the increase of the volume on the major road, the headway between two successive vehicles becomes smaller, making it more difficult to create a headway greater than the critical gap.

The number of gaps that CAVs can help create for the minor road vehicles turning left is shown in Figure 28. The results are based on a different level of penetration of CAVs and different major road volumes. Figure 28 shows the results of the possible number of gap creations by CAVs for left turning vehicles on the minor road. Since those vehicles would need to find a safe gap on the major road in both directions of the traffic flow, the probability of finding such a gap is less for the left turning vehicles than for the right turning vehicles.

Similarly, the number of gaps to be created by CAVs for the left turning vehicles from the minor road increases with the increase of the CAV percentage and the major road volume. However, as the major road traffic volume increases, the number of such gaps decreases because more vehicles on the major road leading to fewer longer gaps.

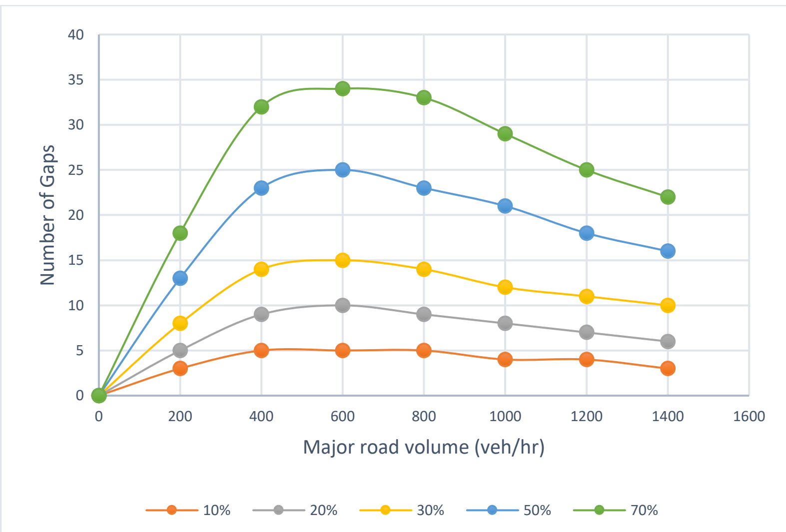

Figure 28 - Number of gaps CAVs may possibly create to help left turning vehicles.

C. Simulation Results

Section V.B shows the levels of traffic volume and proportions of CAVs in mixed traffic to guide the scope determination of the simulation. Different traffic demand levels have been considered on the major and minor road along with different CAV percentages on the major road. The minor road volumes used in the simulation platform are 100, 150, 200, and 250 vehicles per hour, whereas the major road volumes vary from 600 vehicles per hour to 1600 vehicles per hour. The CAV percentages to the total volume on the major road are 30%, 50%, and 70%.

Two types of locations (or traffic control) are considered, one is at an unsignalized intersection with a stop control and the other is at a signalized intersection where a semi-actuated traffic light is used based on data from a presence detector. Results presented in this section are from the outputs of VISSIM (version 10) with ten different simulations running in each scenario. These different simulation runs are from using different random seeds to account for variations in vehicle arrivals in the real world.

1. Unsignalized Intersection

The simulation for an unsignalized intersection is based on the control logic explained in Section IV and the main focus is on the improvement of minor road waiting time and queue length.

a. Stopped Delay on Minor Road Approach

The average stopped delay is the time lost when a vehicle is stopped in the queue, waiting for a safe gap in the minor street approach. The simulation results on the average stopped delay, grouped by different volume levels of CAV, are shown in Figure 29. Significant reductions on stopped delays at the minor road approach can be achieved. It is observed that a higher CAV percentage in the mixed traffic flow generally is more effective in reducing the delay, but the effectiveness gradually comes down when the traffic volume on the mainline continues to increase. On the other hand, when traffic flow on the minor street approach increases, the improvement on stopped delay for the minor road approach also drops, showing that a queue is likely building up on the minor road approach.

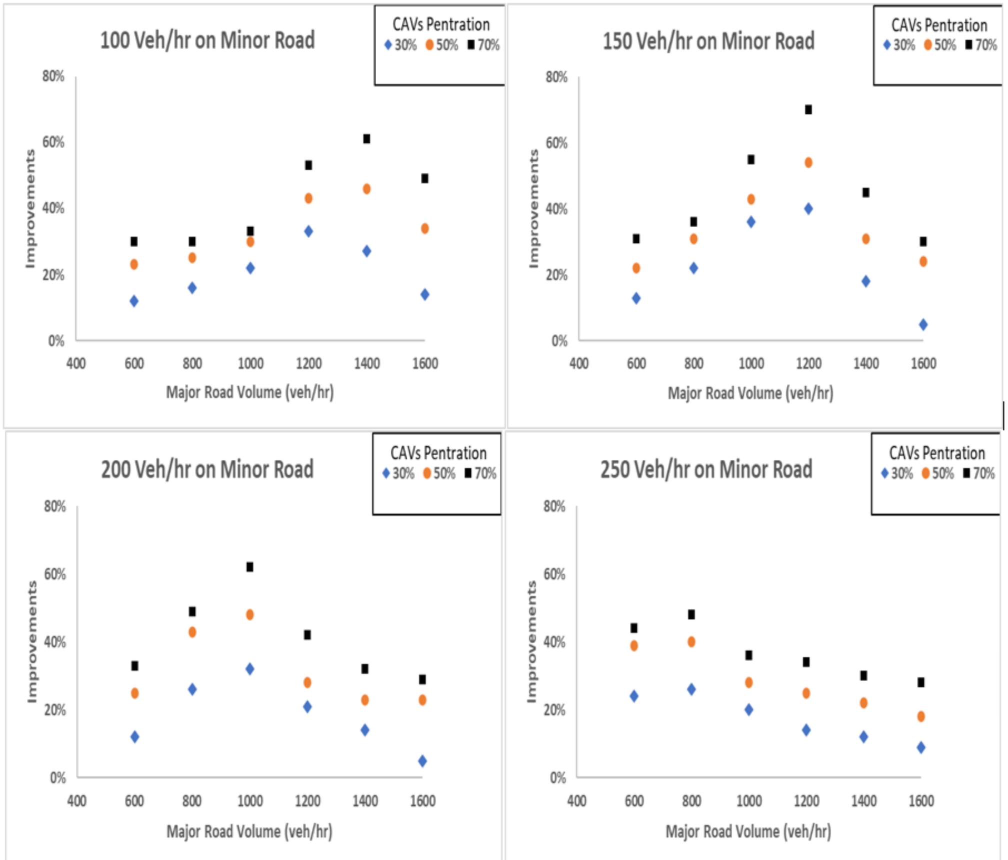

Figure 29 - Improvements on stopped delay at the minor road approach with different major and minor road volumes and CAVs percentages.

Each sub-figure in Figure 29 shows three different CAV penetrations compared with the case when there are only ordinary vehicles as a benchmark. The average stopped delay of the minor road approach shows improvements at all traffic levels of the major and minor road volumes, in the mixed traffic with CAVs. The results show that the stopped delay of the minor road approach may be reduced by as much as 70% when the percentage of CAVs also reaches 70% and the minor road volume is set at 150 vehicles per hour. Even with a lower CAV percentage on the major road carrying a flow of 1200veh/h, results show that the minor road stopped delay can be reduced up to 57% compared with the case of no CAVs on the major road.

As shown in Figure 29, when the penetration level of CAVs increases, the stopped delay of the minor road approach generally decreases for a certain level of traffic volume on the mainline. This is primarily because the increase of flow in the major road and the increased CAVs can help create more safe gaps, and this can lead to less waiting time for the minor road vehicles. However, if the major road volume keeps increasing, at 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 size reduces the possibility for CAVs to create safe gaps for the minor road vehicles.

When further examining the stopped delay on the minor road approach, it is found that the increase of the minor road volume affects the waiting time of the vehicles on the minor road approach. The increase of the minor road volume would increase the need for CAVs to create gaps. With low to medium traffic flow on the major road, the increase in the minor road volume will result in improvements on the stopped delay of the minor road approach. However, with the increase in the major road volume, the increase in the minor road volume will cause the improvements of the stopped delay at the minor road approach to drop. This can be attributed to the fact that the intersection capacity is limited and higher volumes on the mainline and the minor road cannot be accommodated simultaneously.

b. Queue Length on Minor Street Approach

Queue length is generally defined as the distance of the rear end of the furthest stopped vehicle from the stop line. In VISSIM, queue length at intersections is defined from the queue counter location on the last vehicle's entry link in the queuing state. Similar to stopped delays, the average queue length at the minor road approach is estimated at different major and minor road volumes and different CAV percentages.

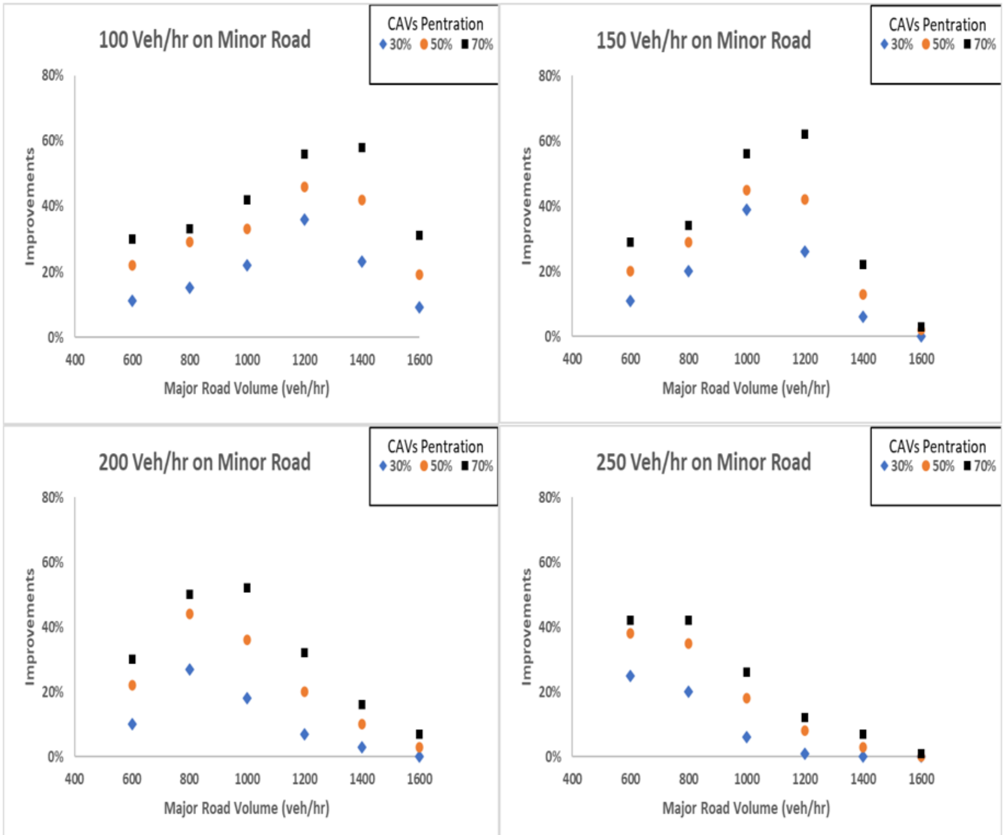

Figure 30 - Improvements in the queue length at the minor road approach at different major and minor road volumes and different CAVs penetrations.

Figure 30 shows the changes in queue length at the minor road approach. Each sub-figure represents a different minor road volume level at 100, 150, 200, 250 vehicles per hour, respectively, and the counterpart traffic volume on the major road are set as 600, 800, 1000, 1200 1400, and 1600 vehicles per hour.

Since queue length and waiting time on the minor road approach are closely correlated, it is anticipated to see a reduction of delay as a result of the decrease in queue length. As a result, the queue length improvements are expected to follow the pattern of the delay changes in Figure 29. The increase of the number of CAVs on the major road helps reduce the queue length on the minor road approach when the major road traffic volume is not very heavy. On the other hand, the increase of volume on the minor road will increase the need for gap creation on the mainline, which increases the queue length as the major road flow continues to increase due to the limitation in the intersection capacity.

Specifically, it can be seen from Figure 30 that the queue length at the minor road approach is reduced with the increase of the number of CAVs on the major road. For example, the queue length at the minor road approach is reduced by about 62% after the CAV penetration has reached 70% and the volume level on the minor road is at 150 vehicles per hour and on the major road is 1200 vehicles per hour. Even when the CAV proportion is reduced to 50% and 30% on the major road, the results still show a substantial decrease in the queue length.

From Figure 29 and Figure 30, we can state that deploying CAVs in the road network with the proposed strategy can improve traffic efficiency and help reduce congestion as well as queue length at the minor road approach. It may also be argued that the implementation of the control algorithm could positively influence drivers' attitude and behavior by reducing their frustrations.

c. Fuel Consumption

The waiting time at the minor road approach directly increases overall fuel consumption and emissions. Figure 31 shows how the control algorithm can effectively reduce fuel consumption for the waiting vehicles compared with the no CAVs situation. With the increase of CAV penetration in the mainline traffic flow, the reduction of fuel consumption becomes larger.

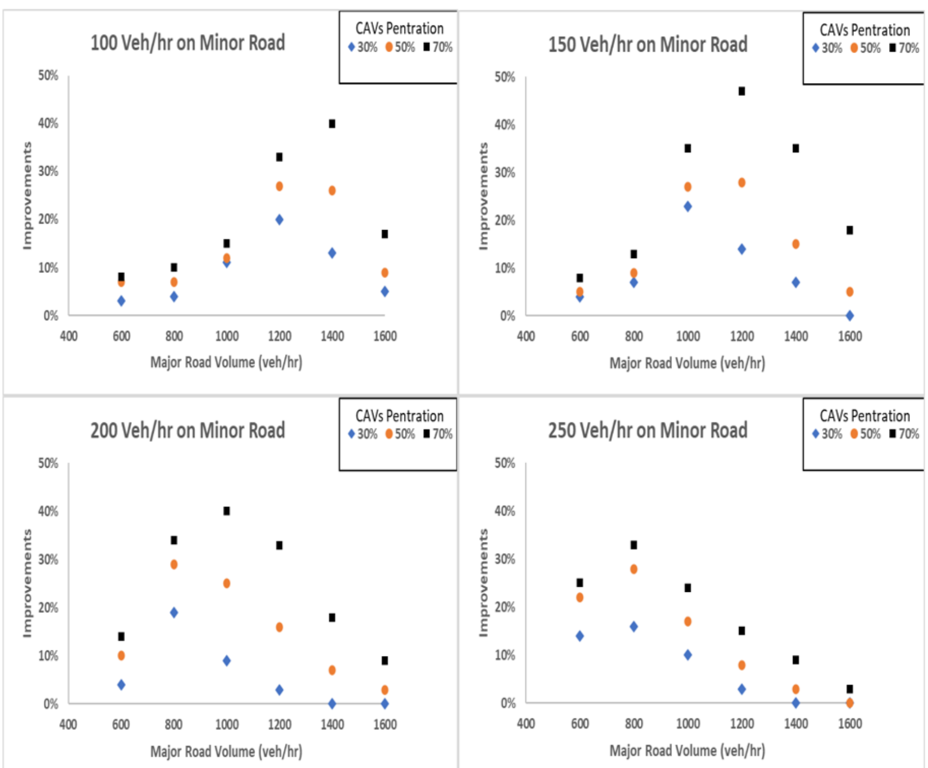

Figure 31 - Fuel consumption reductions for minor road vehicles at different major and minor road volumes and CAV percentage.

Figure 31 shows that CAVs on the major road can help reduce fuel consumption at all proportion levels. For example, the results indicate that an increase in CAV's penetration to 70% at 200 vehicles per hour on the minor road approach would improve fuel consumption by more than 40%. With higher traffic volumes on the minor road, the benefit in fuel consumption savings is not as large, but a reduction of approximately 32% can still be achieved.

d. Average Delay on Major Road Approach

The impact on the major road traffic flow is also studied by obtaining the average delay on the major road before and after the proposed control algorithm. Since delay can be obtained before adding CAVs to the mainline stream, the change in average delay is calculated as follows:

$$Additional\ Average\ Delay = Delay\ with\ CAVs - Delay\ without\ CAVs \quad (23)$$

The average delay of the major road approach is obtained from VISSIM before and after the implementation of the control method.

Table 2 shows a comparison between the delay added to the major road due to speed reduction by CAVs for gap creation. It can be seen that, at low traffic volumes on the major road, the delay added to the mainline vehicles is almost zero while improving the delay at the minor road approach by 25%. Even at a higher level of mainline traffic volume, the additional delay on the major road is only 11%, whereas the improvement on the minor road approach is roughly 62% under the same traffic condition. A significant increase in the added delay is found when the mainline traffic volume reaches 1200 vehicles per hour, accompanied by a volume of 250 vehicles per hour on the minor road. More results are shown in the Appendix.

Table 2 - Comparison between delay added to the major road and the improvements at minor road approach.

Minor Street Volume (vph)	Major Street Volume (vph)	% of AV	% of Delay added (major street)	% of Improvements in Delay (Minor Street)
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%

e. Intersection Delay

The intersection delay measures the combined delay from the major road and the minor road.

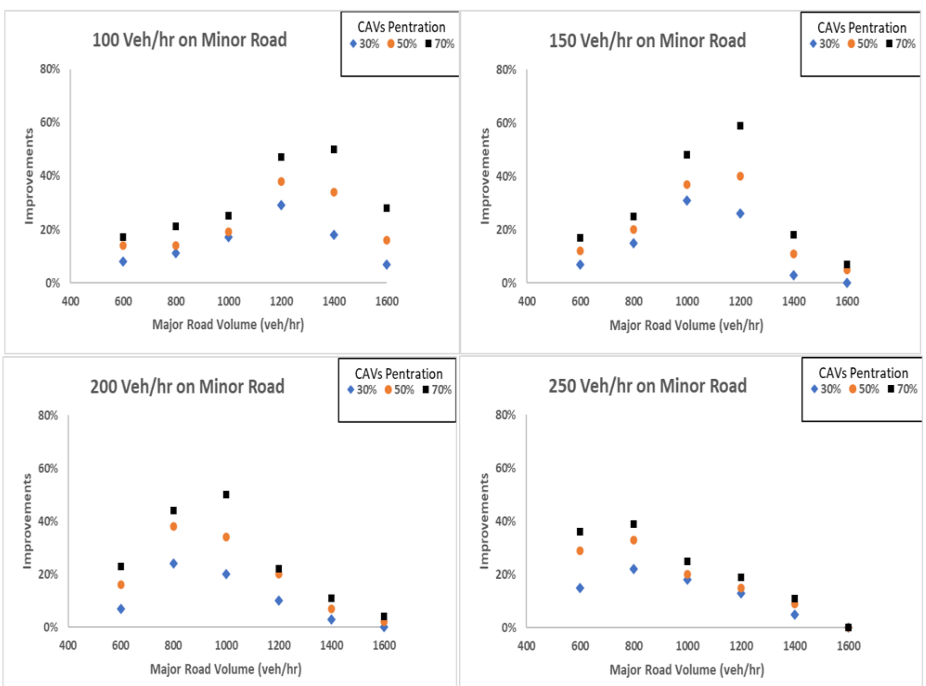

Figure 32 - Intersection delay at different CAVs percentages.

As shown in Figure 32, the combined improvements in the intersection wide average delay increase when the number of CAVs increases on the major road. The reduction at the minor road approach outweighs the added delay to the mainline traffic flow. However, as the traffic volumes on the major road and the minor road continue to increase, such improvements gradually go down, reflecting the limited capacity of the intersection.

2. Semi-actuated Signal

Another part of this research is to study the effectiveness of the control strategy in delay reduction at an intersection under semi-actuated signal control. At many such locations today, green signal switching occurs frequently in order to serve the waiting vehicles at the minor road approach.

During simulation, a minimum green and a maximum green time are used for the semi-actuated signal. The traffic flow is classified into three levels: low, medium, and high traffic volume, and the corresponding maximum green for the major road is set as 50, 60, and 70 seconds, respectively. By default, if no calls are placed (no vehicles are detected) on the minor road approach, the green light will stay on for the major road, or in green rest mode. The minimum green for the major road also varies with the volume levels, as 10, 20, and 30 seconds, respectively. At the minor road approach, the maximum waiting time (before actuating the green light) for low, medium, and high volumes is set as 10, 15, and 20 seconds, respectively. Those times are selected based on observed vehicle waiting times from the field test sites to be discussed in Section VI.

a. Signal Interruptions

The signal interruptions are counted when the minor road vehicles are not able to find a safe gap to enter the major road and the maximum waiting time is reached. The signal will switch to serve a minimum green to the minor road approach by stopping the major road flow. Figure 33 illustrates the number of signal interruptions at different CAVs penetration levels with a different allowable maximum waiting time on the minor approach. When the minor road volume increases to 200 vehicles per hour, the results are shown in Figure 34.

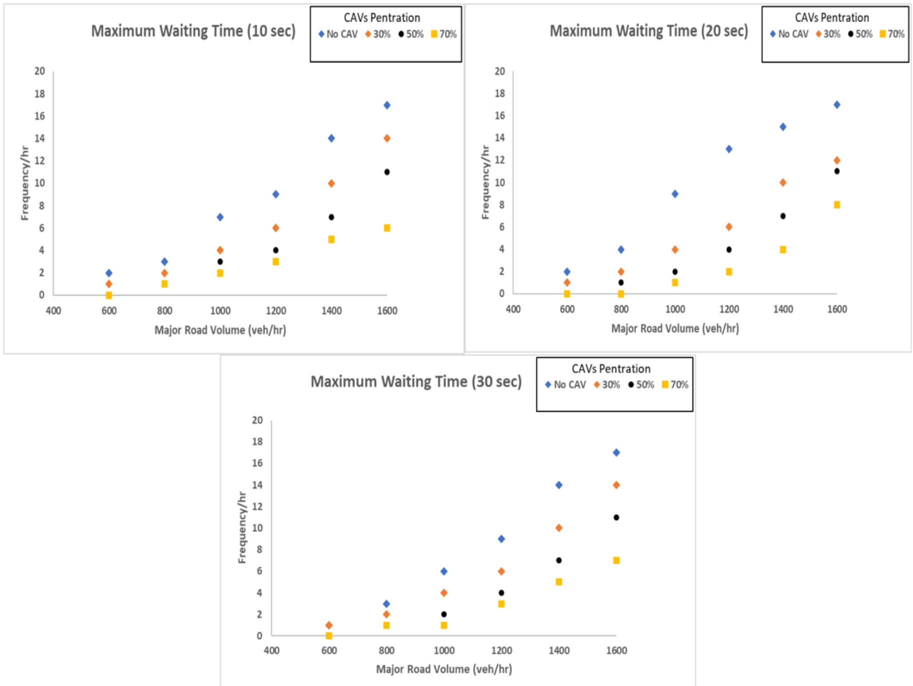

Figure 33 - Signal interruptions to the mainline traffic at different percentages of CAVs with 100 vehicles per hour on the minor road.

With the increase of CAVs on the mainline traffic flow, the number of signal interruptions reduces. This is because more CAVs increase the probability of safe gap creations and reduce the need for signal switching. At a lower range of traffic volume on the major road, the number of mainline interruptions is smaller than when the major road volume increases. Furthermore, when the minor road volume increases, the possibility of interrupting the mainline flow increases.

At the volume of 200 vehicles per hour on the minor road, the changes in the number of signal interruptions to the mainline traffic follow the trend shown in Figure 34. However, those changes are more sensitive to the maximum waiting time allocated to the minor road vehicles. As illustrated in Figure 34, by extending the maximum waiting time to 30 seconds from 10 seconds, the number of signal interruptions drops significantly from the range of 50~70 to 10~30. This is, understandably, due to a much longer time the minor road vehicles can wait before the signal switch is called for.

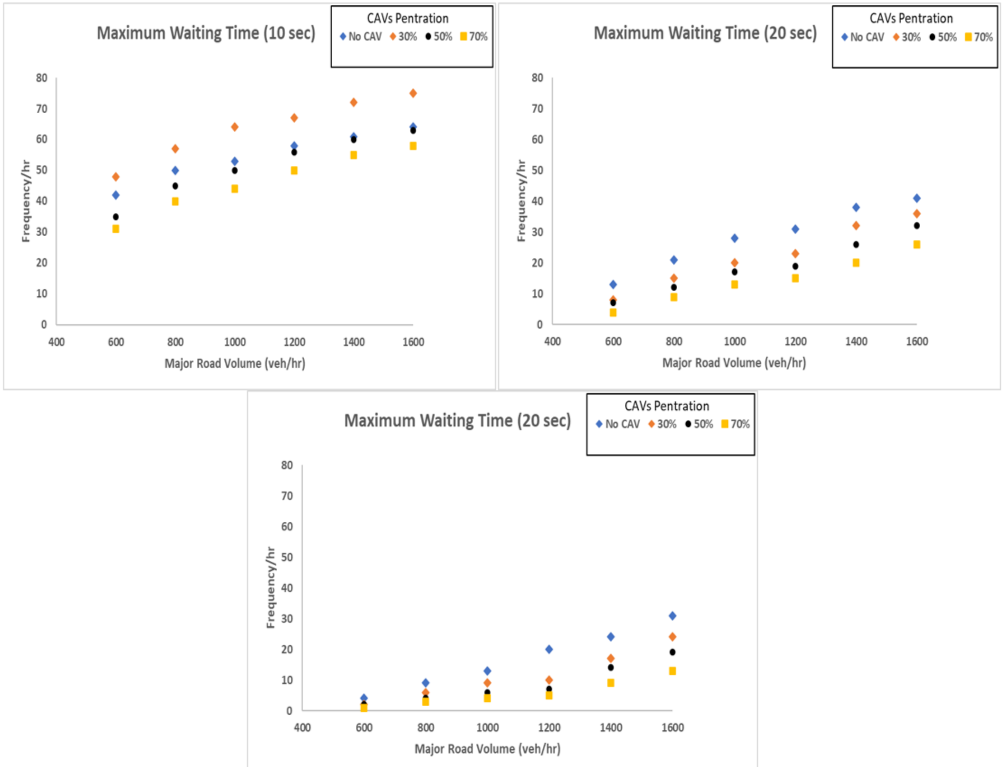

Figure 34 - Signal interruptions to the mainline traffic flow at different percentages of CAVs with 200 vehicles per hour on the minor road.

b. Control Delay

Control delay is commonly used as a performance measurement for signalized intersections. The HCM defines the level of service of signalized intersections based on control delay, and the delay is calculated as the difference between the actual travel time and the ideal travel time. Figure 35 presents the control delay of the targeted intersection at different vehicle volumes on the major and minor road, along with different percentages of CAVs. Each sub-figure presents the control delay when the minor road volume is set at 100, 150, 200, 250 vehicles per hour.

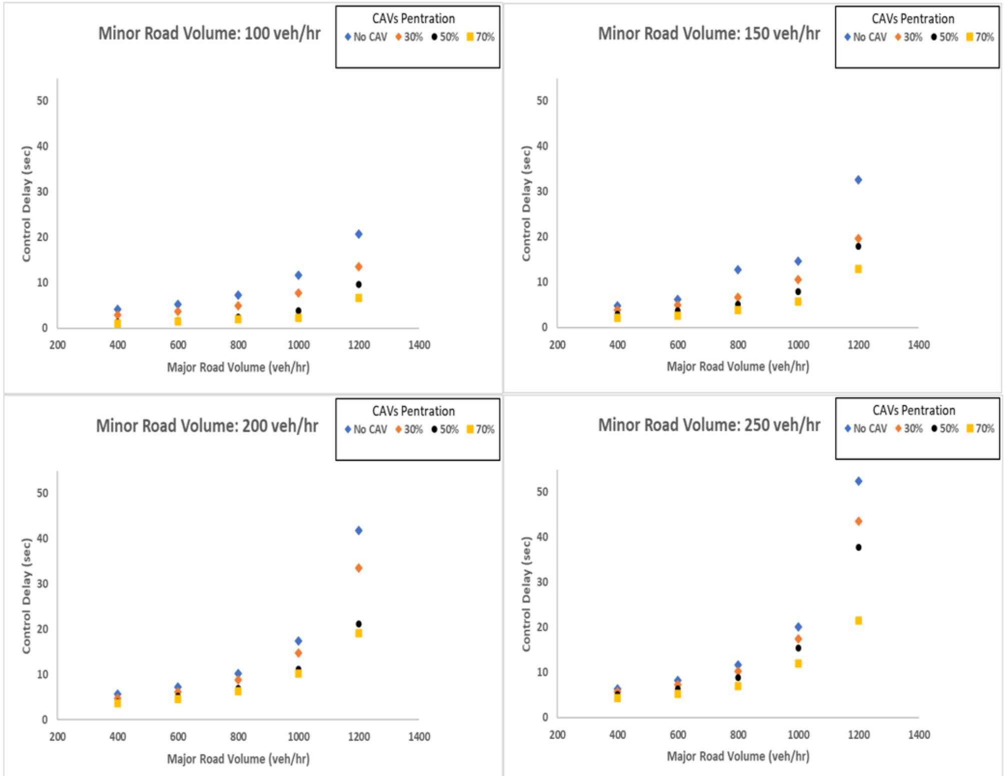

Figure 35 - Control delay of the intersection at different percentages of CAVs.

For all volume levels at the minor road, with the increase of the major road volume and the proportion of CAVs, the reduction in the mainline delay becomes larger due to the reduced interruptions to the major road traffic signal. On the other hand, the results in Figure 35 show that, regardless of the use of CAVs, with the volume increase on the mainline and the minor road, the control delay drastically increases due to the conflict between those two flows at the intersection with limited capacity.

c. Intersection Capacity

Since CAVs help create additional usable gaps for the minor road vehicles, the number of vehicles on the minor road that need signal accommodations decreases. This is equivalent to an increase in the intersection's mainline capacity. The results of the increased capacity are modeled and shown in Figure 36, as influenced by different traffic volumes on the major and minor roads, along with different CAV percentages.

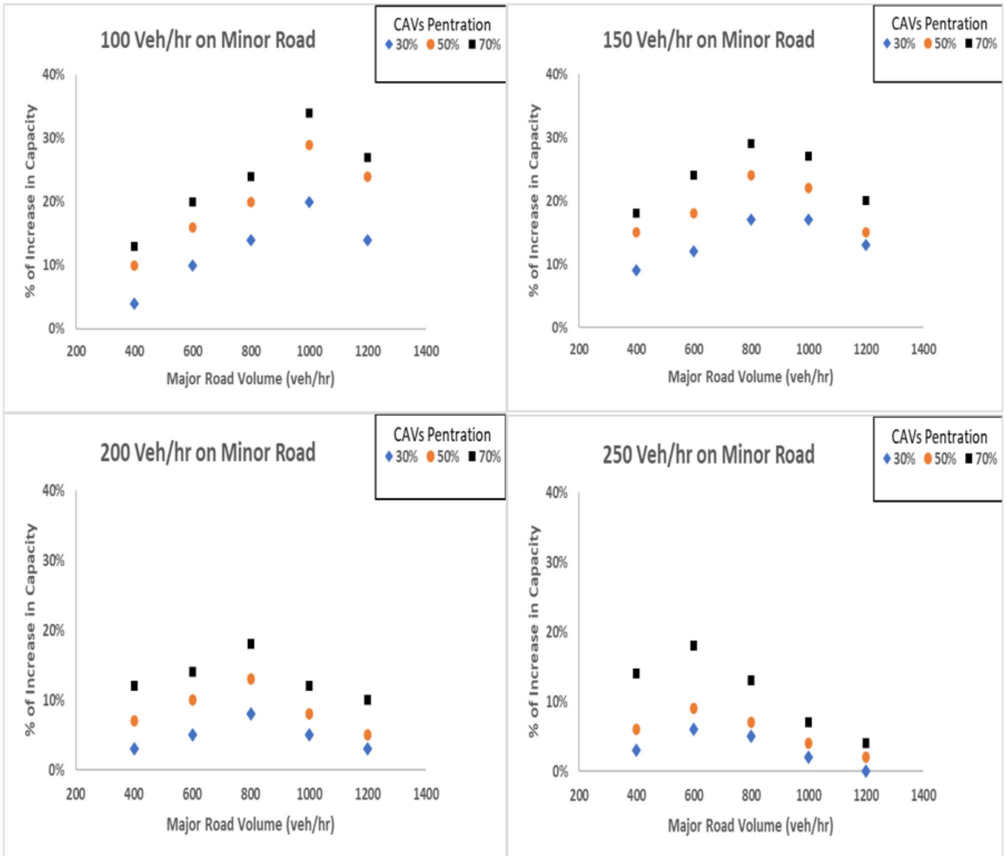

Figure 36 - The increase of intersection's mainline capacity due to reduced need to switch traffic signals to the minor road.

As shown in Figure 36, when the minor road traffic volume is at 100 vehicles per hour, the capacity will increase until the major road volume reaches 1000 vehicles per hour. Once the mainline traffic volume exceeds 1000 vehicles per hour, this capacity increase will drop due to the rising difficulty in creating usable gaps for the minor road vehicles to enter the major road. With the increase in the minor road volume, the combined traffic demand from the major and minor roads makes the number of additional gaps created by CAVs very limited, regardless of the CAV percentage in the mainline flow.

VI. FIELD TEST

A. Introduction

The driving task on the minor road approach is to find an appropriate gap to enter the major road safely without significantly affecting the approaching vehicles on the major road. The operation of an intelligent transportation system can be substantially affected by a poorly operating unsignalized intersection (Salleh, 2012). The safety and performance of unsignalized intersections are influenced by the gap acceptance behavior of the drivers (Nagalla, et al., 2017).

Since CAVs hold a high expectation of becoming a reality, their data communication and vehicle control ability is utilized to help ease the operation at an intersection with gap selection challenges. The algorithms developed in this study and the simulations presented have helped understand the gap characteristics and the impact on the traffic flow in various traffic conditions.

In this section, a field test is conducted to investigate the feasibility in implementing the control algorithm. This effort is made at two intersections where two vehicles are used as CAVs to execute the control logic (the framework in Section IV). Data obtained is from the onsite test vehicles and those approaching the intersection on the main and minor roads. This section discusses the application details and the results of the field test.

In addition to the speed and location data of the approaching vehicles, tracking the following information during field test is also a key part of the project:

- The number of accepted and rejected gaps by the minor road vehicles when a usable gap is created.
- The maneuver direction of the minor road vehicles (right vs. left turns).
- The gap selection data for all vehicles to calculate the critical gap used in the simulation platform.
- The acceptance rate of the minor road vehicle to develop a gap utilization factor for the simulation platform.

B. Site Selection

The criteria for site selection include:

1) Enumerators and equipment have good access and protection during the data collection process.
2) Reasonable traffic flow levels on both major and minor roads.
3) Adequate sight distances to ensure that sight distances do not affect interactions between minor road vehicles and the test vehicles.
4) Suitable safe roadside waiting spots for the test vehicles to enter the major road, far enough from the intersection.

Many T-intersections around Akron, Ohio have been visited to identify suitable locations for data collection. Two locations selected for the test were Wilbeth Road with Inman Street located south of Akron, OH, and Fishcreek Road with Sowul Boulevard in Stow, OH. Both intersections are three-legged, where the major roads are undivided with no extra median markings or channelizing islands. The intersection in Akron is operated by a semi-actuated signal and the intersection in Stow is unsignalized with a stop control. Other information about the two sites is provided in Table 3.

Table 3 - Site Characteristics.

Site Number	Name of Streets Major	Name of Streets Minor	Speed Limit (mph) Major	Speed Limit (mph) Minor	City	Number of Directional Lanes Major	Number of Directional Lanes Minor
1	Wilbeth	Inman	35	25	Akron, OH	1	1
2	Fishcreek	Sowul	35	25	Stow, OH	1	1

1. Wilbeth Road and Inman Street (Akron)

This location in south Akron is controlled by a traffic signal that can be operated in semi-actuated mode or a flashing-yellow on the major road and flashing-red on the minor road, as shown in. The speed limit of the mainline approach is 35 mph (Wilbeth Road), and 25 mph for the minor road (Inman Street). The intersection can accommodate both turning maneuvers (right and left) to enter the major road.

Prior to the field test, a proof-of-concept lab test was conducted at the City of Akron Traffic Engineering Office to verify that the control logic is supported by the technology. The primary focus of the control logic concerns extension of green time for the mainline traffic if a valid application can be made, that is, a usable gap can be created by CAVs for the waiting vehicle at the minor road approach.

Prolonging the green time can be achieved via two methods, one is by extending the green time repetitively for a pre-determined short interval and the other is through delaying the detection data reporting of a vehicle presence at the minor road approach (by holding off the detector status change). Both options have been tested in the city's signal shop using the same (Econolite Cobalt) signal controller and detection device as used in the field location, and positive results are obtained in each option. This indicates that the control logic of using longer green time for the mainline traffic to reduce signal switching, is technically feasible.

Although the traffic signal system at the Wilbeth intersection can handle the control logic tested in the signal shop, Ohio laws require special approval for this type of unconventional operations before they can be practically used in the field. Thus, during the field test the flashing-yellow for the mainline and red-flashing for the minor road method is used. Under this type of signal control, vehicles coming up to the minor road approach are required to stop and wait for a safe gap, either already existing in the traffic stream or with the assistance of CAVs through the algorithm, to enter the mainline traffic.

The waiting spots, where the test vehicles stay before joining the mainline traffic, are located from the eastbound and westbound directions 800-1000 ft to the intersection. To facilitate the V2I communication used in the field test, an observer is also located at a parking space right by the intersection. See Figure 37.

Figure 37 - The Wilbeth test intersection in Akron.

2. Fishcreek Road and Sowul Boulevard (Stow)

The Fishcreek location is an unsignalized intersection in Stow, OH and there is only one lane in every direction, as shown in Figure 38. The waiting spots for the test vehicles from the eastbound and westbound directions are approximately 1200 ft from the intersection.

Figure 38 - The Fishcreek test intersection in Stow.

The speed limit on the minor road (Sowul) approach is 25 mph, while the speed limit on the mainline stream is 35 mph, as shown in Figure 39. The intersection is located in a wide-open area so the vehicles coming to the stop-line of the minor road approach have a very long sight distance to see the approaching vehicles on the major road.

Figure 39 - Speed limit on both the main and minor roads at the Fishcreek intersection.

C. Data Plan

To ensure the reliability and enhance quality of the collected data, two collection methods were adopted. A high-quality video was recorded using a Mini-DVI drone (Figure 40) so that the manually collected data can be verified. The field tests cover different times of the day and days of the week to increase the generality of the data collected. Each test usually took from one to two hours, and a video of a drone was recorded simultaneously. After each field test, the data obtained manually was compared with the drone videos at the Transportation Lab at The University of Akron.

Figure 40 - Drone used in the field test.

For each test, the dataset includes the following data:

1) Major road: (1) each test vehicle's travel speed after entering the major road, (2) the separation distance between the test vehicle and the leading vehicle as well as with the trailing vehicle.
2) Minor road: (1) the waiting time at the intersection before accepting a gap, (2) the decision of the driver (to accept or reject) when a gap is created, and (3) the movement (left or right turn).

For safety reasons, the gap creation procedure is not executed if any one of the following cases applies (refer to Figure 41):

1) A pedestrian is at the intersection trying to cross the intersection.
2) One of the test vehicles is not able to enter the major road because the headways between mainline vehicles are too small for gap creation.
3) The test vehicles cannot coordinate movements due to blocking by other vehicles.
4) A necessary condition in the control logic (Chapter IV) cannot be satisfied.

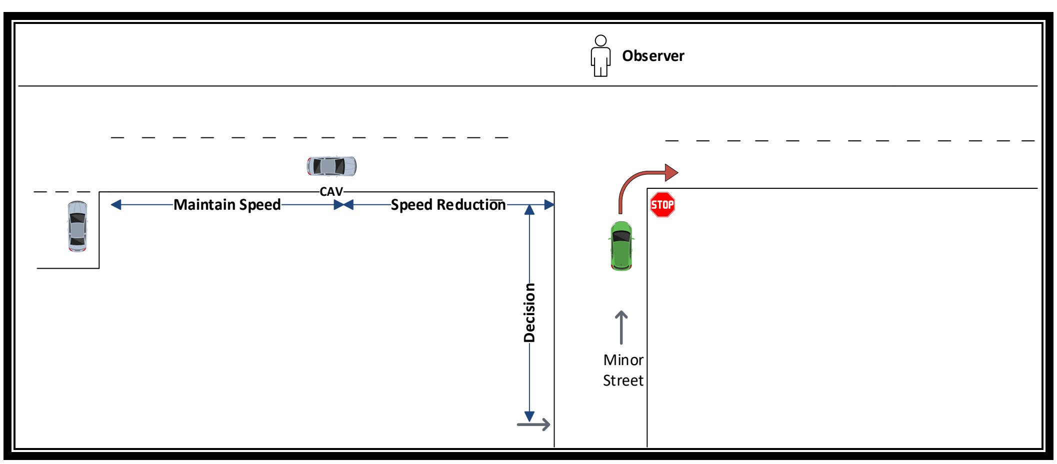

Figure 41 - Field test settings.

D. Implementation Procedure

Because this project is a proof-of-concept study (with a small budget) about the proposed algorithm to improve intersection operations, expensive CAVs and supporting roadside equipment cannot be practically used in the field test. Instead, the two test vehicles (driven by researchers) function as the intended CAVs, one going eastbound and the other going westbound. The locations where the two vehicles enter the mainline traffic flow are selected based on calculations to ensure that there is enough distance for the vehicles to join the traffic stream and gain comparable speed of the traffic flow before they are requested to create gaps.

According to the average traffic flow speed measured from the field location, a speed reduction end point is established using the critical gap as a reference. This end point is very important because it is the last distance point (and time) for the test vehicle to start reducing speed for gap creation. Beyond this point, the test vehicle may no longer be able to create a usable gap without a faster deceleration – a situation that is unsafe and should be avoided. As shown in Figure 42, the red line defines this distance to the intersection, where if the test vehicle starts to reduce speed while inside the distance, the minor road vehicle may not be able to accept the created gap because it would be smaller than the needed critical gap.

Figure 42 - Control points of the Fishcreek intersection.

The entire process of the gap creation procedure starts with one observer's work near the minor road approach. The observer stays in a place near the intersection (not to distract the minor road vehicle in gap selection). When a vehicle on the minor road is coming to the intersection, the observer informs the test vehicles to enter the major road after an adjustment is used to account for the time lag for the minor road vehicle to reach the stop-line Once the minor road vehicle arrives at the stop line, the test vehicles can start speed reduction before reaching the speed reduction end point. If the minor road vehicle accepts the gap to enter the major road, it is counted as a successful completion. On the other hand, if the minor road driver rejects the gap the test vehicles have helped create, it would be considered a rejection.

E. Critical Gap Selection

As discussed in Chapter III, the decision to select an available gap is dependent on the critical gap. Since the critical gap is affected by the intersection geometry, community drivers, weather, and other environmental factors, using a critical gap obtained from the local data can help estimate drivers' choices more accurately.

The critical gap used in this research is based on field observations at each intersection prior to the field test. The data collected from the field at both intersections are shown in Table 4. The critical gaps of both locations are estimated by following Raff's method, which is based on the cumulative accepted and rejected gaps, where the critical gap is the crossing of both acceptance and rejection curves, which is discussed in Section VI.G. (Gue, et al., 2014).

Table 4 - Gap selection data to find critical gap.

Location	Akron	Stow	Total
Gap Selected	197	315	512

F. Minimum Headway

The empirical minimum headway data for vehicles approaching the intersection on the major road are also obtained at the two intersections studied during the feasibility study. The data come from two sources: a drone recording and an observer's manual counting, at the same location. Different times of the day are used to encompass different traffic volumes and arriving patterns.

The headway data are utilized in the simulation work discussed earlier, including the minimum headway in the probability functions and in the field test to guide gap creation decisions by CAVs according to the control logic.

G. Results

Figure 43 shows the process of a gap creation and utilization. The gap between the two vehicles on the major road is too small before the test vehicle reduces speed, as shown in Figure 43b. the gap became big enough to be utilized by the minor road vehicle as the test vehicle reduces its speed, as shown in Figure 43c. Figure 43d shows the minor road vehicle after making a left turn to join the major road.

Figure 43 - Example of gap creation and utilization.

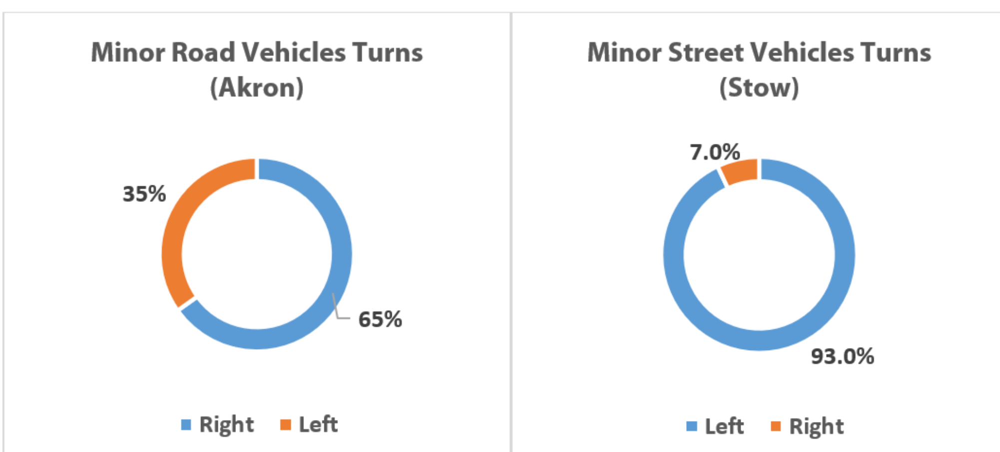

Figure 44 - Minor road vehicle maneuvers.

Field data show that the percentage of vehicles turning right is 65% of the total arrivals at the Wilbeth intersection in Akron, as shown in Figure 44. In comparison, the left turns at the Fishcreek intersection in Stow is more than 90% of the total number of vehicles, as shown in Figure 44.

In the entire field test, a total of 121 successful gaps have been created, around 60 tests for each intersection. Table 5 shows the results of the field test data collected at both intersections. The acceptance rate of gaps created for the minor road vehicles at the Akron location was 64%, whereas 36% of the usable gaps were rejected.

The acceptance rate of the created gaps at the Stow location is also shown in Figure 45, with a 62% verses 38% split against the rejection rate. At both intersections, it can be seen that drivers are more likely to accept gaps created with the help of CAVs, instead of following a 50% split according to the Raff's critical gap definition. This finding is interesting, possibly due to an increase in the willingness to accept the created gaps after minor road drivers notice the slowdown of the CAVs.

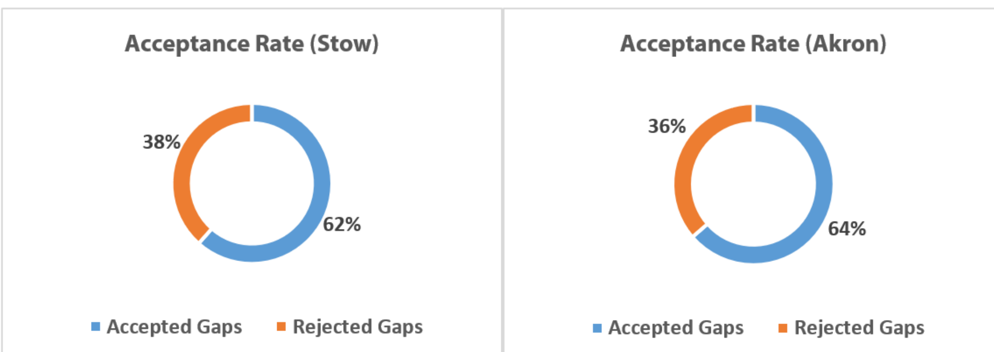

Figure 45 - Acceptance rate vs. rejection rate.

Table 5 - Gap acceptance verses rejection percentages at both intersections.

Location	Minor Road Movement		Acceptance Rate		Total
	Right	Left	Accept	Reject	
Akron	43	23	42	24	66
Stow	8	51	34	21	55
Total	51	74	76	45	121

Using the field data and following Raffs' method to calculate the critical gap, the accumulative probability of accepted vs. rejected gaps is calculated, as shown in Figure 46. The critical gap is found to be the crossing point between the two cumulative probability curves. Specifically, at the Akron location, the critical gap is found to be 6.5 seconds, whereas at the Stow location it is 7.0 seconds. These results are very close to but slightly higher than the values suggested in the HCM.

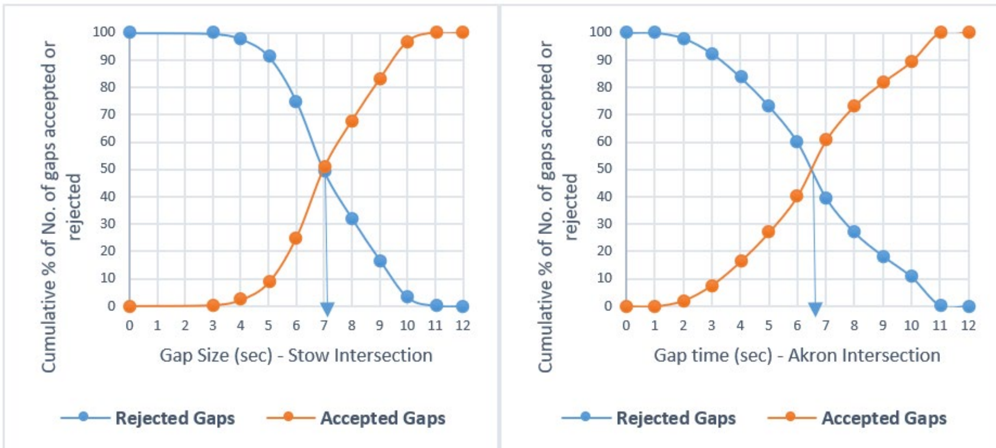

Figure 46 - Data based critical gap by Raff's method.

VII. CONCLUSIONS

Traffic operations at many intersections of a major road with a minor road are often interrupted by a small number of vehicles from the minor road to join the mainline flow. Because improper gap selections frequently happen by the minor road vehicles at such locations controlled by a stop sign, traffic signals are commonly used to enhance safety as well as reduce the loss in efficiency by using a semi-actuated control method. Using technology such as CAVs to create safe gaps for the minor road vehicles holds a potential to improve the operational efficiency without sacrificing safety for a mixed traffic with ordinary vehicles. This research has 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 enter the major road, thus reducing queueing problems and interruptions to the major road traffic flow. Since a mixed traffic flow in the next twenty to thirty years is highly likely, the proposed system in this project is built on a mixed traffic environment that considers both CAVs and OVs.

A probability function on headway distribution is developed to show the possibility that CAVs in the traffic flow may help create usable gaps on the major road traffic flow. Since the right turn movements from the minor road conflict with only one direction approach of the major road, the number of possible created gaps is greater than the left-turn movement. Left turn movements conflict with two approaches of the major road, which reduce the possibility of CAVs creating gaps.

A simulation platform was developed using VISSIM software in two case studies to validate the effectiveness of the proposed algorithm. The critical gap and the minor road vehicle waiting times used in the simulation are based on field observations. The measurement of effectiveness used in this dissertation to evaluate the proposed method includes delay, queue length, control delay, and capacity of both directions to study the overall intersection's efficiency and safety.

The method proposed in this research effectively minimizes the delay and queue on the minor road approach while not causing a significant delay on the major road at unsignalized intersections. We can state that deploying CAVs in the road network with the proposed method can positively impact the traffic efficiency, as the waiting time and queue length is reduced for the minor road approach even with high volumes on both approaches. When a semi-actuated signal control case is implemented, the result shows that the creation of additional gaps by CAVs can reduce the number of interruptions of the mainline traffic stream.

The results have shown that the minor street approach delay reduction can be as high as 90% compared with no AVs. Even with low AV penetration, the minor street approach delay is still reduced by 50% to 70% with all traffic levels in both directions. We can observe that deploying AVs in the road network with the proposed method can positively impact the traffic efficiency, as the waiting time delay and queue length is reduced for the minor street approach even with high volume on both approaches.

The field investigation was conducted to study the feasibility of the implementation of the control logic in real traffic conditions. It has involved both semi-actuated and unsignalized intersections. The results of the field test showed that most drivers on the minor road are able to accept the gaps created on the mainline by CAVs.

A. Future Work

Several important aspects can benefit future work on this research and potential field implementation, including:

1) The method can be expanded for a four-leg intersection and multiple lanes on the major street. This completed project with its original development work can serve as a basis for future methodology improvement.
2) Additional algorithms may be developed through hardware-in-the-loop simulation to explore the system's ability to minimize waiting time, increase throughput, and optimize traffic signals.
3) Further investigation is needed to conduct a real-time operational test using autonomous vehicles over difference aspects of traffic operation. It can help agencies, cities, and governments gain confidence and acceptance of CAVs to operate in an environmentally comfortable urban setting.

VIII. OUTPUTS, OUTCOMES, AND IMPACTS

A. Outputs

Publications and reports resulting from this study are listed below:

- Presentation. "Improving Operational Efficiency of a Major-Minor Intersection in Mixed Traffic Flow with Autonomous Vehicles." International Conference on Advanced Transportation, Enhanced Connection, Najing, December 2021. http://www.cota-home.org/cictp/CICTP2020-21.html
- Presentation. "Improving Operational Efficiency in Access Control with Connected and Automated Vehicles in Mixed Traffic Flow." 23rd COTA International Conference – Technology Innovations-Empowered Sustainable, Intelligent, Decarbonized, and Connected Transportation, Beijing, July 2023. https://www.cota2023.cn/
- Publication. F. Lanazi and Ping Yi*, "Control Logic Algorithm to Create Gaps for Mixed Traffic: A Comprehensive Evaluation," *Open Engineering*, *Vol. 12*, 2022.
- Publication. F. Lanazi, Ping Yi*, N. EiGehawi, "Improving the performance of Unsignalized T-Intersections with CAVs Mixed Traffic," *Journal of Applied Engineering Science*, March, 2021
- Presentation. " Improving Operational Efficiency of a Major-Minor Intersection with CV." CCAT Global Symposium, February 2019. Presenter: Dr. Ping Yi

B. Outcomes

This research project has produced significant outcomes that hold potential implications for traffic operations and intersection efficiency. By leveraging the capabilities of CAVs, the project aims to enhance traffic flow at unsignalized intersections while maintaining safety. The proposed framework, designed for a mixed traffic environment comprising both ordinary vehicles (OVs) and CAVs, introduces a systematic approach for CAVs to create safe gaps in the mainline traffic stream. Through simulation and field tests, the effectiveness of this approach was validated in terms of reducing delay, queue length, and interruptions to the major road traffic flow. The results demonstrate that deploying CAVs according to the proposed method can lead to improved traffic efficiency and reduced delays, particularly for minor road approaches. This research underscores the potential benefits of integrating CAVs to address traffic challenges at intersections in the context of a mixed traffic scenario.

C. Impacts

The outcomes of this research project have the potential to bring significant impacts to the field of transportation and traffic management. By proposing a systematic framework that utilizes CAVs to create safe gaps for minor road vehicles, the project addresses intersection efficiency and safety challenges. The implementation of this approach can lead to reduced delays, improved traffic flow, and minimized interruptions at unsignalized intersections. The findings suggest that incorporating CAVs into the road network using the proposed method can positively influence traffic operations, enhance intersection efficiency, and contribute to safer roadways.

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APPENDIX

DELAY ADDED ON MAJOR STREET COMPARED WITH IMPROVEMENTS IN MINOR STREET APPROACH DELAY

FIELD TEST DATA COLLECTION (AKRON)

FIELD TEST DATA COLLECTION (STOW)

Performance Indicators

DELAY ADDED ON MAJOR STREET COMPARED WITH IMPROVEMENTS IN MINOR STREET APPROACH DELAY

Minor Street Volume (vph)	Major Street Volume (vph)	% of AV	% of Delay added (major street)	% of Improvements in Delay (Minor Street)
150	600	30%	1%	15%
	600	50%	1%	25%
	600	70%	1%	31%
	800	30%	1%	24%
	800	50%	2%	32%
	800	70%	2%	39%
	1000	30%	1%	29%
	1000	50%	2%	44%
	1000	70%	3%	51%
	1200	30%	2%	32%
	1200	50%	3%	48%
	1200	70%	3%	56%
250	600	30%	3%	15%
	600	50%	3%	29%
	600	70%	3%	34%
	800	30%	3%	30%
	800	50%	4%	41%
	800	70%	6%	48%
	1000	30%	4%	55%
	1000	50%	7%	65%
	1000	70%	8%	71%
	1200	30%	6%	81%
	1200	50%	10%	86%
	1200	70%	11%	89%
350	600	30%	5%	22%
	600	50%	4%	32%
	600	70%	4%	38%
	800	30%	5%	52%
	800	50%	6%	58%
	800	70%	8%	64%
	1000	30%	7%	72%
	1000	50%	9%	79%
	1000	70%	11%	82%
	1200	30%	10%	76%
	1200	50%	15%	82%
	1200	70%	18%	88%
450	600	30%	5%	27%
	600	50%	5%	35%
	600	70%	5%	39%
	800	30%	6%	48%
	800	50%	9%	65%
	800	70%	9%	75%
	1000	30%	8%	56%
	1000	50%	13%	75%
	1000	70%	15%	86%
	1200	30%	14%	63%
	1200	50%	20%	79%
	1200	70%	24%	84%

FIELD TEST DATA COLLECTION (AKRON)

No.	Major Street				Calculated		Minor Street		
	Front Gap ft	Back Gap ft	Time to int sec	Speed of AV ft /sec	Speed mph	β %	Left/Right	A/R/U	Waiting time at intersection
1	180	210	10.89	36.73	25.04	28%	R	A	7
2	NC	150	11.3	35.40	24.14	31%	R	R	7
3	NC	NC	9.9	40.40	27.55	21%	R	A	6
4	225	NC	10.3	38.83	26.48	24%	R	A	6
5	NC	120	10	40.00	27.27	22%	R	A	3
6	NC	NC	10.49	38.13	26.00	26%	R	R	8
7	150	180	10.44	38.31	26.12	25%	R	R	11
8	NC	105	10.26	38.99	26.58	24%	R	R	12
9	NC	NC	11.24	35.59	24.26	31%	R	A	5
10	180	NC	9.86	40.57	27.66	21%	L	R	6
11	NC	210	10.22	39.14	26.69	24%	R	A	4
12	120	210	8.25	48.48	33.06	6%	R	R	18
13	90	60	10.48	38.17	26.02	26%	R	**R**	10
14	NC	120	9.36	42.74	29.14	17%	R	**A**	**3**
15	105	NC	9.48	42.19	28.77	18%	L	R	3
16	NC	NC	8.03	49.81	33.96	3%	R	**A**	**4**
17	150	90	9.45	42.33	28.86	18%	R	R	12
18	120	75	9.1	43.96	29.97	14%	R	A	6
19	105	NC	11.75	34.04	23.21	34%	R	A	12
20	90	60	9.89	40.44	27.58	21%	L	R	15
21	60	90	10.72	37.31	25.44	27%	R	A	14
22	NC	NC	11.07	36.13	24.64	30%	L	**A**	**3**
23	NC	150	11.55	34.63	23.61	33%	R	A	4
24	105	210	11.17	35.81	24.42	30%	L	A	6
25	NC	90	10.54	37.95	25.88	26%	R	A	4
26	120	90	10.05	39.80	27.14	22%	R	R	22
27	NC	150	10.3	38.83	26.48	24%	L	A	10
28	NC	NC	10.35	38.65	26.35	25%	L	A	5
29	75	75	9.56	41.84	28.53	18%	L	A	23
30	NC	240	10.42	38.39	26.17	25%	L	R	14
31	NC	NC	9.56	41.84	28.53	18%	R	R	10
32	150	NC	10.31	38.80	26.45	24%	L	R	12
33	60	NC	10.27	38.95	26.56	24%	R	A	3
34	NC	45	10.13	39.49	26.92	23%	L	A	12
35	120	105	11.09	36.07	24.59	30%	L	R	40
36	NC	NC	10.2	39.22	26.74	24%	L	A	6
37	NC	75	11.27	35.49	24.20	31%	L	R	14
38	75	NC	9	44.44	30.30	13%	L	R	16
39	NC	NC	9.07	44.10	30.07	14%	L	A	8
40	NC	135	10.22	39.14	26.69	24%	R	A	12
41	60	90	11.06	36.17	24.66	30%	R	A	4
42	NC	120	10.35	38.65	26.35	25%	L	A	5
43	NC	135	9.33	42.87	29.23	16%	L	R	21
44	NC	NC	11.53	34.69	23.65	32%	R	A	4
45	NC	105	10.17	39.33	26.82	23%	L	A	5
46	75	60	10.4	38.46	26.22	25%	R	R	25
47	90	NC	10.55	37.91	25.85	26%	R	A	4
48	NC	105	10.5	38.10	25.97	26%	L	A	3
49	NC	NC	9.05	44.20	30.14	14%	L	A	6
50	NC	105	9.1	43.96	29.97	14%	R	A	3
51	105	120	10.12	39.53	26.95	23%	R	A	13
52	NC	75	9.45	42.33	28.86	18%	R	A	19
53	NC	120	8.63	46.35	31.60	10%	L	A	6
54	NC	NC	10.35	38.65	26.35	25%	R	R	10
55	NC	60	10.75	37.21	25.37	28%	R	R	11
56	105	NC	8.4	47.62	32.47	7%	L	R	14
57	105	NC	8.61	46.46	31.68	9%	R	R	14
58	NC	75	10.5	38.10	25.97	26%	R	A	2
59	NC	NC	9.05	44.20	30.14	14%	R	A	5
60	NC	105	9.1	43.96	29.97	14%	R	A	3
61	60	90	10.72	37.31	25.44	27%	R	A	14
62	NC	NC	10.07	39.72	27.08	23%	R	A	2
63	NC	150	10.55	37.91	25.85	26%	R	A	3
64	105	210	11.17	35.81	24.42	30%	R	A	6
65	NC	90	10.05	39.80	27.14	22%	R	A	4
66	120	90	10.54	37.95	25.88	26%	R	R	21

FIELD TEST DATA COLLECTION (STOW)

No.	Major Street East				Calculated		Major Street West				Calculated		Minor Street		
	Front Gap	Back Gap	Time to int	Speed of AV	Speed	β	Front Gap	Back Gap	Time to int	Speed of AV	Speed	β	Left/Right	A/R/U	Waiting time at
	ft	ft	sec	ft /sec	mph	%	ft	ft	sec	ft /sec	mph	%			
1	8	NC	10.62	37.66	25.68	27%	NC	Nc	10	40.00	27.27	22%	L	A	6
2	NC	6	10.9	36.70	25.02	29%	NC	6	10.55	37.91	25.85	26%	L	R	4
3	NC	NC	9.3	43.01	29.33	16%	0	0	0	-	-	-	R	A	1.5
4	NC	NC	11.2	35.71	24.35	30%	NC	NC	10.95	36.53	24.91	29%	L	R	15
5	NC	NC	10.1	39.60	27.00	23%	NC	5	10.82	36.97	25.21	28%	L	R	15
6	NC	6	11.2	35.71	24.35	30%	NC	NC	11	36.36	24.79	29%	L	R	16.1
7	NC	NC	10.9	36.70	25.02	29%	NC	NC	11.28	35.46	24.18	31%	L	A	4
8	NC	NC	11.3	35.40	24.14	31%	0	0	0	-	-	-	R	A	9
9	NC	6	10.8	37.04	25.25	28%	4	NC	10.36	38.61	26.33	25%	L	R	10
10	NC	NC	11.35	35.24	24.03	31%	NC	5	9.3	43.01	29.33	16%	L	R	12
11	NC	7	10.44	38.31	26.12	25%	NC	NC	10.75	37.21	25.37	28%	R	A	2
12	NC	8	10.18	39.29	26.79	23%	NC	NC	11.7	34.19	23.31	33%	L	R	13
13	NC	NC	10.6	37.74	25.73	26%	NC	8	10.18	39.29	26.79	23%	L	R	14.1
14	NC	NC	11.2	35.71	24.35	30%	NC	5	11.2	35.71	24.35	30%	L	R	20
15	NC	NC	10.82	36.97	25.21	28%	NC	NC	10.9	36.70	25.02	29%	L	A	5
16	NC	9	11.2	35.71	24.35	30%	6	NC	10.2	39.22	26.74	24%	L	A	9
17	NC	NC	10.6	37.74	25.73	26%	NC	NC	11.4	35.09	23.92	32%	L	A	4
18	NC	NC	10.6	37.74	25.73	26%	8	9	10.32	38.76	26.43	24%	L	R	11
19	NC	9	9.89	40.44	27.58	21%	NC	NC	11.7	34.19	23.31	33%	L	R	11
20	NC	NC	11.3	35.40	24.14	31%	9	NC	10.12	39.53	26.95	23%	L	A	4
21	NC	4	10.9	36.70	25.02	29%	3	NC	11	36.36	24.79	29%	L	A	7
22	NC	10	12	33.33	22.73	35%	NC	NC	11.2	35.71	24.35	30%	L	A	3
23	NC	4	11.7	34.19	23.31	33%	NC	NC	10.85	36.87	25.14	28%	L	A	3
24	NC	3	10	40.00	27.27	22%	NC	NC	11.9	33.61	22.92	35%	L	A	9
25	4	9	12	33.33	22.73	35%	NC	NC	10.7	37.38	25.49	27%	L	R	15
26	NC	NC	10.9	36.70	25.02	29%	NC	NC	10.23	39.10	26.66	24%	L	A	2
27	NC	NC	10.41	38.42	26.20	25%	NC	NC	10.9	36.70	25.02	29%	L	R	10
28	NC	8	11.2	35.71	24.35	30%	NC	NC	11.68	34.25	23.35	33%	L	A	15
29	NC	NC	10.49	38.13	26.00	26%	NC	NC	11.1	36.04	24.57	30%	L	A	4
30	NC	NC	10.5	38.10	25.97	26%	5	NC	11.45	34.93	23.82	32%	L	R	12
31	NC	6	9.5	42.11	28.71	18%	NC	NC	10.58	37.81	25.78	26%	L	R	12
32	NC	NC	10.12	39.53	26.95	23%	NC	NC	10.62	37.66	25.68	27%	L	A	4
33	NC	NC	11.2	35.71	24.35	30%	NC	NC	10.51	38.06	25.95	26%	L	R	13
34	NC	4	10.4	38.46	26.22	25%	0	0	0	-	-	-	L	A	3
35	NC	NC	10.18	39.29	26.79	23%	0	0	0	-	-	-	L	A	10.46
36	NC	NC	10.66	37.52	25.58	27%	0	0	0	-	-	-	L	R	10
37	6	NC	10.5	38.10	25.97	26%	0	0	0	-	-	-	L	A	12
38	NC	NC	10.46	38.24	26.07	26%	0	0	0	-	-	-	L	R	16
39	NC	4	11.28	35.46	24.18	31%	0	0	0	-	-	-	L	A	10
40	6	8	10.46	38.24	26.07	26%	0	0	0	-	-	-	R	A	8
41	4	6	10.96	36.50	24.88	29%	0	0	0	-	-	-	L	R	22
42	NC	NC	9	44.44	30.30	13%	NC	NC	9	44.44	30.30	13%	L	A	4
43	12	18	11	36.36	24.79	29%	10	NC	10	40.00	27.27	22%	L	A	5
44	NC	NC	9.5	42.11	28.71	18%	NC	NC	9	44.44	30.30	13%	L	A	11
45	NC	NC	10	40.00	27.27	22%	NC	15	11	36.36	24.79	29%	L	A	8
46	NC	7	10	40.00	27.27	22%	NC	NC	11	36.36	24.79	29%	L	A	12
47	NC	5	10	40.00	27.27	22%	10	12	11.5	34.78	23.72	32%	L	A	7
48	NC	7	9	44.44	30.30	13%	15	4	10	40.00	27.27	22%	L	A	8
49	NC	NC	1.5	266.67	181.82	-419%	15	7	11	36.36	24.79	29%	L	R	9
50	7	NC	10	40.00	27.27	22%	NC	NC	9.5	42.11	28.71	18%	L	A	13
51	7	NC	10	40.00	27.27	22%	NC	15	9.5	42.11	28.71	18%	L	A	6
52	NC	NC	10	40.00	27.27	22%	NC	5	9	44.44	30.30	13%	L	A	6
53	NC	NC	10.5	38.10	25.97	26%	5	NC	11.45	34.93	23.82	32%	L	R	12
54	NC	6	9.5	42.11	28.71	18%	NC	NC	10.58	37.81	25.78	26%	L	R	12
55	NC	NC	10.12	39.53	26.95	23%	NC	NC	10.62	37.66	25.68	27%	L	A	4

2.B CCAT affiliated students holding leadership positions	Number of students	
Education and Workforce Development Goals		
1. OUTPUTS	**Research Performance Measures**	
1.A Number of Workforce Online learning modules created and developed toward the certification of completion training for the emerging CAT field technician	Number of learning modules	
1.B Development of Articulation agreements for C++ software programs and Applied Data Science program with partner institutions	Number of Articulation/Transfer Programs	
1.C Development of an active WCC Pre-Engineering Program in STEM disciplines leading to an AAS degree	Number of students completed Associates Degree for Pre-Engineering Science Transfer	
	Number of students completed Associates Degree for Engineering Technologist-Manufacturing Degree	
1.D Number of curriculum development and professional development activities for instructors in related CAT technologies	Number of Professional Dev. Activities in IT [CAT]	
	Number of participants	
1.E Number of K-12 Career pathways activities related to CAT career fields.	Number of K-12 Activities in CAT Career Areas	
	Number of participants	
Outreach Goals		
1. OUTPUTS	**Research Performance Measures**	
1.A Media stories referencing CCAT, CCAT research or other activities	Number of media stories	
1. B Newsletters, press releases, and website	Number of newsletters	
	Number of press releases	
	Number of website hits	
2. OUTCOMES	**Research Performance Measures**	
2.A Research Champions	Industry principals	
	Number of industries represented	1
	Government principals	
	Number of government agencies represented	
Collaboration Goals		
1. OUTPUTS	**Research Performance Measures**	
1. A Collaboration with other agencies	Number of agencies providing matching funds	
	Number of agencies participating in CCAT events	1
	Number of agencies committed to CCAT projects	1
	Number of individuals from external agencies attending CCAT events	
1. B Collaboration with other organizations	Number of organizations providing matching funds	
	Number of organizations participating in CCAT events	1
	Number of organizations committed to CCAT Projects	1
	Number of individuals from external organizations attending CCAT events	

Part I: UTC Program-Wide Performance Indicators

UTC Name: Center for Connected and Automated Transportation (CCAT)
University: University of Michigan
Grant #: 69A3551747105

OSTR Goals

METRIC	Research Performance Measures	University of Akron
1. Number of transportation-related courses offered during the reporting period that were taught by faculty and/or teaching assistants who are associated with the UTC.	Undergraduate courses	2
	Graduate courses	1
2. Number of students participating in transportation research projects during the reporting period funded by this grant.	Undergraduate students in research	10
	Graduate students in research	4
3. Number of transportation-related advanced degree programs that utilize grant funds during the reporting period to support graduate students.	Masters level programs	1
	Doctoral level programs.	1
4. Number of students supported by this grant during the reporting period.	Undergraduate degrees	6
	Masters degrees	1
	Doctoral degrees	1
5. Number of students supported by this grant who received degrees during the reporting period.	Undergraduate degrees	6
	Masters degrees	1
	Doctoral degrees	1
6. Number and total dollar value of research projects selected for funding during the reporting period using UTC grant funds (Federal and/or Recipient Share) that you consider to be applied research and advanced research.	Number of applied research projects	1
	Dollar value of applied research projects	$75,000
	Number of advanced research projects	
	Dollar value of advanced research projects	

Part II: CCAT UTC Specific Performance Indicators

UTC Name: Center for Connected and Automated Transportation (CCAT)
University: University of Michigan
Grant #: 69A3551747105

Technology Transfer Goals		
1. OUTPUTS	Research Performance Measures	University of Akron
1.A. Disseminate research results through publications, conference papers, and policy papers	Technical reports	1
	Papers at conferences, symposia, workshops, and meetings	2
	Peer-reviewed journal articles	2
1.B. Develop inventions, new methodologies, or products	Annual number of research deployments	
1.C. Research projects funded by sources other than UTC and matching fund sources	Number of projects	
	Dollar amount of projects	
2. OUTCOMES	Research Performance Measures	
2.A. Incorporate new technologies, techniques or practices	Number of technology transfer activities that offer implementation or deployment guidance	
2.B. Improve the processes, technologies, techniques in addressing transportation issues	Number of research deliverables disseminated from each research project	2
3. IMPACTS	Research Performance Measures	
3.A. Increase the body of knowledge and safety of the transportation system	Number of instances of technology adoption or commercialization	
	Number of conferences organized by the CCAT consortium members	
3.B. Improve the operation and safety of the transportation system	Number of instances of research changing behavior, practices, decision making, policies (including regulatory policies), or social actions	1
Leadership Development Goals		
1. OUTPUTS	Research Performance Measures	
1.A Keynote speeches or invited speaker presentations	Number of media engagements	
	Number of academic engagements	2
	Number of industry engagements	
2. OUTCOMES	Research Performance Measures	
2.A Leadership positions held	Regional organizations	
	National organizations	
	International organizations	