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Assisted Car Platooning and Congestion Control at Road Intersections

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Abstract: Enhancing road safety and traffic efficiency are the important aspects and goals that automakers and researchers trying to achieve in recent years. The autonomous vehicle technology has been identified as a solution to achieve these goals. However, the adoption of fully autonomous vehicles in the current market is still in the very early stages of deployment. The objective of this paper is to develop a Cooperative Adaptive Cruise Control (CACC) model at a road intersection using platooning car-following mobility models, object detection at traffic light units, and Vehicle-to-Everything (V2X) communication through vehicular ad hoc networks (VANETs). The mobility model considers traffic simulation using the SUMO-PLEXE-VEINS platforms integration. Next, a prototype of an assisted car platooning system consisting of roadside unit (RSU) and on-board units (OBU) is developed using artificial intelligence (AI)-based smart traffic light for obstruction detection at an intersection and modified remote-control cars with V2X communication equipped with in-vehicle alert notification, respectively. The results show accurate detection of obstruction by the proposed assisted car platooning system, and an optimised smart traffic light operation that can reduce congestion and fuel consumption, improve traffic flow, and enhance road safety. The findings from this paper can be used as a baseline for the framework of CACC implementation by legislators, policymakers, infrastructure providers, and vehicle manufacturers.

Keywords: Cooperative vehicular communication, intelligent transportation system, intersection, platooning, intelligent traffic light

1. Introduction

Intelligent Transportation System (ITS) is a multi-system structure that incorporates management, control, information collection and actuation system, which have to be perfectly related and synchronized to achieve the objectives of the entire system. It represents the integration of Information and Communication Technologies (ICT) and application with the aim to improve the road safety, traffic flow efficiency, and enhance the commuting experience, through the realization of future automated driving [1-2]. Academia groups and some industrial automakers such as Tesla and Waymo company are technologically ready to provide fully autonomous driving. In coming years, autonomous vehicle is envisioned to have a far-reaching application rather than just sending people from one location to the other [3]. A soft transition between semi-automated to fully autonomous driving is prevalent, where the control capacities in the Advanced Driver Assistance System (ADAS) play a very important role during this transition.

Over the last century, automobile manufacturers have been focusing on building cars with stronger materials and adding passive safety systems, such as seat belts and airbags. However, in the past decade, the focus has shifted

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towards smarter vehicles system. National Highway Traffic Safety Administration (NHTSA) has conducted a study on the leading causes of death in the United States and surprisingly, traffic crashes are at the 7th highest rank [4]. An in-depth investigation of this study shows that the human driver is the main contributor that amounts to around 94% of traffic crashes. Therefore, a provisional conclusion can be made that road safety might be improved if human intervention can be reduced from the driving equation. Meanwhile, the Dutch navigation technology company, TomTom shows the statistics that traffic congestion has continued to increase globally with 239 cities in the index reporting an annual increase since the year 2018 [5]. Malaysians in the capital city of Kuala Lumpur spend an extra 170 hours per year in traffic congestion. Traffic congestion not only reduces productivity of the workforce, but simultaneously decreases the quality of life of individuals. Emergency services such as ambulances and fire trucks would also be hampered from functioning effectively as they struggle to reach their destinations. This will result in high fuel consumption and air pollution that is detrimental to the environment and society.

The cause of traffic congestion in urban areas can be mainly attributed to traffic light scheduling and the slow response time of drivers towards the changing states of a traffic light. Recent findings have shown that the adaptive traffic light phase cycle based on trends in traffic density on the road does not solve the traffic congestion problem [6-9]. This baseline idea is only useful in unsaturated conditions, but the performance significantly degrades in saturated and over-saturated conditions. Instead, it will only shift the problem to other junctions [10]. The slow response time of drivers will further amplify the delays at junctions. When the light turns green, subsequent delays by cars in the queue will eventually cause a large pile-up that leads to inefficient traffic intersection throughput. To make matters worse, the number of vehicles on the roads keeps increasing yearly. In 2019, Malaysian Automotive Association (MAA) reported that the number of new motor vehicles registered in 2018 was 598,714 units, an increase of 3.8% compared to the previous year.

In the late 1990s, the commercial introduction of ADAS started with the introduction of the Adaptive Cruise Control (ACC) feature on luxury vehicle brands [11]. ACC system is an enhancement to the conventional cruise control (CC) system. Rather than a vehicle speed-regulated CC, an ACC system allows drivers to maintain a desired cruise speed and the following gap to a preceding vehicle using sensors such as radar or LIDAR. This information is used to generate appropriate throttle or brake commands to maintain a predefined headway with the preceding vehicle. Nowadays, ACC is commercially available on medium-class vehicle models. The next step in the evolution of ADAS is the Cooperative Adaptive Cruise Control (CACC), a merging concept between ACC and cooperative elements such as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication or sometimes referred to as Vehicle-to-Everything (V2X) through the establishment of vehicular ad-hoc networks (VANETs).

Platooning is a concept in the field of intelligent transportation systems (ITS) that involves a group of vehicles travelling closely together in a coordinated manner. It is a form of cooperative driving where vehicles maintain a small inter-vehicle gap and synchronize their movements, typically using advanced V2X technologies. Platooning allows vehicles to travel in a tight formation by taking advantage of aerodynamic benefits, leading to fuel efficiency and reduced emissions. Additionally, platooning enables vehicles to react quickly and efficiently to changes in traffic conditions, as they can communicate and coordinate their movements. It is one of the key strategies in ITS to improve traffic efficiency, reduce congestion, and enhance road safety. However, previous works have been predominantly focused on the development of CACC and vehicle platooning in a highway scenario. Moreover, research from [12] validated in a simulation that the throughput of an urban road system can be doubled without changing the signal control, just making the automobiles cross the intersections in a platoon rather one by one with the typical reaction times of human drivers. Worsening traffic congestion has negative effects on the community as well. Traffic congestion generates external costs such as increasing air and noise pollution, higher probability of accidents, and extra travelling time. Emergency services such as ambulances, police cars and fire trucks would be hampered from functioning effectively as they struggle to reach their destinations, and it creates more stress for drivers, cyclists, and pedestrians.

This paper proposed the integration of an intelligent traffic light and car platooning system in urban scenarios. The vehicle on queue featured with ACC and augmented with V2X capabilities will be coordinated to start moving once the traffic light status change from red to green. This paper develops a synchronized traffic light system based on Artificial Intelligence (AI) image processing to ensure junctions are cleared of obstruction before the execution of vehicle platoon through VANETs and analyse the effect of an intelligent road intersection on traffic congestion reduced based on simulation to execute the longitudinal control of vehicle platoon. The remainder of this paper is structured as follows: In Section 2, the software simulation, hardware, and protocol used in this paper will be introduced. The analysis and findings of the platooning system will be presented in Section 3. Finally, the paper is concluded in the Section 4 of the paper.

2. System Model

The approaches to model different aspects of assisted car platooning and congestion control at road intersections are divided into four parts: PLEXE -VEINS simulation, AI-based image processing prototype, a VANET-based I2V and V2V communication to model the CACC environment. Figure 1 shows the proposed VANET architecture.

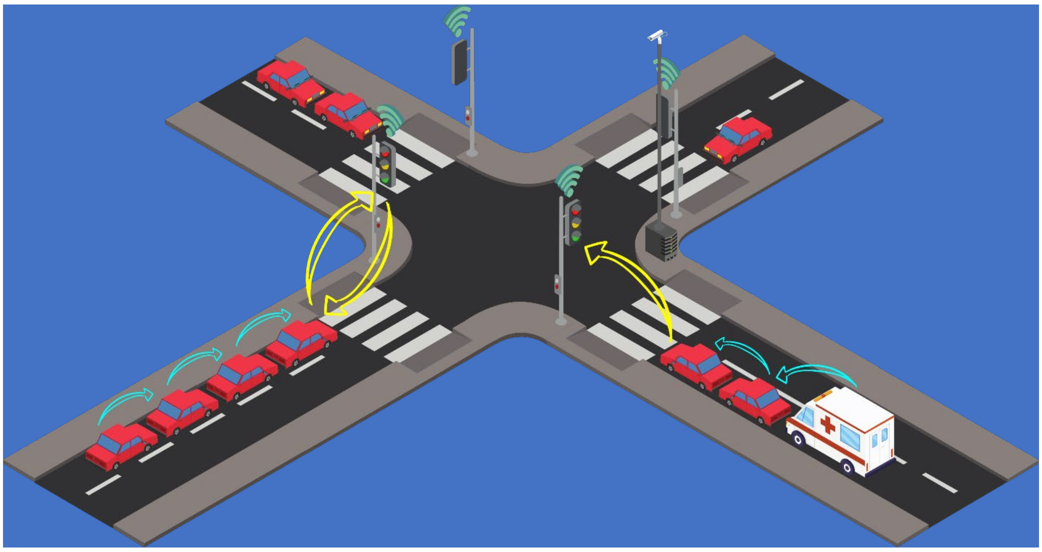


Fig. 1 - Proposed VANET architecture

2.1 Modelling of Vehicular Platooning Using PLEXE -VEINS

Cooperative driving and vehicle platooning required complex control law and theory, communication, and networking, as well as mechanics and physics considerations. With the lack of an integrated modelling framework and theory, as well as the prohibitively high costs of using prototypes for what-if analysis. The availability of tools such as PLEXE, an open-source extension to VEINS that integrates all the necessary components ranging from controller models to platooning management manoeuvres, enables the realisation of the proposed platooning study. VEINS is an open-source framework for running vehicular network simulation [13]. It is based on two well-established simulators: OMNeT++, an extensible and modular C++ based network simulator, and SUMO, a microscopic and multi-modal road traffic simulator. The term microscopic in this context means that each vehicle in the simulated environment is modelled explicitly and has its own unique ID, route, speed, and moves individually through the network.

In this work, the implemented CACC model is based on a classical control theory provided in PLEXE [14]. The control law for CACC that applied in the *i*-th follower of the platoon is [15]:

$$\ddot{x}_{i_{des}} = \alpha_1 \ddot{x}_{i-1} + \alpha_2 \ddot{x}_0 + \alpha_3 \dot{\varepsilon}_i + \alpha_4 (\dot{x}_i - \dot{x}_0) + \alpha_5 \varepsilon_i \tag{1}$$

where 0 denotes the leader vehicle of the platoon, i denotes the current following vehicles, $i-1$ denotes the preceding vehicle, $\ddot{x}_{i_{des}}$ is the desired acceleration of *i*-th vehicle, $\ddot{x}$ is the current acceleration of the vehicle and $\dot{x}$ is the speed of the vehicle.

Furthermore,

$$\varepsilon_i = x_i - x_{i-1} + (l_{i-1} + gap_{des}) \tag{2}$$

$$\dot{\varepsilon}_i = \dot{x}_i - \dot{x}_{i-1} \tag{3}$$

where ε_i is the inter-vehicle spacing error, l_{i-1} is the preceding vehicle length and gap_{des} is the desired spacing.

$$\alpha_1 = 1 - C_1; \quad \alpha_2 = C_1; \quad \alpha_5 = -\omega_n^2$$
$$\alpha_3 = -\left(2\xi - C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\right)\omega_n$$
$$\alpha_4 = -C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\omega_n \tag{4}$$

where C_1 is the weight factor of the leader respective to the preceding vehicle ($0<C_1<1$), ξ is the damping ratio of the controller and ω_n is the bandwidth of the controller.

This study aims to do a comparative study and analysis between CACC that is enabled with the platooning feature in VANETs against the Krauss car-following mobility model that is used as a default model in the SUMO simulation for a signalised intersection of an urban scenario. The Krauss model is a microscopic traffic flow model that updates the position and velocity of each vehicle in the simulation at each time step, based on previous time step's position, speed and acceleration information. The acceleration of each vehicle is determined by several factors, including the traffic density, the speed of other vehicles, and the curvature of the road. The Krauss model relies on human decision-making and reaction times, which can lead to inconsistent inter-vehicle gaps and reduced traffic throughput. In contrast, CACC utilizes advanced sensors and communication systems to maintain a consistent headway and optimize vehicle movements in an automated way. Therefore, the coordinated decisions at intersections made by CACC provides improve traffic efficiency and reduce congestion.

2.2 All-Red Clearance Interval Using Object Detection

In this work, an all-red clearance interval is proposed to serve two main purposes:

- To prevent conflicting movement of vehicle and ensure the intersection is clear of obstruction before the execution of platooning begin.
- To allow time for vehicles that entered the intersection during the yellow-change interval to clear the intersection prior to the next phase.

The previous study in [16] stated that the use of this specific interval shows a significant reduction in crash rates. Besides, it also proves the reduction in the number of red-light running violations. Thus, in this work, an all-red clearance interval is utilised as part of the design of the traffic light AI image processing for object detection and monitoring of road intersection traffic conditions. In addition, the traffic light will consistently communicate and exchange Signal Phase and Timing (SPaT) information with the nearby vehicles through V2I communication.

OpenVINO toolkit has been used to develop the application of object detection, which is designed to increase performance and reduce development time for computer vision solutions. The pre-trained person-vehicle-bike detection model [17] with mean Average Precision (mAP) of 65.12% is used to significantly reduce the time and computational power needed to train the proposed system model. Movidius Neural Compute Stick (NCS) has been chosen as the hardware Vision Processing Unit (VPU) in the demo setup for real-time inferencing as it supports 16-bit floating point operations. Inference Engine (IE) utilized the VPU to double the speed of real-time inferencing with a minimal trade-off in accuracy. Once the network is trained and optimized, it is ready to take new unseen data as input and provide an answer it was trained to output.

2.3 Establishment of VANETs for V2V and V2I

VANETs have emerged as a new landscape of Mobile Ad-hoc networks (MANETs) that provide safety and comfort applications to road users via V2V and V2I communication. The communication device located in the vehicle is called an On-Board Unit (OBU) that is usually connected to the CAN bus of the vehicle to retrieve useful information and exchange it with a nearby vehicle or Road-Side Unit (RSU). Note that the traffic light explained in Section II-A is the RSU in this project setting. Despite the great potential of VANETs, current research works are mainly based on simulations or the development of routing protocols, thus reinforcing the need for practical experiments [18, 19]. These communication devices are characterized by high cost, and hardware that has successfully evolved from prototype to commercial version is hardly available.

In this work, a mesh network library, *painlessMesh,* is implemented to establish VANET and demo the flow of the proposed system in a practical context. This library offers its usefulness by allowing a collection of low-cost and resources limited ESP8266 devices (nodes) to form a mesh network. This library is designed to work with the mesh network without the need to stress over how the network is organized or managed. Each node can act as both an Access Point (AP) for connection to other nodes, and as a station (STA) connecting to another node. Any nodes within reachable range will self-organize into a fully functional mesh automatically. Particularly, any node can be disconnected at any moment, whereas any new joining node is integrated automatically. All nodes are time synchronized with a precision of less than 10 ms. With such network flexibility, *painlessMesh* optimizes network reliability by automatically joining a neighbouring network in the event of disconnection. In addition, it is also capable of covering a larger area of network communication through multi-hop messaging.

3. Results and Discussions

3.1 SUMO-PLEXE Software Simulation Results

In this comparative study, an initial investigation is carried out using the Krauss model that mimics human driver behaviour as depicted in Figure 2. The scenario is a screenshot at the simulation step of one second (i.e., before the traffic light turns red). It can be seen that only 3 out of 8 vehicles can pass the current traffic phase and the third vehicle accelerate at the last few seconds during the yellow interval can barely make it through the signalized intersection. The simulation is repeated by altering the Krauss to CACC model as shown in Figure 3. During the runtime, a group of 8 vehicles of platoon is travel as a single unit by maintaining a very closed inter-vehicle gap towards the signalized intersection. The platoon leader receives the SPaT information when entering within 100 meter of traffic light zone. By knowing the current phase and remaining time, the current platooning formation will compute and decide which vehicle could pass safely across the intersection. Subsequent platoon split operation is performed to segregate the current formation into 2 groups. The first group of 4 vehicles of platoon will drive through the signalized intersection normally, whereas the second group of the platoon will elect a new leader and thus stop at the signalized intersection and wait for the next green phase cycle to pass. The inconsistency of the inter-vehicle gap interrupted the traffic flow and causes a chain reaction among the vehicles behind that driver. Even when the driver tries to accelerate again, this effect will not disappear, instead, it will gradually propagate backwards against the direction of traffic, causing significant traffic throughput reduction. According to current legislation, each driver should maintain a minimum of two-second interval rule as safety distance between vehicles, which might be increased depending on driving conditions. This safety distance accounts for human reaction time, which does not utilize the full resources of road infrastructure.

In addition, the pattern of the third vehicle accelerating in the last few seconds to pass through the signalized intersection is based on the Krauss model. This can be explained as the driver faced a dilemma zone where they must decide between braking hard to stop before the intersection or speeding through the intersection at the risk of running a red light. Within the dilemma zone, a decision to pass through the intersection might result in a right-angle crash, whereas a decision to stop might cause a rear-end collision. With the proposed model, the flow of vehicles is automated at the signalized intersection. This will eliminate the huge inter-vehicle gap and decision-making from humans when experiencing the dilemma zone.

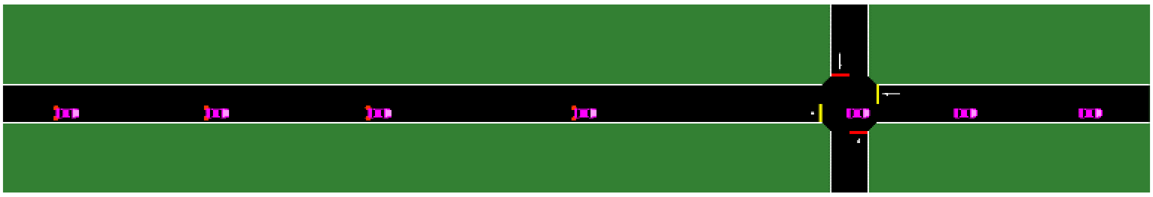


Fig. 2 - Krauss model simulation. Third vehicle counting from right was just able to make it through the intersection

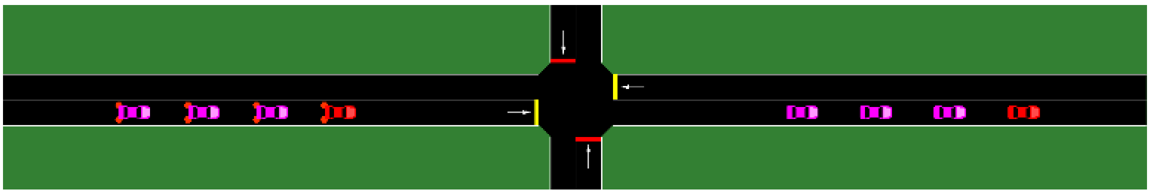


Fig. 3 - CACC model simulation. Red vehicles indicate the leader of the platoon

3.2 Prototype of Smart Traffic Light and VANET

The proposed system's hardware-simulated VANET environment can be broken into three main components, as shown in Figure 4. The first component is the traffic light unit powered by the Up2 board and the Movidius NCS. It will monitor the real-time condition at the road intersection by using object detection. The second and third components in the system are the leader and follower vehicles in the platooning formation, as discussed in Section III-A. All the components are integrated with NodeMCU, which runs on the ESP8266 Wi-Fi SoC for *painlessMesh* network establishment. In the proposed system, the traffic light unit will constantly broadcast the SPaT information (V2I) to the surrounding vehicle. For vehicles that are further away from the traffic light unit, they will also be able to receive the SPaT information through multi-hop messaging (V2V) from the preceding vehicle. The demo setup also provides an interactive graphic user interface (GUI) to display the current traffic cycle remaining time. This system can be made more effective if it can utilize the SPaT information to inform the road user on current and future events, via integration with ECU controls.

Before the traffic light turn green for the next phase, if there are vehicles that are trapped at the intersection, the traffic light control unit will go into all-red clearance interval to wait until the intersection is clear of obstruction before the next green cycle begins. To demonstrate this scenario, two remote control cars were modified by attaching the NodeMCU to L293D DC motor driver shield to take over the longitudinal movement. The platoon system begins when the remote-control cars entering the traffic light zone and it will autoconfigure with the neighbouring connected cars to elect the leader of the platoon. The platoon operation begins when the traffic light turns green, the leader vehicle will receive the “GO” notification broadcasted from the traffic light, and this information will be disseminated to the follower vehicle on the same platoon. Thus, all the vehicles will travel across the signalized intersection in a synchronous fashion. An example of the demo setup is shown in Figure 5.

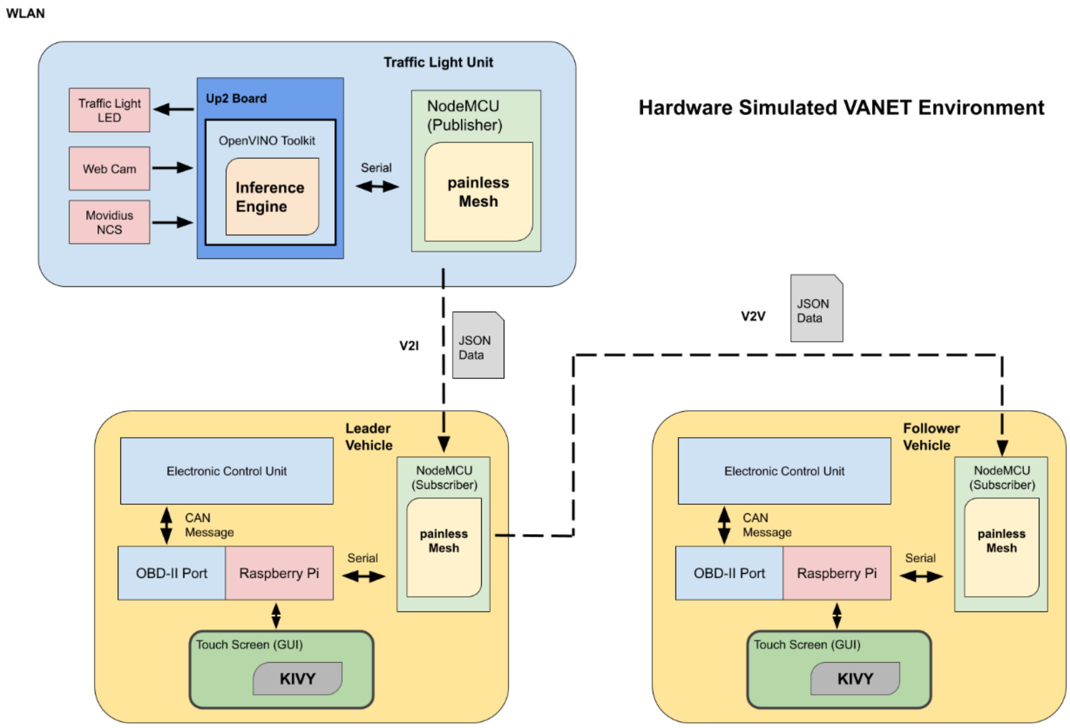
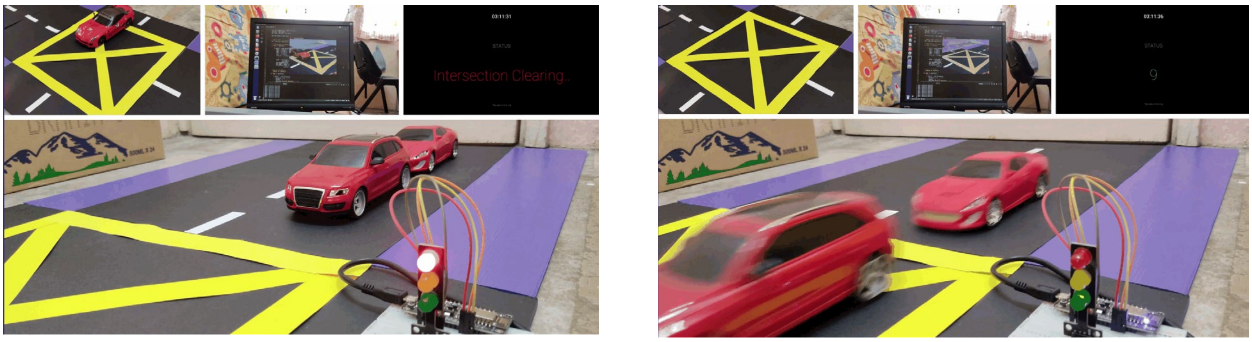


Fig. 4 - The VANET architecture of this project



(a) (b)

Fig. 5 - The demo setup of assisted car platooning using VANET (a) obstruction at intersection, smart traffic light maintains at red; (b) obstruction is cleared, platooning decision between smart traffic light to leading vehicle (I2V) and leading to following vehicles (V2V)

3.3 System Evaluation of Prototype

Latency is a critical component for both end-user experience and infrastructure stability to ensure the Quality of Service (QoS) in a VANET environment. In this project, a one-way network trip delay measurement is used as a performance evaluation metric to monitor the behaviour and performance of the *painlessMesh*. The initial setup is using two nodes communicating point-to-point, where one of the nodes that is assigned as a measuring node (requester) will send a delay measurement request to the other node (responder) on the network, and the measuring node will also be connected to the computer for data logging. Based on the dispersion of 932 captured measurements, it is observed that the box plot is normally distributed with a median of 0.067s, and 75% (third quartile) of delay is below 0.12s.

Next, one more node is added into the network to observe the latency behaviour, resulting in 1812 measurements (906 measurements for each node A and node B) have been collected and interpreted as follows: Interquartile Range (IQR) from the 3-node network is positively skewed and it is wider than the IQR from the 2-node network. Positive skewness in the distribution portrays that each node in the network will experience a greater probability of achieving a lower latency (range between 1st quartile and the median), which is favourable in the proposed system requirement. However, this observation also indicates that increasing the number of nodes into the network will cause each node to experience a wider spread of delay inconsistency as compared with the base case. This is due to the limitations of NodeMCU, such as shortage of memory and operation in the 2.4 GHz band. It is expected that switching to a better hardware that can support the IEEE 802.11p 5.9 GHz operating frequency band will significantly reduce channel congestion and interference experienced in the network. The object detection feature is tested with two different inputs, a video clip of complex intersection scenario and a real-time webcam input with the proposed car prototype. By referring to Figure 6, the bounding boxes, and the label above them show the predicted class ID and the confidence score of the detected object. The object detection results at the road intersection can accurately detect both the real and prototype car with varied distance and angle from the camera. This makes the camera deployment in the traffic light easier as it does not require installation in a very specific angle and position to work.

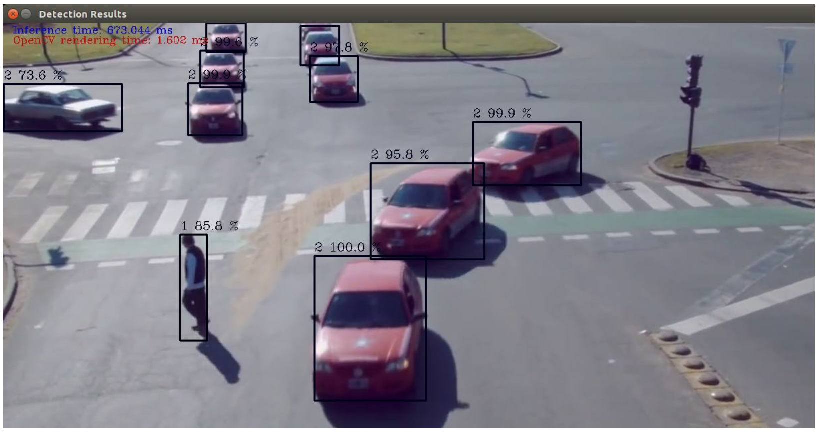


Fig. 6 - Detection result of the inference engine tested with video clip.
The predicted class ID: 1 is pedestrian; 2 is vehicle

4. Conclusions

Platooning lays the foundation for intelligent transportation systems and optimal traffic management. In this paper, several considerations for technologies for Cooperative Adaptive Cruise Control (CACC) at a road intersection have been presented. The study compares the Krauss model and the CACC model for vehicle platooning at signalized intersections. The model utilizes AI image processing, V2X communication, and VANETs to ensure junctions are cleared of obstruction before vehicle platoons execute. The findings from this paper can be used a baseline for the framework of CACC implementation by legislators, policy makers, infrastructure providers as well as vehicle manufacturers. Future work could focus on evaluation of the proposed models and systems in a real-world deployment.

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