Plenary Autonomous Intersection Management Protocol for Heterogeneous Connected Vehicles

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***Abstract*—This paper proposes a centralized autonomous intersection management scheme for heterogeneous connected vehicles (HCVs). Contributions of this work are as follows. First, we sustainably classify heterogeneous vehicles with their distinctive safety-related characteristics. Second, we conduct a safe and efficient coordination algorithm with respect to some criteria such as vehicle types, road priorities and right of way rules. Third, we consider the impact of different road conditions, vehicle characteristics, load, and braking technology on the system performance. Forth, we demonstrate the efficiency of the system under various traffic densities with symmetric and asymmetric vehicle distribution. Besides, system performance is to be compared with traffic lights (TLs) scenarios in terms of throughput, average travel time (ATT), intersection busy time (IBT), channel busy rate (CBR), and packet loss rate (PLR) in various road conditions.**

***Index Terms*—HCVs, DSRC, vehicle classification, stopping distance, coefficient of friction, road conditions, RSU.**

I. Introduction

Most of the today's vehicle safety systems are usually pivotal and sensor-based thereby, they always strive to interpret the current traffic situation from the limited vehicle's view using various sensors. More and more, these systems are inclined to communicate using vehicular communication technologies such as dedicated short-range communications (DSRC) or ITS-G5 [1] to extend the vehicle viewpoint in non-line of sight situations and improve traffic safety. Exchanged information assist the driver to timely react to the hazardous situations. Vehicular cooperative communications are realized through vehicle-to-infrastructure (V2I) or vehicle-to-vehicle (V2V) architectures spanning a wide range of applications. Traffic safety as the most notable application must regard to protect not only cars, but also vulnerable road users (VRUs) such as motorcyclists or cyclists as they are more susceptible to fatal and serious injuries. Nowadays, this paradigm has been scarcely addressed. In the traffic safety domain, intersection safety plays a significant role [2] as a huge number of accidents occur especially at the urban intersections [3]. In addition, currently there is no differentiation between vehicles on the road. In order to improve the reliability of the vehicle safety system, exchanged data needs to include more specific information about the vehicle's characteristics in the surrounding. As the characteristic behavior of the vehicle might be totally different, it is important to be considered when defining a dangerous situation. For example, the velocity (v) or the braking distance (D_b) are quite different or the lanes might be restricted to certain vehicles or even predetermined in case of trams. To the best of the authors' knowledge, this paper is the premier effort that has highlighted the novelty of integrating vehicle classification (VC), road conditions, and HCVs in a safe and efficient plenary approach [3].

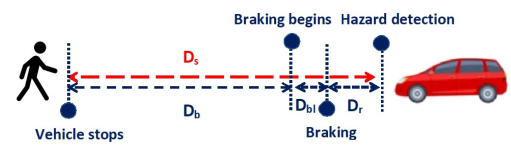

Fig. 1. Stopping distance components

II. System Model

A. Vehicle Classification (VC)

VC plays a prominent role in traffic safety and efficiency by extracting diverse kinematic and physical vehicle's information [4]. In our earlier research [5], we introduced a safety-centric VC method using vehicular networks for multiple types of vehicles. Based on the aforementioned work, we consider safety measures such as reaction distance D_r, stopping distance D_s, v, deceleration d, D_b, braking-lag distance D_{bl}, etc. for VC. A vehicle's D_s is formalized as the summation of D_{bl}, D_b and D_r as depicted in Fig. 1 [5], [6]. Moreover, system model takes into account various road conditions such as dry, wet, snowy and icy as they can greatly impact the coefficient of friction (CoF), warning time and D_s. Furthermore, load of the vehicle is recognized as a prominent factor that can immensely impact the CoF. This load effect is more remarkable for heavy vehicles resulting in longer D_b. As an extension to our previous effort [6], system interpolates the impact of load and CoF of different roads on acceleration a of the light and heavy-duty vehicles. Besides, we have added electric-scooters (e-scooters) and electric passenger vehicles (EPVs) to the road participants. We have also calibrated trams dynamics such as d and a as they have significant impact on other vehicles and scheduling mechanism performance.

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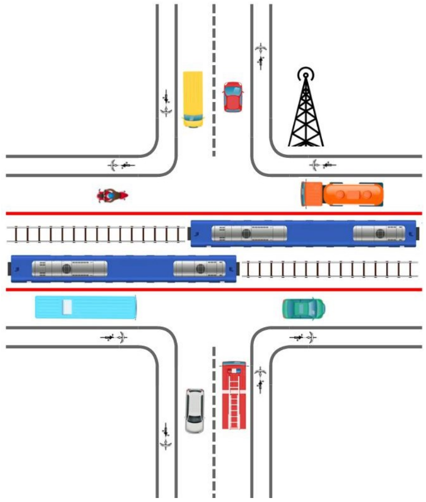

Fig. 2. Intersection layout

B. DSRC Communication Protocol Extension

We have employed DSRC technology as the communication protocol utilizing 5.9 *GHz* frequency band [7]. Physical and MAC layer of DSRC inherits IEEE 802.11p operations [7]. It supports carrier sense multiple access/collision avoidance (CSMA/CA) mechanism and enhanced distributed channel access (EDCA) to provide diverse quality of service (QoS) required by different applications. Our approach exploits the highest category of EDCA known as AC_VO to carry safety messages. Multichannel operation in DSRC is carried out via IEEE 1609.4 standard [7]. Channel number 178 that serves as control channel (CCH) is designated for safety messages whilst several service channels (SCHs) such as 174 are dedicated to traffic services. In the networking and transport layers, it adopts IEEE 1609.3 that defines the wave short message protocol (WSMP) [8]. We have extended the DSRC protocol such that WSMP packets referred to wave short messages (WSMs) [8] can announce proprietary vehicular information. Two types of extended WSM packets are used in the system operation; V2IP that is disseminated from vehicles towards road-side units (RSU) holding the vehicles' states, and I2VP that the RSU broadcasts to the vehicles including allowed-to-go vehicle IDs. To avoid channel congestion, the proposed technique opted for considerably small packet sizes for V2IP and I2VP. This could repress the channel congestion issue and secure the timeliness of the available information in each vehicle.

C. Autonomous Intersection Coordination Algorithm

Fig. 2 depicts an urban intersection topology with trams, vehicles and bicycles or e-scooters lanes. An RSU adopts V2I communications to schedule the vehicles traversal at the intersection in a free space propagation model. Approaching HCVs periodically send safety packets to the RSU containing vehicle type, vehicle ID, road ID, lane ID, arrival time, direction and location. Subsequently, the RSU reliably interprets the available data and broadcasts a list of allowed vehicle IDs. Afterwards, the allowed vehicles can cross the intersection whereas others receive the warning message (WM) and stop at the intersection. Furthermore, the system design benefits from first-come first-serve (FCFS) policy to sort the vehicles according to their arrival times. As a result, the RSU schedules the passage of ordered vehicles based on some criteria such as direction, vehicle types and road priorities. Straight, right and left define the direction priorities. In the proposed method, trams have the highest priority and right of way and they can travel nonstop. Emergency vehicles (EVs) hold the second right of way and only yield to the trams. Besides, simultaneous right turns and opposite left turns are permitted. The algorithm also enables the vehicles with lower priorities to travel through the intersection in parallel with higher priority vehicles if no collision points are detected between the two groups of vehicle trajectories. Furthermore, if vehicles with identical priorities approach the intersection at the same time, the system breaks the deadlock by assigning priorities to the roads.

D. WMs Dissemination

Any vehicle constantly monitors its D_s and its distance to the intersection. It receives a WM to stop if it is not permitted to pass through the intersection and its distance to the crossroad is equivalent to D_s. This mechanism is computed locally on each vehicle to reduce the RSU overhead and increase the system dependability. Moreover, for timely warning, some parameters like reaction time, braking, braking-lag and stopping times, and velocity are taken into consideration. In the system, all road users expect for trams might receive the WM. D_s is affected by the road and vehicle conditions. The minimum notification time compromises reaction, braking-lag, braking, and stopping times. Warning mechanism considers a reaction time (T_r) of one second for the driver to react betimes after receiving the WM [5]. The WM must be sent at the minimum notification time or even before that to avoid collisions [9]. With regard to heavy vehicles, load highly impacts CoF leading to longer D_b [5], [6].

E. Simulation

We exploit simulation of urban mobility (SUMO) [10], objective modular network testbed in C++ (OMNeT++) [11] and vehicles in network simulation (Veins) [12] for the realistic system simulation and validation. Simulation benefits from intelligent driver model (IDM) as the mobility model. This model denotes a more realistic attitude of the vehicles compared to other models like Krauss where vehicle's speed is determined with respect to the distance to the front vehicle. Vehicles begin travelling on the road with the maximum speed (50 km/h) in an urban environment. EVs are permitted to drive with 100 km/h. Due to safety observations, icy road limits the police and rescue vehicles speed to 75 km/h whilst fire-brigade speed is restricted to 60 km/h. Further, bicycles, e-scooters and mopeds are envisaged to make use of 20, 25 and 40 km/h respectively. We implemented multiple asymmetric and symmetric sparse and congested traffic scenarios on the road to investigate the system performance in different road conditions. Sparsely populated traffic contains 12 and and 24 veh/km^2 whereas congested scenarios include 36 and 48 vehicles in a square kilometer. In addition, system efficiency is compared to conventional TLs with respect to different signalling time in symmetric and asymmetric traffic. Symmetric traffic indicates that incoming vehicles are uniformly spread on the four legs of the intersection such that vehicles leaving the intersection also conform to this paradigm. On the other hand, in the asymmetric traffic, two third of the approaching vehicles travel on the horizontal road. As a result, outgoing traffic also complies with this distribution. To examine the system performance in the signalized intersection, TLs green phase duration is adjusted according to asymmetric and symmetric scenarios. To this end, 36 and 12 seconds are set for the TLs for horizontal vehicle and bicycle lanes in the asymmetric traffic while vertical vehicle and bicycle lanes TLs utilize 24 and 8 seconds respectively. Furthermore, in the symmetric traffic 36 and 12 seconds are set for the vehicles and bicycles lanes across all roads. In contrast to the previous research, we have considered the impact of different road conditions in signalized intersection scenarios to equalize the comparison conditions for TLs and autonomous scenarios.

F. Performance Evaluation

There are a couple of metrics that help us to evaluate the performance of the system in symmetric and asymmetric traffic experiments as follows.

1) Packet Loss Rate (PLR): Successful packet delivery to the RSU and vehicles is one of the most significant performance factors of a reliable wireless communication. Here, PLR is estimated for RSU and vehicles as a whole in different autonomous scenarios knowing the number of sent and lost transmitted packets.

2) Average Travel Time (ATT): ATT is an important element in traffic efficiency that should be taken into consideration for designing an efficient autonomous intersection. The shorter trip time is commensurate with a lower delay at the intersection.

3) Intersection Busy Time (IBT): We aim to investigate the IBT for signalized and autonomous intersection scenarios to analyze the behavior of the proposed system compared to conventional TLs.

4) Intersection Throughput: This metric signifies the capacity of non-signalized and traditional intersections by showing the number of vehicles that can cross the intersection in a specific period of time.

5) Channel Busy Rate (CBR): CBR is crucial especially in highly populated areas where a wireless channel is prone to congestion leading to packets drop [13]. CBR is dependent on the transmission rate, traffic load, and packet size

III. Conclusion and Outlook

This paper envisions to provide safety at the autonomous intersection using a centralized approach wherein heterogeneous classes of vehicles share the roads. In addition to traffic safety, we target to optimize the efficiency of the autonomous intersection such that it reliably outperforms TLs in both asymmetric and symmetric traffic under different traffic load as well as various road conditions. System performance is evaluated using several metrics such as throughput, PLR, ATT, IBT, and CBR. In the future, we plan to study the system performance under various realistic propagation models in terms of packet success ratio. The proposed system extends the DSRC functionalities in order to transmit particular information between the RSU and vehicles. Further, in addition to the vehicle's specific safety parameters, a WM was applied to timely warn the vehicles. Moreover, compared to the distributed intersection management methods, the centralized scheme could broaden the communication coverage and lessen the likelihood of collisions. Additionally, the proposed solution strove to strengthen the vehicle perception and vision range, and eliminate the deficiencies of sensor-based driving assistance systems.

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