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Assessment of Pedestrian-to-Vehicle Communication Pre-Crash Safety Warnings to Avoid Collisions

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ABSTRACT

In recent years, road safety is getting more attention to reduce road pedestrian accidents caused by vehicles. The research community is trying to find new techniques related to accident avoidance in the existing vehicle driver assistance systems. These techniques involve the exchange of safety critical information between pedestrians and vehicles. This is called vehicle-to-pedestrian (V2P) communication system, which provides road safety and management to different Vulnerable-Road-Users (VRUs). Furthermore, V2P communication systems use various technologies and different methods to cooperate with the VRUs. These attributes can be considered to design constraints for V2P communication system. In this paper, the authors examine V2P safety aspects and have simulated different V2P scenarios considering real environments. Moreover, the authors analyze the V2P safety in different scenarios by considering the timely exchange of safety messages. The authors presented these results in different V2P approaches for separate VRU groups in different pre-crash situations.

KEYWORDS

5G, ITS-G5, V2P, V2X, VRUs

1. INTRODUCTION

From the start of 21st century, the automobile industry has evolved with the introduction ofConnected and Automated (CA) vehicular systems. This CA vehicular communication system is aimed to enhance road safety. In a CA system, the VRUs include pedestrians, bicyclists, and two-wheel rides. In 2018, the International Traffic Safety Data and Analysis Group (IRTAD) reported that there were 1605 and 10,386 VRU accidents in USA and Germany, respectively (Hess, 2004). Researchers are continuously striving to develop techniques to reduce VRU fatalities. Advanced techniques have been developed as a part of Intelligent Transportation Systems (ITS). In an ITS system, there is a communication system called Vehicle-to-Everything (V2X), that supports communication between several elements on

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road for CA safety (fig. 1). V2X includes a networking between vehicles and road-side-infrastructure known as Vehicle-to-Pedestrian (V2P), Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I). The term V2P integrates the networking among different VRUs and vehicles. Road safety can be enhanced by designing an active ITS safety critical system where V2P exchanges information with different VRUs (Lu, Men, 2005).

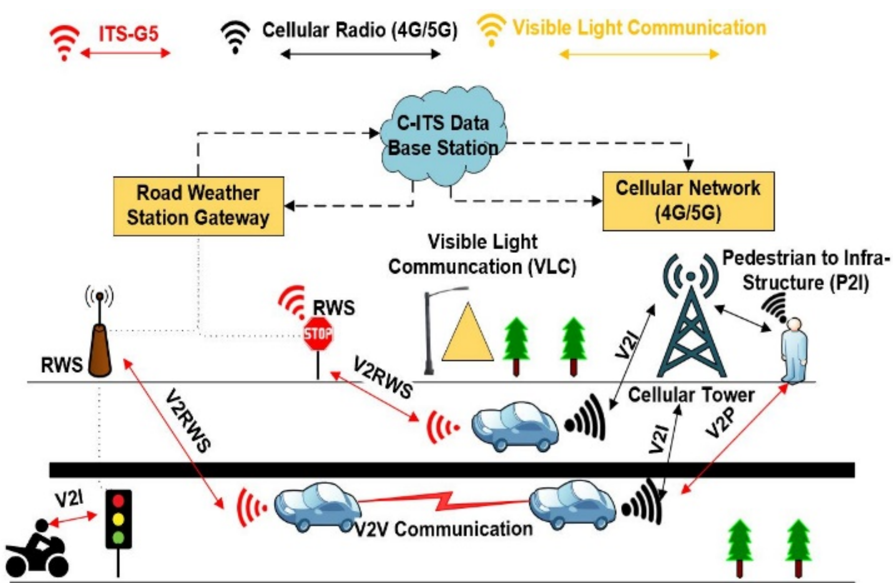
To provide safety critical messages, the V2P communication system needs to enable a collision detection feature. In this collision detection system, the vehicles, pedestrians, and smartphones need to periodically exchange beacon messages and after receiving the beacon messages, a Collision-Detection-Algorithm (CDA) is initiated. The exchange of beacon messages between vehicles and VRUs needs a seamless connectivity to effectively avoid road accidents. This seamless connectivity can be provided by combining communication technologies by creating a heterogeneous network (e.g., ITS-G5 + 4G/5G) (Cheng, Hong, 2005, Gandhi, Tarak, 2007).

2. AIMS, SCOPE, EXPECTED OUTCOME, AND STRUCTURE

In recent years, the majority of tresearch on vehicular communications considers V2V and V2I scenarios. In his paper, we introduce V2P scenarios considering a VRU group. We discuss characteristics of different VRUs and propose a framework for VRU group safety. We also present a comprehensive evaluation of prior work related to V2P and V2P safety applications together with their design challenges. In addition, we perform a case-study that evaluates the performance of different V2P safety approaches considering several VRU groups in four different pre-crash scenarios. Furthermore, we discuss the technical challenges to integrate VRUs safety system into a V2X systems.

The study also estimates the amount of information to be collected during the simulation process that is exchanged between vehicles, and this information is sufficient to warn pedestrians. These simulations result illustrate that the drivers would also be able to avoid V2P collisions by generating alerts. Finally, this study not only offers road safety for VRU groups but would also assist the stakeholders to develop ITS solutions. In this paper, we develop and execute a V2P communication

Figure 1.
Key elements involved in V2X communication



mechanism by considering different pre-crash scenarios and evaluate their feasibility in operational environment.

This paper is structured as follows: Section IV discusses the V2P system architecture and classification of VRUs, Section V discusses the communication technologies for V2P, Section VI presents the framework and simulation settings followed by the Section VII that illustrates the simulation scenarios. Section VIII discusses the results and finally Section IX summarizes the paper with future research directions.

3. RELATED WORK

In recent years, a trend showing a rapid increase of accidents involving pedestrians and vehicles has been observed (Hess, 2004, Lu, Men, 2005; Cheng, Hong, 2005).A VRU group includes the cyclists, pedestrians, motorbikes, wheelchairs, etc., and a significant number of persons have lost their lives in traffic accidents. Notably, despite of a continuous reduction in the sum of road accidents, the number of cyclist and pedestrian casualties has remained approximately the same. Therefore, these VRU groups require distinctive safety features, and challenges should also be identified. Hence, the safety of cyclists, pedestrians, and other non-vehicle occupants i.e., wheelchair etc., are fundamental areas of research concerning Connected and Automated Vehicles (Gandhi, Tarak, 2007). In the majority of the cases, pedestrians vehicles with pedestrians due to mobile device distraction (Anderson, Craig, 2005) or other internet of things (IoT) gadgets (Bonnefon, Jean-François,2020; Wu, Xinzhou, 2014; Tahir, Naeem, 2020). This situation illustrates a clear reduction of awareness as well as dangerous negligence by the mobile device user (Camara, Fanta, 2020; Tahir, Naeem, 2020).

Even though there are some conventional methods to safeguard VRU groups from vehicles (Maracke, C, 2020; Wu, Xinzhou 2007) most of them are connected to a VRU group acoustic alert (Anaya, José, 2014). Nevertheless, this solution is often not enough to divert the attention of VRUs from their smartphones. The use of detection systems for VRU groups can be deployed in the infrastructure, vehicles or with pedestrians themselves to provide alerts to the pedestrians, drivers, or both. There is another warning method called as in-vehicle warning that is becoming more popular now, i.e., forward collision, crossroad, and blind spot warnings. The modern domain of V2V and V2I communications provide an advanced warning system for right or left turn and intersection movement assist, for instance. Here, the warnings generated from the in-vehicle system in the nearby area of a VRU on the side road may result in an effective solution. Meanwhile, the most reasonable and simple warning system for a VRU group is a hand-held device.

Being the mobile device a key reason for distraction, the current proliferation of these devices create challenges but also provides possible solutions, these devices can be used as warning devices as well. This intelligent device is making people's lives more comfortable (Sugimoto, Chika, 2008; Tahir, Naeem, 2019). So, the researcher community and industry are now focusing to develop user specific applications to deliver accurate warnings for VRU groups by using V2P/P2V communications (Bhargava, Bharat, 2011; Tahir, Naeem, 2020).

4. V2P SYSTEM ARCHITECTURE AND CLASSIFICATION OF VRUS

To enhance the road safety, an effective V2P system architecture needs to be developed. . This V2P architecture is presented in Fig. 2, illustrating the V2P crash avoidance system. In a crash avoidance system, there is a periodic exchange of safety critical messages between VRUs and vehicles. This V2P communication uses either short-range Visible Light Communication (VLC), ITS-G5 (IEEE 802.11p) or wide area cellular technologies such as 4G and 5G. The combination of short- and long-range technologies provides a seamless heterogenous connectivity between vehicles and VRUs. Basically, a V2P system performs its functions in three stages: discovery, tracking and track estimation (Anderson, Craig L., 2002). The above-mentioned factors have guided to develop system architectures for different V2P systems. In this section, we briefly discuss the different components of V2P architecture and the beacon safety messages.

Fig. 2 shows the V2P communication system architecture. The V2P communication system can be broadly categorized into the below mentioned parts:

1. VRU device i.e., mobiles, smart watches, etc.
2. Vehicle device (On-board units)
3. Roadside infrastructure (RSU-RWS)
4. Data processing units (local servers)

In a V2P system, there are two kinds of communication techniques, direct and indirect communication. Direct communication takes place between vehicles and VRUs and indirect communication involves roadside infrastructure between vehicle and VRU communication. In both approaches, a three-phase information exchange is performed for a V2P system (Wu, Xinzhou, 2007). Nevertheless, if we consider an indirect communication (via infrastructure) scenario, then a V2P system depends on the data processing unit to carry out discovery, tracking and track estimation phases. The processing unit checks the probability of a crash depending on the track estimation. Then, it notifies the vehicles and VRUs via roadside infrastructure to perform a required action. The VRUs and vehicles might then complete the required action phases (Wu, Xinzhou, 2014). Fig. 2 illustrates the cases of direct and indirect V2P communications system architecture.

4.1 Classification of VRUs

4.1.1 VRUs

There are two kinds of VRUs. The first one is called active VRU in which a VRU device actively contributes to the V2P communication by transferring messages about the VRU position, vehicle speed, etc. But this active VRU mechanism requires the VRU devices to be equipped with various technical features i.e., communication, GPS technologies, etc. The second type of VRU is called passive VRU devices, in which they can only ’listen’ to the data messages from a vehicle or when the VRU devices transmits a response after receiving a message from vehicle. The passive VRU devices listen to the vehicles for data messages and vehicles might not be able to be sense the VRU’s presence but VRUs must be able to aware of vehicles to prevent possible accidents (Camara, Fanta, 2020).

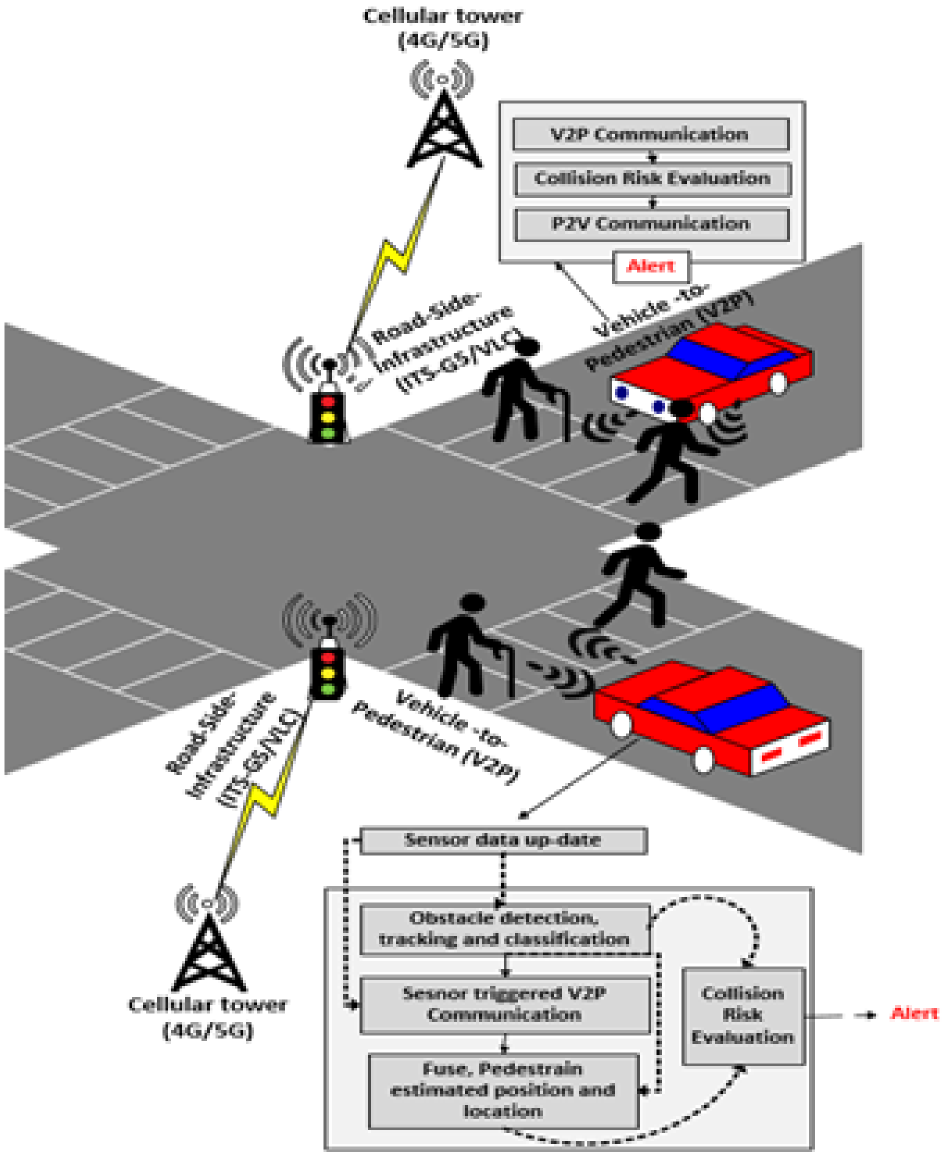
4.1.2 Safety Messages

A V2P safety critical message may include information related to speed, position, and direction of a particular VRU or vehicle. These beacon messages are used in the discovery, tracking and track estimation phases by the receivers of these messages. The transmission frequency of these messages from vehicles is usually 10 Hz (10 safety messages/sec). The VRUs may also transfer safety critical messages with a variable frequency. This variable frequency depends on several parameters i.e., position, direction, speed, etc. (Tahir, Naeem, 2020).

5. COMMUNICATION TECHNOLOGIES

There are numerous technologies that have been designed and developed for V2P communication systems. Some of the attributes of the V2P systems mainly depend on the preference of the fundamental communication technologies. Some of the examples of such characteristics are communication range, V2P communication devices and availability of roadside infrastructure. This section briefly discussed the important communication technologies with its core features.

Figure 2.
Vehicle-to-pedestrian communication architecture



5.1 IEEE 802.11p (DSRC/ITS-G5)

IEEE introduced IEEE 802.11p in 2012 by adding Wireless Access in Vehicular Environments (WAVE), in to a vehicular networking system. It specifies development in the 802.11 that is needed to support several Intelligent Transportation Systems (ITS) applications. The operational frequency of IEEE 802.11p is 5.9 GHz (5.85GHz–5.925 GHz) in the licensed ITS band. It specifically supports all the V2X applications to provide road safety. IEEE 802.11p supports reliable transmission of beacon messages in high mobility environments with low latency. The standard supports a relatively short communication range up to 1000m to cover whole V2X network. But this range is enough to support communication at high vehicle speeds i.e., 40m/s. IEEE 802.11p is used to develop two standards Direct Short-Range Communication (DSRC) and ITS-G5 protocols. These protocols are normally deployed with roadside infrastructure (Tahir, Naeem, 2020; Maracke, C, 2020) to decrease the deployment costs. IEEE 802.11p features reliable and low latency communication, making it one of the best available solutions for V2P safety applications.

5.2 Cellular

Cellular technology is an efficient solution to provide seamless connectivity in V2X communication for road safety applications. Some of the prior work (Maracke, C, 2020) has been performed to create V2P communication system using cellular technologies. This prior work has used 3rd Generation partnership Project (3GPP) based 3G, 4G or 5G for V2P communication with VRU devices (smartphones). The cellular infrastructure provides a better network coverage for V2X communication by covering more road infrastructure. Nevertheless, the network scalability and latency performance of cellular based V2P system must be carefully examined to verify their compatibility for V2P safety applications. Currently, the Cellular V2X (C-V2X) is in a development phase as a part of next generation 5G network. The C-V2X is designed to offer multiple services for different V2X applications including V2P (Wu, Xinzhou,, 2014). But still, developing the C-V2X design and compatibility for V2P communication system requires considerable efforts and time. Because of its long-range coverage and high market demand, cellular technology is a good contender for V2X safety applications i.e., V2P etc.

5.3 Wi-Fi

Wireless Fidelity (Wi-Fi) (Hess, Paul Mitchell, 2004) defines family protocols of wireless networks, established on the IEEE 802.11 standard, that is generally used for Internet access and Local-Area-Networking (LAN). With the use of Wi-Fi, several efforts have been performed to create a V2P communication system by using Wi-Fi (Anaya, José, 2014). For VRU devices, smartphones are the best available choice, supporting communication range of up to 100–150m. This communication range is enough to cover the rural and urban areas with an vehicle speed up-to 50-60km/h. Nevertheless, it could not be a good choice for suburban areas with vehicle speeds up-to 100km/h because of less available time for the driver’s response in emergency situations. Additionally, the requirement for the Wi-Fi association is also a challenging thing for vehicles mobility as it probably takes too long before the transmission of of safety messages. One of the advantages for a Wi-Fi-based V2P system is that it does not require separate infrastructure (Sugimoto, Chika, 2008).

5.4 Visible Light Communication (VLC)

VLC is a data communication technology that uses visible light ranges from 400-800 THz. VLC is a technology that is introduced under the umbrella of optical wireless communication. It is typically used for short-range communication by using LEDs to transfer data up-to 500 Mbps. Researchers are now continuously trying to use VLC communication in vehicular communication. Because it can help to play an important role in V2X communication to enhance road safety. VLC can be a good option complementing other wireless technologies for efficient and reliable exchange road traffic data. The reliability and range of VLC for V2X communications can be affected by the environmental conditions (Tahir, Naeem, 2019). But there is plus for using VLC is that it has a feature to support V2P communication in both line-of-sight (LOS) or non-line-of-sight (NLOS) conditions. VLC works the best in light-of-sight (LOS) conditions, but it can also work in non-LOS situations.

6. FRAMEWORK DESIGN AND SIMULATION SETINGS

In this section we discuss the simulation architecture for this paper. Because simulations are basically needed to design and develop a real-time traffic environment such as map topology, communication specifications, traffic requirements and road traffic infrastructure.

For this simulation, we have used the open-source simulator Webots, that is adopted to simulate CA vehicles. In order to create a realistic environment for 3D traffic, advanced data from the external sources (e.g., NASA SRTM) was included with the OpenStreetMap data. Then, this data is inserted into the Webots to build a CAD environment by Open-Street-Map (OSM) distributor (Bhargava, Bharatm, 2011). For the extension of CAD simulation to the network level with diverse traffic, the open-source Simulation of Urban MObility (SUMO) and Veins (Vehicles in Network Simulation) was combined with Webots to create a flexible traffic network having different traffic conditions. OMNeT++ was chosen to provide a connected vehicle environment supporting V2X communication protocols such as ITS-G5 (IEEE 802.11p), 4G/5G and Wi-Fi. (Dhondge, Kaustubh, 2014; Tahir, Naeem, 2020). These modules were linked to the Traffic Control Interface (TRACI). TRACI was built on TCP client/server architecture and operates in a parallel way with SUMO and Veins that works as the server for OMNET and Webots, as presented in Fig. 3.

Considering the simulation scenarios, we have conducted four different pre-crash scenarios by using our simulation platform. These simulations have been performed by considering V2V, V2I and V2P scenarios. The simulation parameters are presented in Table 1. We have added vehicles in the simulations after every 2 seconds and pedestrians are added in every 1.5 seconds. The transmission power of VRUs and vehicles are adjusted to 21mW that will allow the communication in a range of 500m. We have also used two-ray interference technique as a path loss specification in order to estimate real-time path propagation of V2I, V2P and V2V scenarios (Danys, Lukas, 2019). Table 2 provides the detailed parameter settings for our scenarios.

7. SIMULATIONS SCENARIOS

In this section, we discuss four simulation scenarios (fig. 4). These four pre-crash scenarios have been simulated; (1) Pedestrian and vehicle moving in parallel, (2) Pedestrian crossing road in-front of vehicle, (3) Vehicle left turn into bicyclist's lane, and (4) Vehicle right turn turning right into bicyclist's lane. Table 2 shows the forementioned four pre-crash scenarios with different simulation run-times, warm-up time and crash times. The warm-up time is the length of time allowed for vehicles to move into a normal traffic state. The crash time shows the time of simulation when the VRU and vehicle crashes with each other.

Figure 3.
Simultaion platform for V2P communication

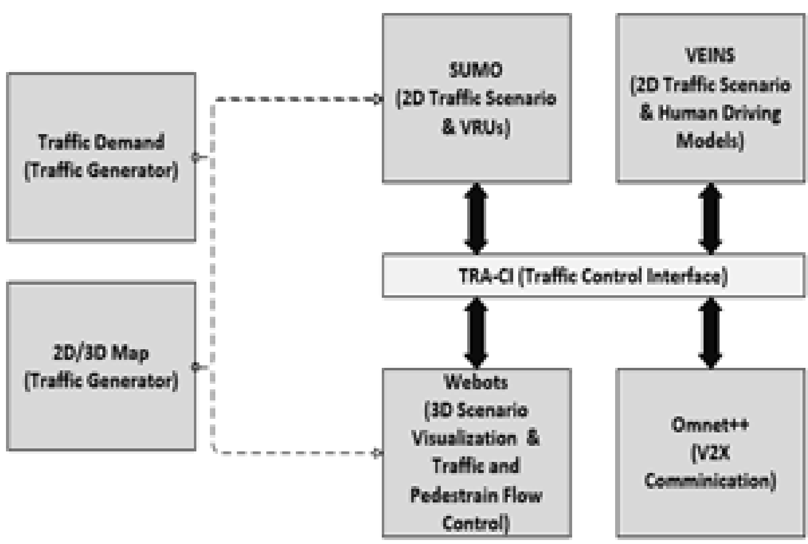


Table 1.
Simulation parameters

Simulation Parameters	Value
Vehicle speed (Maximum) (km/h)	60
Road layout	Two lanes (Two way) and intersection
Number of vehicles	100–160
Pedestrians speed (Maximum) (m/s)	1.6
Number of pedestrians	100-150 (max)
Pedestrian speed	3 km/h
Number of bicycles	1
Bicycle speed (Maximum)	4.5 Mbps
Road length (m)	1000*1000m
Data rate	7 Mbps
Periodicity of vehicle beacon messages	10 Hz
Vehicles Transmission (mW)	20
VRUs transmission power (mW)	20
Size of beacon messgae (bytes)	128
Window size	1s, 3s,5s
Beacon periodicity for VRUs (Functional Processing) (Hz)	2
Beaconing Interval	100 ms
Simulation Time	30 s

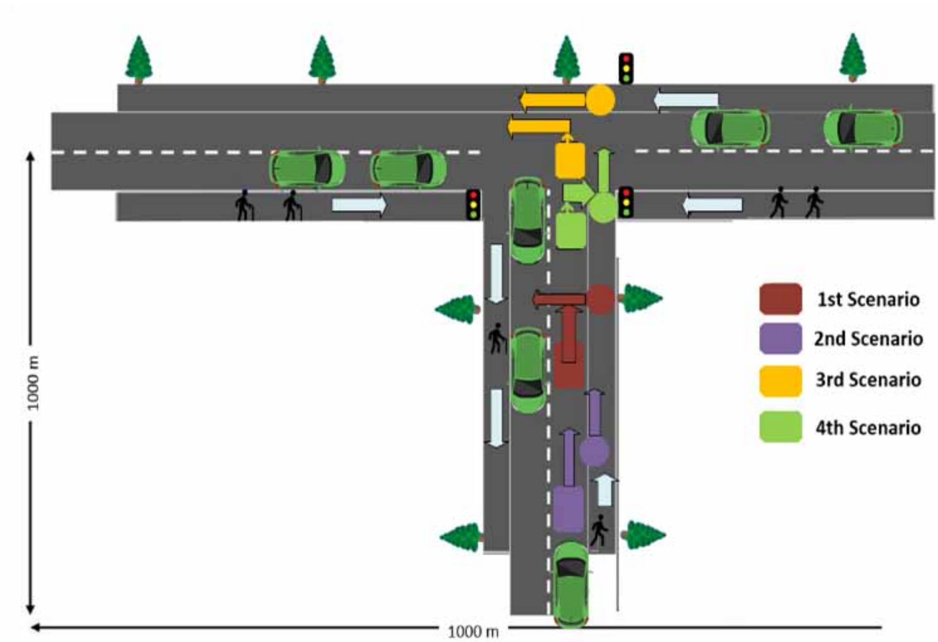
Table 2.
Parameters for V2P scenarios

Scenario	Simulation Length (seconds)	Warm-Up (seconds)	Wait Time (s)	Time to Spare (s)	Crash Time (seconds)
1	36	33	20	15	36
2	46	14	24	17	46
3	50	46	21	14	50
4	49	12	27	20	49

To avoid the effect of time, long driving periods have been avoided in the simulation process. Car break has also been considered between four simulated scenarios. Additionally, the used Latin-Sequence design also assisted to manage the prejudice between all four scenarios. We have performed our simulations in four separate phases for each pre-crash scenario considering both active and passive VRU configurations. Then, we calculated the average values for the assessment of the final simulation outcomes.

To assess the advantage of a V2P/P2V safety alert, two parameters have been used: The Post-Encroachment Time (PET) and the crash rate. The percentage of crash rate for vehicle drivers that struck the pedestrians between total number of simulations. The PET is the total time difference when a pedestrian leaves the location of a possible crash and the arrival time of a vehicle in that location

Figure 4.
The four differnet pre-carsh scenarios considered in the simulation



(Sewalkar, Parag, 2019; Lima, Danielli A, 2016). Normally, the PET is applied in V2P/P2V collision scenarios to calculate a margin for pedestrian safety.

7.1 Data Recording and Performance Variables

In the simulation process, we have considered the orientation and locations of all moving objects on every single step, including all VRU groups and vehicles. The simulation process focused on the performance variables together with the gap selection findings before crash, movement time, and vehicle or pedestrian direction:

- **Waiting time:** Wait time is the size of gap temporarily before crossing.
- **Gap taken:** It is the gap between VRUs and vehicles.
- **Entry time:** The time between when the VRUs cross the gap on the road.
- **Time to spare:** The time between the pedestrian and the face-off vehicle.
- **Collision:** A VRU cross is categorized as a crash if the spare time is £ 0.
- **Attention to traffic:** Percentage of the time that a VRU group member used to look and wait at traffic signal during simulation.

All simulation scenarios are averaged around the 20 road-crossing to find out the results.

8. RESULTS AND DISCUSSION

This section presents and discusses the results and key characteristics of VRUs in V2X networking. For the analysis, we have considered four parameters to assess the V2P communication in the mentioned pre-crash scenarios: The vehicles accessible reaction time and the safety information received by the VRUs. To calculate the vehicle's response time before car crash, the timestamp of the very first beacon message heard from the vehicle by subsequent VRU (discovery phase) was used (Misener, Jim, 2016). For each pre-crash scenario the Response Time is defined in (1):

$$RT = CT\text{-}FBT \quad (1)$$

where:

RT = Response-Time
CCT = Car Crash Time
FBMT = First Beacon Message Time

The VRUs transmitted safety information provides the opportunity to evaluate the reliability for tracing and track estimation phase. The total number of safety messages transmitted by the VRUs for a particular vehicle is taken into consideration. Table 3 illustrates the total received safety messages and Response-Time by each single pre-crash situation considering passive as wel as active techniques.

As seen in the Table 3, the passive technique has a better response time than the active technique. This difference is because of the waiting time (2 sec) by VRU devices before the transmission of the safety message. The study in (Dhondge, Kaustubh, 2014) shows that the crash awareness message needs to be delivered about 8 sec before the accident (Rostami, Ali, 2016). In our simulation scenarios, not any of the considered techniques can achieve this requirement in the first and third scenarios. The first scenario has a small response time for the reason that VRU needs to cover a small distance (< 3.5m) prior to a collision by vehicle. The third setup also illustrates a little response time as the VRU, and vehicles are not able to communicate due to the NLOS condition. Scenarios 2 and 4 show sufficient long Response-Times (Song, Hyok, 2018).

As seen in Table 3, the amount of received safety messages is always less with passive techniques, as compared to active ones. If we look at the first and third scenarios, the VRU only transmit two messages to the vehicle under the passive technique. These messages are enough for the discovery phase but there is not any message available for the tracking and track estimation phase. In the second

Table 3.
Available response time and safety messages considering four pre-crash scenarios under active and passive mechanisms

Scenarios	Response Time (s) (prior to Crash)	Messages Received from VRUs	Messages Received from Vehicles
1st scenario			
Active	2.94	4.32	3.76
Passive	0.99	2.1	3.19
2nd Scenario			
Active	30.6	55	49
Passive	27.79	12.87	21.23
3rd Scenario			
Active	2.93	5.91	4.19
Passive	2.36	1.5	3.9
4th Scenario			
Active	35.70	69.9	59.12
Passive	33.81	15.26	12.83

and fourth scenario, the vehicle collects enough messages for both the active and passive techniques (Nguyen, Quang-Huy, 2020).

Fig. 5 illustrates the average time taken by each car stopped at the road intersection or stuck in the traffic queue. The figure is normalized, and, as can be observed, there is not any considerable difference between the push and pull modes in the simulations. Certainly, the car stop time increases with the increase in pedestrians, while the cars have a tendency to stop longer at the crossing allow the pedestrians to cross the road on right (fourth scenario) and left side (third scenario). In the no traffic light situation, it is more dangerous the push and pull mode that shows the more threat to pedestrians in the simulation.

Fig. 6 presents the Packet Delivery Ratio (PDR) by using 5G and ITS-G5. It presents the findings of the average packet delivery and packet loss by using push and pull modes. The ITS-G5 has a lower packet delivery ratio in the push mode than the 5G pull mode. The lost packets in ITS-G5 are due to the lost packets because of packet collisions or noise interferences between transmitter and receiver. We have considered the SNIR (Signal-to-noise-plus-interference ratio) and Tx+Rx in our PDR. The data packets received by the VRUs are calculated as:

$$PDR_{VRU} = P_{received}\,(VRU)\,/\,P_{sent}\,(Vehicle) \qquad (2)$$

where:

$P_{received}$ (VRUs)= Packet data received by the VRUs
P_{sent} (Vehicles)= Packet Data sent by the vehicles

9. SUMMARY

In recent years, V2X communication have increasingly focused attention into the design and development of VRUs safety, paving the way to their implementation in near future. It is important for a V2X system to integrate different attributes for targeted VRU groups and situations. This

Figure 5.
Normalized (100%) average car stop time considering all four scenarios

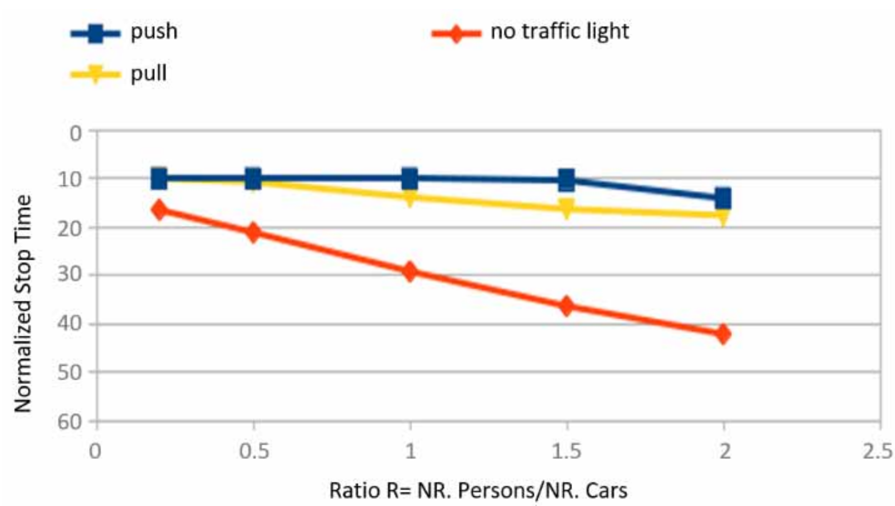
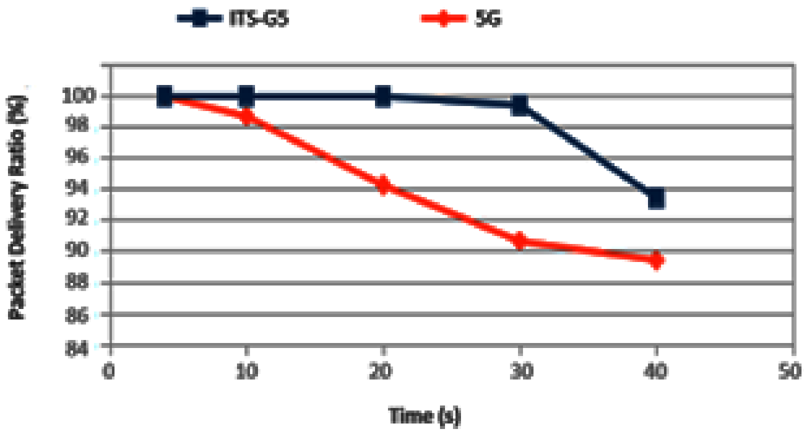


Figure 6.
Packet delivery ratio (%) for V2P communication considering all four scenarios



paper has proposed a approach to design a V2P communication system that can be used for the development of a framework established on the use-case scenarios for V2P. This study likewise offers the technical details of V2P communication technologies and identifies their role in the designing of the suggested V2P framework. This paper also discussed the difference between the VRU passive and active contribution techniques beneath the four important pre-crash situations for dual separate VRU classes. Our simulation results show that ITS-G5 based V2P safety system performance is slightly lower than the cellular based 5G network. Thus, ITS-G5 must increase its performance in some pre-crash conditions in order to provide accident-avoidance warnings. In addition, this study analyzes some technological obstacles to V2X-VRU integration. Future plans include addressing the V2X-VRU integration-related network congestion issue.

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