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 SURVEY

# Vehicle to Pedestrian Systems: Survey, Challenges and Recent Trends

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**ABSTRACT** The accelerated rise of new technologies has reshaped the manufacturing industry of contemporary vehicles. Numerous technologies and applications have completely revolutionized the driving experience in terms of both safety and convenience. Although vehicles are now connected and equipped with a multitude of sensors and radars for collision avoidance, millions of people suffer serious accidents on the road, and unfortunately, the death rate is still on the rise. Collisions are still a dire reality for vehicles and pedestrians alike, which is why the improvement of collision prevention mechanisms is an ongoing necessity. Collision prevention mechanisms have evolved from vision-based systems like radars to systems that transcend the driver's line of sight. These latter systems depend on vehicular ad hoc networks (VANETs) to employ bidirectional communication between vehicles and other vehicles (V2V) as well as between vehicles and road infrastructure (V2I). Recently, research has expanded to include a new communication system between vehicles and pedestrians (V2P) through the latter's smartphones. In this paper, we provide an extensive survey of existing V2P projects, categorize different parameters that influence V2P system design, compare different communication technologies used in V2P systems and present an overview of recent trends that solve problems in V2P systems like network congestion, pedestrian localization, and context information exchange. The main contribution of our work is to pave the road for future research by providing a comprehensive view of projects, challenges and recent trends in the emerging and rapidly growing field of V2P system design.

**INDEX TERMS** Collision detection, collision avoidance, DSRC, safety applications, vehicular ad hoc networks (VANETs), V2P, vehicle-to-Everything (V2X).

## I. INTRODUCTION

The advent of vehicle-to-everything communication is expected to make significant contributions to Intelligent Transportation Systems (ITS), leading to the improvement of road management, pollution control, and collision rate reduction [1]. The collision rate reduction is especially significant since it accounts for an atrocious number of yearly fatalities; for example, in some countries, crashes due to speeding account for triple the annual fatalities accounted for by intentional homicide [2]. The main cause of road accidents is human negligence [3], yet it is suggested that improving preventative measures goes a long way towards mitigating the

dreadful impact of traffic accidents. A trend analysis carried out in [4] shows that the death per capita rate increased by 6% in the USA between 2019 and 2020. The same analysis also showed that the death per capita in the USA is about half of what it was 40 years ago, as evident in Figure 1 [4].

Research on collision avoidance was initially vehicle-centric but has recently grown to encompass other Vulnerable Road Users (VRUs), defined in [5] as road users at high risk of crash involvement, including pedestrians, cyclists, and motor wheelers. This is a positive redirection since more than 50% of the global 1.35 million road-related fatalities in 2018 constituted Vulnerable Road Users (VRUs) [6].

The research on collision avoidance takes two broad directions: the first seeks to mitigate the damage caused by collisions and is termed Passive Collision Avoidance (PCA).

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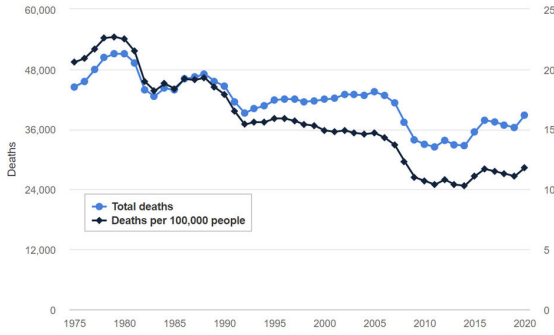


FIGURE 1. Motor vehicle crash deaths and deaths per 100,000 people, USA 1975-2020 [4].

In contrast, the second seeks to prevent the occurrence of collisions and is termed Active Collision Avoidance (ACA) [7].

PCA methods include the creation of dedicated lanes for cyclists as proposed in [8] and [9], pedestrian-friendly bumpers in vehicles [10], LED-equipped helmets [11] and gloves [12], and sensor-enabled airbag systems [13]. However, these aforementioned safeguards are of questionable effectiveness since they have not yet been thoroughly evaluated [14]. ACA methods are further sub-categorized into two broad categories: those that presume visibility or line of sight (LOS), including Radar, Lidar, and Vision based systems [7], and those geared towards Non-Line of Sight (NLOS) scenarios, which are the primary object of interest in this paper. NLOS ACA methods broadly revolve around the idea of communication between vehicles and vulnerable road users (V2X) using radio frequency identification (RFID), dedicated short-range communications (DSRC), WIFI technologies, or cellular V2X. The different approaches to collision avoidance are summarized in Figure 2.

This paper takes an interest in N-LOS approaches since they are unperturbed by adverse weather situations and lighting conditions [15]. They depend on information exchange between vehicle On Board Units (OBUs) and VRU devices [16]. This is crucial because most fatal traffic accidents occur due to limited visibility and insufficient time for proper response [17]. These measures enable the communication, and thus interconnectivity, of different road users [18]. This exploits these users’ essential role in the perception of their surrounding environment and in subsequent information dissemination to other road users [19].

N-LOS approaches to VRU safety, more commonly referred to as vehicle-to-pedestrian (V2P) systems, can be categorized differently based on multiple diverse parameters of system design. One example of a broad distinction depends on the role of the VRU device in the system. At the simplest end of the spectrum, there are awareness applications that grant total agency to the driver and limit the role of the VRU device to a “Hello” signal to declare existence. At the more complex end, there are collision avoidance applications in which the role of the VRU device could expand to include algorithmic computations and trajectory predictions [20].

TABLE 1. Summary of acronyms.

Acronym	Full Form
ACA	Active Collision Avoidance
ALM	Aggregate Local Mobility
BSM	
CAMs	Cooperative Awareness Messages
CDAs	Collision Detection Algorithms
CITS	Cooperative Intelligent Transportation Systems
CV2X	Cellular Vehicle-to-Everything
CSI	Channel State Information
DSRC	Dedicated Short Range Communication
IoT	Internet of Things
IoV	Internet of Vehicles
ITS	Intelligent Transportation System
IP	Internet Protocol
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MBB	Mobile Broad Band
MEC	Multi-Access Edge Computing
MTW	Motorized Two-Wheeler
NLOS	Non-Line of Sight
OBU	On Board Unit
P2V	Pedestrian-to-Vehicle
PCA	Passive Collision Avoidance
RFID	Radio Frequency Identification
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad-Hoc Network
VRU	Vulnerable Road User
WAVE	Wireless Access Vehicular Environment

The sordid statistics of VRU fatalities in road accidents recently prompted a multitude of research endeavors in the field of V2P system design. However, these endeavors employ varying parameters with different properties and limitations, and much still needs to be done to overcome the challenges in V2P system design.

In this paper, we survey previous efforts in designing V2P systems; we lay the ground for future research by categorizing V2P systems according to design parameters and comparing the technologies used in V2P system design. Furthermore, we discuss the challenges of V2P design and present some of the efforts geared toward overcoming these challenges. Finally, we survey the most recent trends in the field of V2P systems.

We summarize the contributions of this paper as follows.

A- Outlined factors that influence V2P system design specifications like VRU types, VRU roles, VRU devices, communication technologies, notified parties, and purpose.

B- Compared the different technologies used in V2P system design in terms of range, latency, and ease of deployment

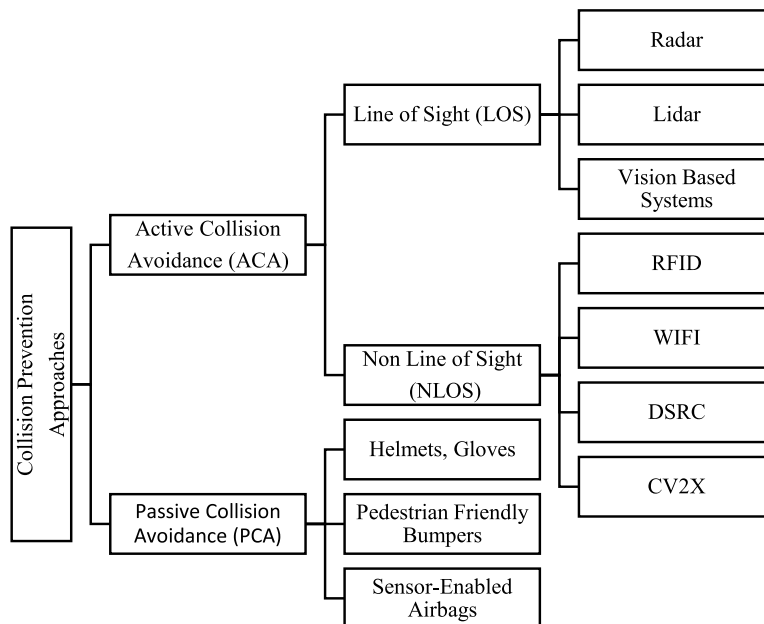


FIGURE 2. Collision prevention approaches.

C- Surveyed thirty-eight V2P systems published in previous research and outlined each system’s VRU type, communication technology used, and VRU device.

D- Outlined the current challenges of V2P system design as an indication of possible areas of future research

E- Reviewed thirty papers published between 2019 and 2022 to analyze recent trends and outlined their contributions towards the field of V2P system design and technologies.

The remainder of this paper is organized as follows. Section II offers background information on V2P system design, including categorizations by different design parameters, a comparison of different technologies used, and an overview of previous endeavors. Section III presents a review of efforts to tackle certain challenges to V2P system design. Section IV is a survey of recent trends in V2P design, technologies, and solutions. Finally, section V concludes this paper with a general discussion of results, implications, and future directions.

A summary of acronyms used in this paper is outlined in Table 1.

## II. OVERVIEW OF V2P SYSTEM DESIGN

This section presents an overview of V2P system design by categorizing V2P systems by different design criteria, comparing the technologies used in V2P system design, and presenting a survey of previous V2P system design endeavors.

### A. PARAMETERS OF V2P SYSTEM DESIGN

NLOS approaches to ACA, henceforth referred to as V2P systems, are subject to a multitude of categorizations depending on the parameter in question. They can be categorized by the intended recipient into: pedestrian, cyclist, or motorized two-wheeler (MTW)). Another way of categorizing is by the pre-crash scenario, whether the direction of the VRU is parallel

or perpendicular to the vehicle before the collision. They can also be categorized by the mode of communication and the existence of intermediary nodes between the vehicle and the VRU. Further categorizations include whether the system notifies the vehicle driver, the VRU, or both and whether the VRU’s role in the system is active or passive. The technology used and the type of VRU device are interrelated parameters that are discussed in greater detail in the following part of this paper. Finally, one secondary classification is whether the purpose of the entire system is the safety or convenience of road users, but the former is the subject of most research, including this paper. Figure 3 summarizes the different design criteria and subsequent categorizations.

These different categorizations are all interconnected and influence the choice of parameters in V2P system design. For example, while the authors in [21] argued that VRU movement patterns and response times are distinctive from those of vehicles, a similar argument could be made about the distinctions between pedestrians and cyclists or motorized two-wheelers. In fact, not all pedestrians exhibit the same patterns; while typical adults move at a speed of 1.4 m/s [22], aged and physically disadvantaged pedestrians are likely to move at much slower rates, and children are likely to move in much less predictable patterns. The above distinctions would influence the choice of VRU role and VRU device. For example, a tag-based approach is more effective for children for unilateral communication since children cannot play the role of an active VRU.

In the choice of VRU device, dedicated devices have the obvious disadvantage of low market penetration [23]. Smartphone-based technology is much easier to deploy than dedicated devices, though the former has a lower battery life since VRUs use smartphones for battery-draining infotainment purposes as well (music, movies, and social media).

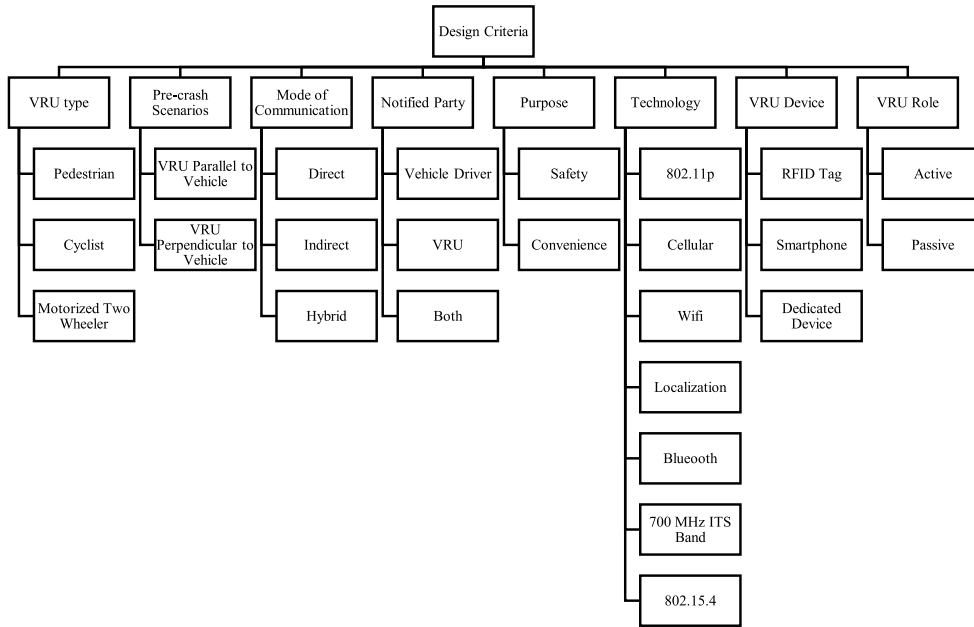


FIGURE 3. Categorization of V2P system design criteria.

Furthermore, the mode of communication and technology used both have an effect on important design parameters like latency and range; the role of infrastructure in indirect communication may increase the range at the expense of also increasing communication latency. The interplay of these groupings and categorizations influences system design parameters and thus must be taken into account.

### B. COMPARISON OF TECHNOLOGIES

Conventional LOS-dependent non-cooperative methods proved to have limited effectiveness in a dynamic or cluttered environment, and their limitations were further accentuated by physical and clothing disparities among pedestrians [24]. They were shown to be consistently ineffectual when VRUs appeared in the driver's LOS less than 2.7 seconds before collision [21]. The NLOS approaches discussed in this paper have the collective advantage of overcoming these limitations due to their essential nature of being independent of line of sight. However, these technologies differ among themselves in terms of communication range, latency, infrastructure requirement, and deployment costs in terms of the required VRU devices.

NLOS V2P communication was first implemented via Radio Frequency Identification (RFID) tag-based protocols, but these suffered from relatively low communication range (<60 m), inability to relay additional context information as well as the inconvenience of requiring an independent device at the VRU end [21]. WIFI communication first employed the IEEE 802.11g technology but still suffered from limited range (<120 m) as well as high latency due to connection establishment requirements. The limitations of legacy WIFI were overcome by IEEE 802.11 a/b dependent WIFI direct technology, which enables the direct communication of

WIFI devices without access points [21]. While WIFI direct significantly reduces connection establishment delay from 8s to 1s, it is still unfeasible in situations where the group leader, who acts as an access point, is continuously changing, since the need to continuously reform groups creates its own delay. These limitations ceased to exist when the IEEE 802.11p dependent Dedicated Short Range Communications (DSRC) protocol was developed, for unlike WIFI direct, it did not suffer interference from conventional WIFI hotspots with high power access points, nor it did suffer from the limited privacy imposed upon WIFI direct due to its Internet Protocol (IP) nature [21]. While DSRC was initially developed for vehicle-to-vehicle (V2V) communications, a collaborative research effort between Honda and Qualcomm leveraged the existing V2V technology for use in the V2P domain [24]. The fact that DSRC was initially designed for V2V means that it was designed with requirements of low latency and high interoperability for high mobility environments [21] with an effective range of 300m, as well as omnidirectional 2-way-sensing capabilities [25]. Another advantage is that a DSRC stack can be implemented within the WIFI chipset on a smartphone to leverage the GPS capabilities as well as the inertial motion sensors of the latter [24]. Furthermore, Qualcomm announced they will be able to upgrade existing firmware to work in the DSRC band without any additional hardware costs [21].

In contemporary research, the only technology worth serious comparison to IEEE802.11p-based DSRC is Cellular Technology [26], [27], [28]. Advocates of cellular technology reasonably argue that it offers a superior range to DSRC communications [23], [29]. Some have argued further that the advent of migrating from Long Term Evolution (LTE) based cellular technology to MBB (Mobile Broad Band) 4G

**TABLE 2.** Comparison between the different technologies used in V2P system design.

Technology	Advantages	Disadvantages	Comments
<b>IEEE 802.11p (DSRC)</b>	-Low Latency even in high mobility [21, 22] -Acceptable Range (1 Km) [22] -Doesn't require infrastructure (works with and without) [22] -Fastest Communication [23]	-requires enabling vehicles and smartphones with DSRC tech[35] -Scalability poses the challenge of network congestion [28] -Requires smartphones with high computing power [22]	-Tailored for V2X (originally created for V2V) [21] - Qualcomm announced DSRC tech can be implemented on existing firmware without additional hardware costs [21]
<b>Cellular</b>	-Commercially available in devices (Easy deployment and market penetration) [23] -Longest range due to existing infrastructure [22]	-Additional delay because packets are routed in base stations [23] -In LTE and 3G implementations, latency is too high for high mobility safety critical scenarios [21]	- Shift towards Mobile Broad Band (4G and 5G) is expected to mitigate latency challenges [32, 36]
<b>WIFI</b>	-Easy to deploy [22] - Doesn't need infrastructure [22]	-Legacy WIFI (802.11g) has a limited range (100-150m), which is not enough in high mobility scenarios [22] -Latency due to connection handovers [23] -Packet loss rate increases in high mobility scenarios [15]	-WIFI direct technology overcomes Access Point challenges, but signal propagation properties under mobility are untested [21]
<b>Tag-based localization devices</b>	-Uses a dedicated device→ useful in the absence of smartphones (for children) [22] -Most Cost Effective [23]	-Limited range (<100 m)[22] [37] -Supports a fixed number of transponders hence triggering scalability problems [22]	-Research suggests additional context information is essential for more accurate Localization of pedestrians. This is unachievable using RFID. [21]
<b>Bluetooth</b>	-Suitable for connectivity (smart phone and headgear, for example) [23]	-Limited range (50 m) -Not suitable in dynamic situations [22]	-Localization through iBeacon as a VRU device [23] -Reliable Peer-to-Peer connectivity
<b>700 MHz ITS Band</b>	-Offers better channel access for infrastructure nodes → suitable for infrastructure-assisted V2P [22]	-Path Loss characteristics make it suitable only for urban environments [38]	-Follows the Japanese ITS standard [22]
<b>802.15.4</b>	-Low cost due to lack of need of vehicle sided equipment [39] -Scalable due to lean protocol model [39]	-Limited range (80 m) in NLOS scenario [22, 39] -Additional tag device carried by pedestrians [39]	-Directional antenna can extend range to 200m [39]

and 5G technologies will further accentuate the superiorities of cellular v2p systems over their counterparts due to advantageous bitrate, bandwidth and mobility support [30], [31], [32], [33]. However, research in [34] suggests that DSRC outperforms Cellular technology in terms of latency requirements, particularly in stressful traffic contexts of urban scenarios. Table 2 presents a comparison of the different technologies used in V2P design.

### C. SURVEY OF V2P PROJECTS

Multiple initiatives have endeavored to implement V2P communication, manipulating the interplay of different parameters toward overcoming potential challenges. P Safety [39] is a system that leverages mobile phone GPS to alert drivers of pedestrian position and uses Sector Overlap Detection Algorithm (SODA) to overcome GPS positioning inaccuracies using a threat ranking method to evaluate the degree of risk, with the result of giving the driver 3-4s of warning before collision happens. In [40], a system geared towards

the safety of cyclists at intersections uses 5G V2X technology for the vehicle and IEEE 802.11g WLAN at the cyclist's end. The authors of [41] created a system that uses cellular communication (FOMA) to exchange data in the wide area, and WLAN to exchange information between the driver and the pedestrian, attempting to reduce collisions at intersections. The system obtains location information of drivers and pedestrians, estimates risk, and sends a subsequent response to make a high-risk pair exchange information directly. In [24], a DSRC based system that includes a smartphone based pedestrian distraction monitor was implemented, as well as a classifier of motion states of the pedestrian for additional context information. Furthermore, path prediction modules for both the vehicle and the pedestrian were executed in tandem to suppress false alarms and hence reduce network congestion. The endeavor of [42] includes three approaches of communication that are implemented and comparatively analyzed: existing cellular networks (GSM, EDGE, UTMS), infrastructure-less ad-hoc communication (WLAN, 802.11p)



TABLE 3. Survey and comparison of V2P projects based on design parameters.

Paper	VRU Type			Technology					VRU Device		
	P	C	MTW	RFID	DSRC	Cell.	WIFI	Specification	Phone	Tag	iBeacon
Fackelmeier [37]	✓			✓				RFID Transponder		✓	
SafeWay2School [51]	✓			✓				RFID TAG		✓	
Biebl et al. [52]	✓	✓		✓				RFID TAG		✓	
VizableZone [53]	✓			✓				N/A	✓		
Honda [54]	✓		✓		✓			N/A	✓		
Telstra and Cohda [55]	✓	✓				✓		4G	✓		
Wu et al [24]	✓				✓			IEEE 802.11p	✓		
V2ProVu [15]	✓						✓	IEEE 802.11g	✓		
Sugimoto [56]	✓	✓				✓	✓		✓		
WIFI Honk [35]	✓						✓	WIFI Beacon	✓		
WiSafe [47]	✓						✓	IEEE 802.11a/b/g/n	✓		
Audi [57]	✓	✓					✓	IEEE 802.11 b/g/n	✓		
Lee et al. [58]	✓				✓			IEEE 802.11p	✓		
David [43]	✓					✓	✓	N/A	✓		
Zadeh [59]	✓					✓		4G	✓		
pSafety [40]	✓					✓	✓	N/A	✓		
Artail [60]	✓				✓	✓		IEEE 802.11p	✓		
Nakanishi [61]	✓						✓	N/A	✓		
Bagheri [46]	✓					✓		N/A	✓		
Bagheri [62]	✓					✓		N/A	✓		
V2P Sense [63]	✓					✓		N/A	✓		
LP <sup>3</sup> S [39]	✓			✓				802.15.4		✓	
General Motors [64]	✓	✓					✓	WIFI Direct	✓		
Fujikami et al. [49]	✓						✓	N/A	✓		
Liu et al. [65]	✓						✓	N/A	✓		
Hussein et al. [66]	✓					✓	✓	N/A	✓		
Merdrignac et al.[48]	✓						✓	IEEE 802.11g	✓		
POFS [67]	✓					✓	✓	N/A	✓		
Tahmasbi et al.[21]	✓				✓			IEEE 802.11p	✓		
Ko-TAG [68]	✓	✓		✓				RFID Localization		✓	
Nagai et al. [69]	✓							700 MHz ITS	✓		
C-AEB [70]		✓			✓			IEEE 802.11p	✓		
Thielen et al. [41]		✓			✓		✓	IEEE 802.11p	✓		
Hernandez et al [71]		✓			✓	✓		IEEE 802.11p	✓		
MotoWarn [72]		✓	✓		✓		✓	+Bluetooth			✓
Maruyama et al. [73]			✓		✓			N/A			✓
Redeye [44]			✓				✓	N/A	✓		
Tome B2V app [74]		✓						+Bluetooth			✓

Key: P: Pedestrian C: Cyclist MTW: Motorized Two-Wheeler Cell.: Cellular

and a hybrid of both. Communication exists between three entities (driver, pedestrian, central server) and the different approaches were evaluated based on energy consumption, agility, reliability and cost. It was found that a hybrid solution can choose the most appropriate combination of communication methods based on situational context. They also used additional context information (age, personal profile, movement patterns) to create an intelligent filter for more

accurate collision estimation. However, they worked under the assumption that the GPS-provided information on pedestrian and vehicle position is of sufficient accuracy. In [35], functionality in high mobility environments was achieved by mitigating the overhead association delay of legacy WIFI technology by the use of beacon-stuffed location, speed and direction information exchange. The authors of [43] proposed a scooter collision avoidance system that identifies Red Light

Runners (RLRs) using smartphones of scooter riders as a data source for a classifier that predicts their motion patterns accordingly, it achieved 10% less success than conventional LOS LADAR technology but came at substantially reduced implementation cost. A cluster based architecture that uses WIFI peer-to-peer channels in cluster formation and LTE channels for the transmission of cooperative awareness messages (CAMs) was proposed in [44]. The clustering algorithm was applied to reduce WIFI channel interference, geared towards collision reduction at intersections; and adaptive beaconing was proposed to dynamically reduce the number of generated CAMs while still preserving applicability to safety applications, with the condition that the system can quickly react to radio shadowing. In [45], a cellular based adaptive multi-level approach that switches between energy saving mode in risk free environments and normal mode otherwise was implemented, facilitating cloud based computations using central servers. The fact that beacon messages are treated differently than regular messages was leveraged in [46] to create a smartphone-based 600m range, 300 ms latency system that works without modifying the Android source code, with better penetrability than DSRC since it operates in both 2.4 and 5 GHz bands. An interesting combination of LOS and NLOS approaches was offered in [47], where multi-hypothesis tracking was applied to create a probabilistic association between perception and communication; at the vehicle's end, perception via laser tracking is applied to detect and classify road obstacles, while the VRU transmits GPS location via WIFI. Other efforts include the endeavor in [48] to achieve fast device discovery in WLAN using collective scanning and extension receiving, as well as high precision pedestrian positioning in [49] by using vehicles as anchors besides satellites and tracking the temporal change of channel state information (CSI) to better estimate signal radiation angle. Table 3 summarizes and compares the different V2P Design efforts surveyed based on three design parameters: VRU type, used technology, and VRU device.

### III. CHALLENGES IN V2P SYSTEM DESIGN

Despite the many challenges of including VRUs in CITS [74], there have been efforts to optimize various aspects of VRU design to overcome these challenges, some of which are outlined next.

#### A. CONTEXT INFORMATION EXCHANGE

In the context information exchange, fundamental VRU metrics like position, direction and speed are relayed to vehicle drivers via beacons transmitted at regular intervals [75], [76], [77] in order to feed subsequent collision detection algorithms [78], [79], [80]. However, they were thought to be insufficient by [81] and [82] and beaconing further information to increase the accuracy of predicted results was proposed in [78] and [83]. Such additional information includes: weather conditions, age of VRU, time of day [58], Degree of Risk: Approaching Road, Crossing Road, Near Vehicle [21], VRU Distraction Level [24], VRU Activity: Stopping,

Walking, Crossing Curb [78], [83], [84] using sensors on VRU devices [20], Surrounding Environment: Indoor, Outdoor, In Vehicle [77].

Estimating position and direction from smartphone sensor data is a simple enough task [24], [81], however, more complicated information like motion states and VRU activities require much more substantive processing of data including preprocessing, feature extraction and machine learning model training [85], [86]. Limitations to context information exchange include cost and impact on battery life [29]. Some researchers as in [21] only consider cases where computations are performed locally rather than offloaded. This is discussed in further detail in the following subsection. However, the authors in [29] suggested that beaconing frequency could be adaptively varied to accommodate different levels of risk, which would mitigate the adverse effects of excessive unnecessary beaconing.

#### B. PRECISE PEDESTRIAN POSITIONING

Since most VRU applications depend on smartphones to act as the VRU device, it is necessary to factor into account positioning inaccuracies of smartphones of up to 3-10m. However, many efforts such as [15], [24], and [46] did not take this into account. Both academia and industry have a vested interest in pursuing the development of smartphone positioning accuracy due to its mass market applications that include geo-surveying, lane-level mapping and traffic monitoring.

Smartphone positioning inaccuracies could be primarily attributed to multipath effect [87], efforts against which include hardware efforts and software efforts. Hardware efforts, like optimal antenna site selection and receiver technology, are less popular due to high installation costs and implementation difficulties [88]. Alternatively, multiple efforts have been directed towards filter based approaches to counteract multipath effects, including wavelet filter [89], [90], [91], [92], Vondrak filter [93], Adaptive filter [94], Particle filter [95] that used the Monte-Carlo method as a basis to achieve sequential importance sampling. Other than multipath, errors in distance estimation may grow to environmental factors such as signal noise and attenuation [67]. An attempt to use smartphone sensors to improve positioning accuracy was carried out in [32] and achieved sufficient longitudinal accuracy but deviated too much laterally to satisfy lane-level localization requirements.

3D Localization is an open area for future research [22] and is necessary to avoid false positives in scenarios where pedestrians are crossing the street using an overhead bridge for example.

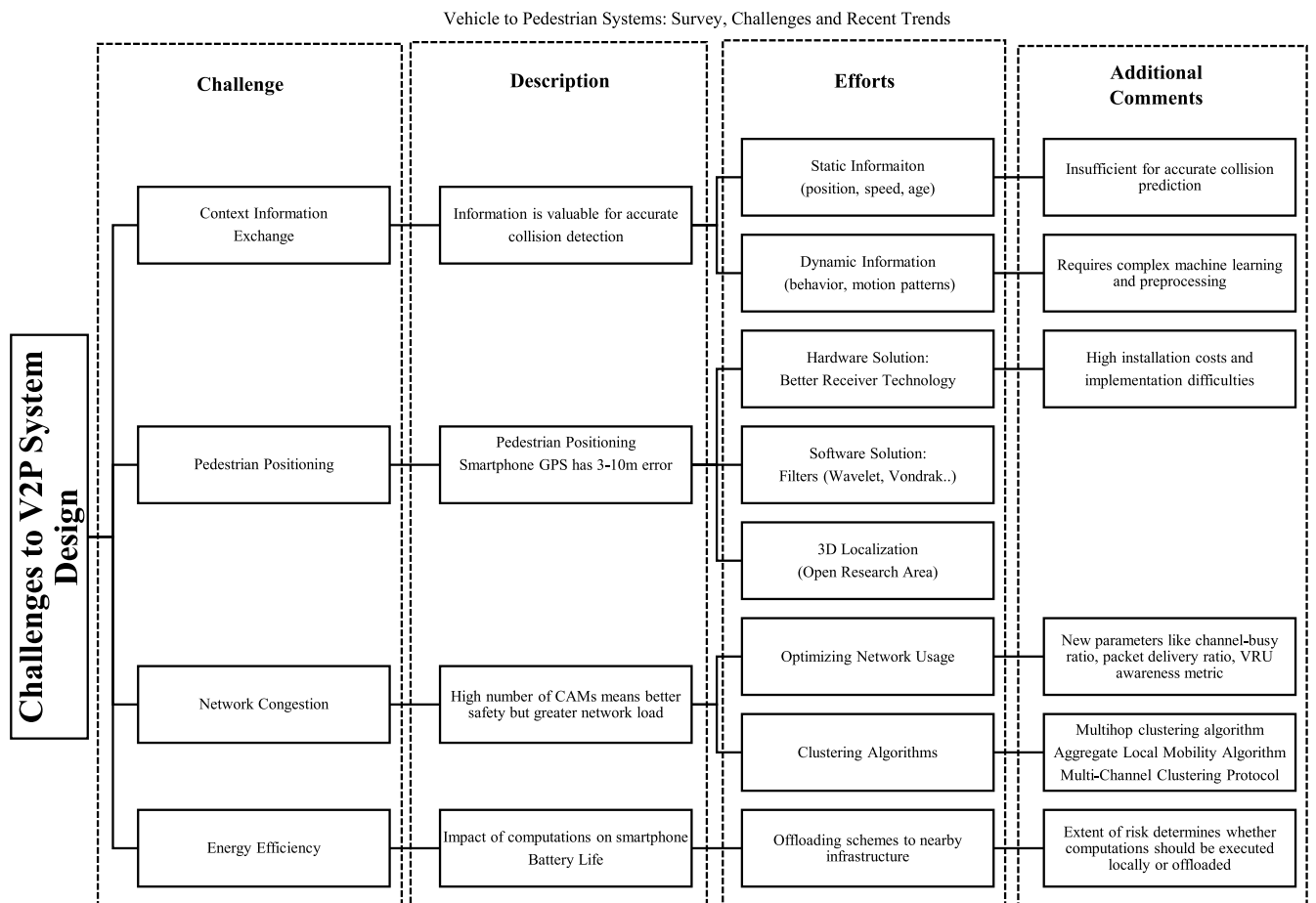
#### C. NETWORK CONGESTION

There is a clear tradeoff between VRU safety and network congestion, manifest particularly in locations with high population density, where networks could get overloaded with warning messages that are not strictly necessary. Multiple efforts have sought to evaluate and optimize network

usage, including authors of [96] who evaluated channel busy ratio, packet delivery ratio and introduced the VRU awareness metric. Furthermore, different clustering algorithms were proposed by [97], [98], [99], [100], [101], [102], and [103] with varying applications as well as communication technologies. In [104], clusters are formed near intersections whereas efforts in [105] were more directed towards highway scenarios. Wireless Access Vehicular Environment(WAVE) architecture was the adopted technology in [106], whereas in [44], Channel Heads used LTE and Channel Members communicated inside the cluster via WIFI. In [104], Channel Heads estimate vehicle density and send information to infrastructure nodes for efficiency purposes. Reference [107] adopted a multi-hop clustering approach wherein the use of WAVE architecture for intra-cluster communication was combined with cellular technology for communication between Channel Heads and surrounding infrastructure nodes. Reference [108] improved cluster stability by using the Aggregate Local Mobility (ALM) algorithm to delay the status change of Channel Heads and Channel Members. Finally, the authors in [109] used a multi-channel clustering protocol for better throughput and real time delivery.

**D. ENERGY EFFICIENCY**

From amongst the solutions proposed to solve the problem of VRU detection and collision avoidance, few considered impact on battery life [29]. The issue of optimizing energy efficiency has led many researchers [110], [111], [112], [113], [114] to come up with offloading schemes so that some/all calculations are off loaded to nearby infrastructure, unlike [24] and [77] in which all computations are assumed to be done locally. Increasing beaconing frequency only in high risk situations, as well as a central cloud solution were presented in [45], while a micro cloud solution was suggested in [115] and [116]. The authors in [29] proposed offloading either context-awareness-related calculations, or collision-detection-algorithm calculations or both, depending on the risk of the situation. They proposed a heterogeneous scheme whereby computations are performed locally in high-risk situations to minimize latency, regardless of energy consumption. In lower risk situations, they offloaded one or both phases of calculations to optimize energy consumption. In Figure 4, a summary of the different challenges and proposed counter measures is illustrated.



**FIGURE 4.** Challenges to V2P system design.



#### IV. RECENT TRENDS

In this section, we survey thirty articles published between 2019 and 2022 to analyze the recent trends in the emerging field of V2P system design.

##### A. SURVEYS

Since this is a relatively new field, with extensive areas of open research, it is important to first draw the attention to the most recent survey papers in the field, as this is where any aspiring researcher should start. However, one potential challenge they would face is that different papers use different terms with overlapping definitions. In [117], a literature-based taxonomy was proposed with the aim of separating different categories of VRUs in a structured manner. This taxonomy is based on two conceptual hierarchies that facilitate a uniform comparability of different terminologies used in the field of V2P applications. It is particularly but not exclusively geared towards facilitating a better understanding the communication between VRUs and automated vehicles. Beyond the taxonomy we classify surveys into scheme-based surveys and technology-based surveys.

Scheme-based surveys include [118] wherein the authors discussed various issues related to V2P system design and also proposed a Mesh-Networking based Vehicular Ad-hoc system (MN-VAS). A survey of different V2P systems was also offered in [23] with the additional proposition of design recommendations for cellular V-2-VRU. Other extensive surveys include [119] and [22], with the latter's author offering distinctions between the approaches of V2P design that cater to different VRU groups under different precrash scenarios. Finally, a survey that focused on pedestrian-to-vehicle (P2V) systems was presented in [120] along with a literature review of methods of pedestrian localization and movement prediction.

Technology-based surveys include [1] wherein the authors reviewed aspects of 3GPP 5G-based cellular system architecture. In [30], a particular emphasis was placed on the interaction of Internet of Vehicles (IoV), 5G standards, and Cellular vehicle-to-everything (C-V2X) communications. The authors of [34] surveyed the IEEE 802.11p technology in the context of its adoption in intelligent transportation systems, both the Medium Access Control (MAC) and Physical (PHY) layers were analyzed in the DSRC environment. Finally, in [28] an emphasis was placed on the latest versions of IEEE and 3GPP technologies, which are IEEE 802.11bd and NR V2X respectively. These technologies were comparatively evaluated to their respective predecessors in terms of their ability to support autonomous-vehicle applications in terms of reliability, latency and throughput requirements.

##### B. V2P SCHEMES

The most recent C-ITS schemes presented include [121] wherein the impact of reconfigurable virtual surfaces used to coat buildings and roads (meta-surfaces) was investigated on a DSRC-based communication system. Another scheme

that attempts to replace the vehicular OBU with a smartphone was proposed in [122] where a smartphone app was used to collect sensor data like GPS, accelerometer, gyroscope) to be used in conjunction with camera-collected data about the length in intersections. In this system, data is uploaded to a cloud server with low latency which validated the feasibility of replacing the vehicular On-Board Unit (OBU) with a smartphone. A cost-effective scheme targeting the implementation of ITS in developing countries was proposed in [123] where drivers' awareness is augmented by a WIFI network between drivers, with an algorithm to ignore beacons that do not contribute to situational awareness. In our earlier work in [125], a lightweight collision detection algorithm was proposed as part of a DSRC-based communication exchange between vehicles and VRUs (via smartphones) with simple and efficient mathematical operations used to verify potential collisions. Finally, the authors of [125] devised a means of aiding visually impaired pedestrians in the absence of auditory signals at road intersections. The system consists of a mobile app that connects with vehicle-mounted external speakers that emit acoustic chirps that are inaudible to the human ear but detectable by the app. The app then tells the pedestrian when it would be best to cross the road.

##### C. SOLUTIONS

As outlined in the preceding section, challenges to V2P system design include network congestion, context information exchange, pedestrian positioning and energy efficiency. Recent efforts involve both analytical investigations and practical solutions to these problems, to be outlined next.

To address the problem of network congestion, four different algorithms were proposed in [126] to reduce unnecessary alerts to VRUs. In [127], the authors proposed a model for a dedicated channel for V2P communication in critical scenarios. Furthermore, a method was proposed in [128] to predict the performance of CITS in dynamic vehicular networks, in a preemptive attempt to tackle deployment problems. The method is based on the analysis of existing/estimated vehicular traffic to ascertain the success of the underlying algorithms of the CITS application. Finally, the authors in [96] sought to quantify VRU awareness in the context of the tradeoff between VRU safety and network congestion depending on the sampling frequency of VRU alerts. They developed a new metric: VRU awareness probability (VAP) which uses the exchange of messages from active VRUs to estimate the probability of detection by nearby vehicles.

To address the problem of pedestrian positioning, the authors in [49] used vehicles as anchors besides satellites, to overcome GPS-related inaccuracies. They also developed a method to estimate the angle of signal radiation by tracking the temporal change in Channel State Information (CSI). Their method requires one antenna on the VRU device (as opposed to eight, conventionally) and achieves better accuracy. The authors in [129] use a Kalman filter to reduce GPS error. In [16], a virtual cycling environment was created to facilitate the study of cyclists' behavior without putting

TABLE 4. Recent trends in V2P systems.

Category	Sub-category	Title	Description	Ref.
Surveys	General Surveys	Literature-based taxonomy	Primarily supports relationship between VRUs and Automated Vehicles	[118]
	Surveys of V2P Schemes	Survey of P2V Systems	Focuses on pedestrian localization and motion prediction	[121]
		Survey of V2P Systems	Proposed mesh network based VANET (MN VAS)	[119]
		Survey of V2P Systems	Proposes design considerations for cellular V2VRU Communication	[23]
		Survey of V2P Systems	Highlights technical gaps and points out future directions	[120]
		Survey of V2P Systems	Focuses on systems that use cellular communication	[135]
		Survey of V2P Systems	Compares different VRU groups in different precrash scenarios	[22]
	Surveys of V2P Technologies	Survey of 5G Evolution	Focuses on interaction between IoV, 5G and V2X	[30]
		Overview of IEEE 802.11p	Focuses on implementation in ITS setting	[34]
		Survey of IEEE and CV2X	Focuses on standardization of 802.11bd and NR-V2X	[28]
Survey of CV2X		Reviews system architecture of 3GPP 5G Technology	[1]	
Proposed Schemes	IEEE 802.11p	Simulates IEEE 802.11p with meta-surfaces	[122]	
	IEEE 802.11p	Lightweight collision detection algorithm	[125]	
	System for P2V and I2V	Replaces OBU with smartphone and cloud server	[123]	
	Visually impaired pedestrians	Accoussist app to enhance auditory warnings	[126]	
	Augment Drivers' awareness	Cost effective for developing countries	[124]	
Analysis and Solutions of System Aspects	Networks	Network Analysis	Predicting behavior of CITS in dynamic VANETs	[129]
		Network Analysis	Quantifies VRU awareness using VAP metric	[97]
		Network Analysis	Developed channel model for V2P system emergencies	[128]
		Reducing Congestion	Developed 4 algorithms to reduce unnecessary VRU alerts	[127]
	Pedestrian Positioning and Motion Estimation	Improving Positioning	Uses vehicles as anchors in addition to satellites	[50]
		Improving Positioning	Uses Kalman Filter to improve positioning	[130]
		Motion Prediction	Uses Machine Learning techniques to predict motion	[132]
		Analysis of cyclists behavior	Created a virtual cycling environment	[16]
		Analysis of pedestrians' behavior	Uses machine learning to distinguish between normal and aggressive pedestrians	[131]
	Context Information Exchange	MEC	Improved latency and energy efficiency	[29]
		MEC	Uses machine learning to determine pedestrian activity	[112]
		MEC	Designs and evaluates new MEC architecture	[113]
		Vehicular Cloud	Data management using micro and macro clouds	[117]
		Analysis of delay of context-information exchange	Uses curb detection module to improve Collision Detection Algorithm	[133]
	Security	Protecting VRU privacy	Architecture based on machine learning to facilitate analysis of big data in a secure environment	[134]

actual volunteers at risk; then they used the data in a VANET simulation. Pedestrian behavior was studied using Machine Learning in both [130] and [131]. In the former, the aim was to be able to distinguish normal pedestrians from aggressive pedestrians using decision tree classifiers in the presence of a server and four standard classifying vectors in the absence thereof. The authors of the latter dealt with movement prediction as a classification problem and used two classification paradigms: the simple support vector machine with a linear kernel and the more complex XG Boost classifier.

Context information exchange is an essential component of V2P systems, however, delays in this exchange can significantly affect the performance of collision detection algorithms (CDAs) as outlined in [132]. The authors investigated this relationship and designed a curb detection module to

improve collision detection accuracy at the moment the pedestrian crosses the curb. The tradeoff between latency and energy consumption with regards to context information exchange was investigated in [29], [111], and [112] which used Multi-access Edge Computing (MEC) to improve energy efficiency by computational offloading to cloud servers in less critical situations. These efforts facilitate the use of a smartphone as an OBU without overexerting its limited battery capabilities.

Finally, while the topic of VRU privacy and data protection is significantly important, it is beyond the scope of this paper. However, we briefly outline one effort in [133] where authors used machine learning classifiers to create an architecture for big data processing in a secure environment. Recent trends are summarized in Table 4.

## V. CONCLUSION AND FUTURE WORK

Traffic accidents are a consistent tragic reality of the contemporary world. While numerous endeavors have strived to mitigate the casualties of such accidents, they still remain to be a significant contributor to global fatalities every year. There is a growing interest in the involvement of pedestrians as subjects in the research field of collision prevention, using vehicle to pedestrian (V2P) communication. In this paper, we provided an extensive survey of previous efforts in V2P systems design. We first categorized various architectures by different design criteria, such as the type of VRU device, the technology used and whether VRU is a pedestrian, cyclist or MTW. We compared the different technologies used in system design and highlighted their relative advantages and disadvantages. We surveyed previous efforts based on the aforementioned design criteria. We highlighted the main challenges of V2P system design and discussed the solutions and efforts geared towards overcoming these challenges. Finally, we presented a survey of the most recent trends in V2P system design to pave the road for future research.

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