V2X-Equipped Smart Intersections – Survey of Surveys, Use Cases, and Deployments

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***Abstract*—The interaction between Vulnerable Road Users (VRUs) and smart intersection participants, such as vehicles and drivers in Cooperative Intelligent Transportation Systems (C-ITS), is one of the main tools in solutions for increasing road safety and minimizing the number of possible road accidents. Vehicle-to-Everything (V2X) communication of advanced C-ITS architectures includes Vehicle-to-Pedestrian (V2P) context for extensive information exchange between road users. V2P employs various direct, indirect, and hybrid communication technologies and uses different techniques to interact with multiple traffic participants, infrastructure, traffic light controllers, and especially VRUs, during unpredictable situations. To address emerging technologies and applications of collaborative smart intersections and explore novel C-ITS solutions designed for this domain, the paper analyses available surveys and introduces the relevant communication schemes, use cases, and recent deployment efforts.**

***Keywords*—V2X, V2P, C-ITS, smart intersection, VRU protection**

I. Introduction

Pedestrians, cyclists, and motorcyclists are known as Vulnerable Road Users (VRUs) in C-ITS terminology. Pedestrians could be children, older and disabled people with a typical walking speed of 1.4 m/s (5 km/h). There is a risk of pedestrians, particularly children, stepping suddenly into the road intersection, which might lead to accidents and require close attention from the drivers of the vehicles on the way. Cyclists and motorcyclists travel at the usual speed of about 4.2 m/s (15 km/h) and 14 m/s (50 km/h), respectively. They are traveling as individuals or groups in a line following each other. Cyclists are more vulnerable on roads because of the difficulty of detecting them, e.g., in the case of junctions, roundabouts, overtaking, and intersections [1].

Moreover, more traffic participants could belong to the group of VRUs classified as road users with personal conveyances, like roller skates, inline skates, skateboards, motorized skateboards, baby strollers, scooters, and motorized and non-motorized wheelchairs for those with disabilities. Report [2] about traffic safety facts data shows that the number of fatalities in users with personal conveyances increased between 2009 and 2018. Moreover, scooter, roller, and cruiser renting and sharing companies have gained momentum and spreading urban areas recently due to positive economic and environmental impact [3].

According to World Health Organization (WHO), the global status report on road safety related to road accidents, the number of road traffic deaths continues to grow. Road traffic crashes now represent the eighth leading cause of death globally, with more than 1.35 million lives each year and causing up to 50 million injuries. According to the report, road traffic incidents have become a leading cause of death for children and young adults between 5 and 29 years of age. The report shows that more than half of global road traffic deaths are amongst pedestrians, cyclists, and motorcyclists, who are still too often neglected in road traffic system design in many countries without considering the value of adding a safety feature for VRUs.

Moreover, a study from WHO about cyclist safety shows that every year, 41 000 cyclists die in road traffic-related incidents worldwide, representing 3% of global road traffic deaths. The report mentions risk factors for cyclist-related injuries and fatalities: speed of motorized vehicles sharing the roads with cyclists, cycling against the traffic, lack of visibility, and non-use of bicycle lights. The report emphasized that Vehicle-to-Everything technologies and smart intersections are proven promising inventions for safer roads with considerable challenges due to increasing road accidents [4].

V2X enables the vehicles to communicate with other vehicles and the surrounding environment to transmit information to each other, such as the position of VRUs in blind spots and the speed of surrounding vehicles. V2X aims to add safety features on the road to prevent traffic incidents and build a safer and smarter road environment. V2X encompasses communication contexts such as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P). V2P can enable safety and convenience for VRUs, making them an essential part of C-ITS applications and the overall ecosystem.

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A smart intersection – as depicted in Fig. 1 combines vehicles, pedestrians, and infrastructure elements (e.g., traffic lights) that are able to communicate and cooperate to improve safety and traffic efficiency. Smart intersections contain various technologies such as the broadest scale of sensing solutions (camera, RADAR, LIDAR, etc.), decision support, and traffic management engines, or even with V2X by directly using V2P, indirectly using V2I or hybrid communication schemes. The general enhancement of road safety and VRU safety can be achieved with smart intersection solutions. Still, it also leads to challenges associated with the VRU integration in the V2X road environment.

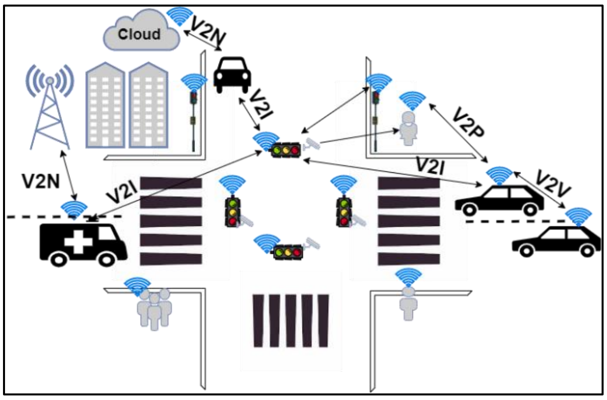

Figure 1. Generic components of V2X-equipped smart intersections.

Smart intersections can communicate by vehicular communications, which empowers vehicles equipped with advanced communication technologies to assist VRUs and vehicle drivers in potentially dangerous traffic scenarios, such as crossing at a red light or a stop sign and pedestrian crossing. Smart intersections can use various technologies for data exchange, such as Wi-Fi and cellular communication, positioning/localization solutions, and digital maps to transmit all the relevant information to surrounding VRUs and vehicles, then channel them into prediction and decision engines. Once the in-vehicle computer receives the data sent by the smart intersection and detects a potential hazard, it can rapidly warn the driver through visual or audio warning alerts [5].

The integration and combination of various V2X communication technologies in intelligent intersections enable a sustainable and enhanced infrastructure for traffic systems and foster connected driving to reach an accidents-free future. In its present state, V2X technologies are implemented as passive warning systems, such as show warnings to vehicle drivers; however, V2X-equipped smart intersections could support active safety technologies such as automatic braking or lane-change assist as well.

This paper surveys and introduces the smart intersection research efforts related to the V2X communication domain. We highlight current state-of-the-art V2X-equipped smart intersection technologies, applications, and deployments. Section II introduces existing surveys and highlights major gaps and missing points. Section III describes generalized use cases of V2X-equipped smart intersections andpresents our survey in addition to the comparison table for the intelligent intersection effort research papers in terms of technologies and conclusions. Moreover, Section III introduces relevant deployment projects of V2X-equipped smart intersections. The paper concludes with a summary of our key findings in Section IV, where the potential directions of our future research are also drawn.

II. Survey of Existing Surveys on Smart Intersections

Intelligent Transportation Systems (ITS) generally aim to provide a safer, more competent, and more efficient traffic environment. Smart intersections are one of the promising and most challenging research topics in the ITS development domain. There are available survey papers in the literature related to advanced intersection schemes/technologies without or only partly relying on V2X technologies.

An enormous number of papers related to the intersection management of Autonomous Vehicles (A.V.s), and their potential to enhance safety and mobility in the future. Those researches presented a survey of studies related to vehicle detection and tracking in intersection scenarios [6]. Xie and Wang introduced a broad survey of intelligent in-vehicle decision support systems for driving at signalized intersections with V2I communication [7]. Moreover, Kalantari *et al*. presented a distributed, collective intelligence framework for collision-free navigation through busy intersections [8]. Furthermore, the paper includes results from other articles related to the driving behavior of A.V.s. Also, Pereira *et al*. present a review of automated vehicles in intelligent urban environments [9]. The survey paper [10] summarizes the developments and research trends in the coordination of connected and automated vehicles at intersections. The introduced comparison tables highlight the specifics of centralized and decentralized coordination control. The papers collected review smart intersection solutions with A.V.s, collision avoidance, and smart traffic lights at smart intersections. The presented results show that the adoption of A.V.s significantly increased during the last decade. Those focused on collision avoidance and smart traffic lights expected that smart intersections would primarily reduce accidents and increase traffic efficiency and congestion. The papers show that integration and compatibility with other road users, such as VRUs, will be a valuable improvement for A.V.s adoption, collision reduction, and traffic safety. However, it is also concluded that smart intersections require a high cost of implementation and maintenance. Moreover, smart intersections with smart traffic lights depend ultimately on accurate real-time traffic data for predictive analytics.

Another type of research and survey focuses on collision avoidance at intersections and on how to implement methods and algorithms to guarantee a collision-free and safe traffic system. Example proposals can be found in articles [11] and [12]. Also, Vaishali

Jeyapriya presented a survey on intelligent systems for automobile collision avoidance at road intersections [13]. Moreover, a model is designed to find safe gaps in the crossing traffic and create optimal trajectories. The authors provided surveys on artificial intelligence and probabilistic collision detection to create efficient decision-making algorithms for collision avoidance at intersections [14, 15].

Extensive research efforts on developing traffic light/traffic control systems exist that enable the deployment of smart traffic light technologies. These efforts include several aspects, such as vehicle and pedestrian detection, public and emergency vehicle approaching, and adaptive scheduling algorithms. The authors comprehensively reviewed existing intelligent traffic light techniques and technologies to reduce traffic density and detect emergency vehicles [16, 17]. Moreover, in the paper [18], the authors presented the challenges researchers must overcome in traffic light recognition (TLR) research. Also, the authors presented a survey on techniques and methodologies for intelligent traffic light design and control in smart cities, such as smart traffic light control and traffic density calculations [19].

TABLE I. EXISTING SURVEYS ON SMART INTERSECTIONS

Existing Surveys on Smart Intersections	Reference papers	Technology	Presented Results
Smart intersections with A.V.s	[6–10]	Autonomous vehicles	• Facilitate A.V.s to navigate intersections safely. • Compatibility requirements are needed with other road users, such as VRUs protection models, to increase the safety of all road participants. • Integration possibility with other technologies such as smart parking and public transportation. • Adoption level of A.V.s in the given environment increased.
Smart intersections and collisions avoidance	[11–13, 20]	Advanced sensors (RADAR, LIDAR) and Cameras.	• Collisions are reduced, and traffic flows are optimized at intersections. • High cost of installation and maintenance with sensors and camera equipment. • Sensors and camera accuracy and reliability improvement as a requirement. • Accidents and injuries at intersections were reduced significantly.
Smart intersections with Smart Traffic Lights	[16–19]	Smart traffic lights and communication systems	• Congestion and waiting times were reduced at intersections. • Dependence on accurate real-time traffic data is a big challenge. • Predictive analytics requirement for more efficient traffic flow. • Machine learning algorithms and techniques enhanced traffic signal timings, optimized traffic flow by changing traffic conditions, and predicted traffic patterns.

The collected and analyzed papers in this section (see Table I for a summary) include two types. We covered articles entirely focusing on a survey related to one or more aspects of the smart intersection domain, and we also introduced papers that included only subsections related to reviews or surveying papers on their topic. However, a thorough and focused survey on V2X-equipped smart intersections is still missing in the available literature. Our article tries to fill this gap.

III. V2X-EQUIPPED SMART INTERSECTION USE CASES, RESEARCH AND DEPLOYMENT EFFORTS

A. *V2X-Equipped Smart Intersection Use Cases*

Nowadays, development is turning everything around to be "intelligent," such as smart cities and smart homes. Traffic intersections are good examples of this trend, where safety is expected to be the major added value of the implemented intelligence. Integrated with other technologies, V2X communication helps to achieve safer road environments: applying V2X-based cooperation at the intersections and with road users will enable the detection of moving entities and events around pedestrians and vehicles, support the avoidance of potential accidents and collisions, and enhance traffic flow.

V2X-equipped smart intersections rely on different communication patterns such as V2P, V2V, and V2I, forming several use cases and application possibilities. One of the critical components of prioritizing and categorizing smart intersection use cases is understanding the goals, the actors, and their interoperation together with the potential barriers or challenges. The below sections introduce the primary groups of V2X-equipped smart intersection use cases we identified based on the above parameters.

1) Smart intersections for VRU protection

Vulnerable Road Users (VRUs) such as pedestrians and cyclists are exposed to vehicles at traffic signal intersections. Smart intersections could form a protection system consisting of infrastructure solutions such as roadside units (RSUs) and road user communication devices such as smartphones to detect VRUs and avoid potential accidents [21]. This protection system uses V2X-equipped vehicles to receive data from pedestrians about their movement by mobile devices with Global Navigation Satellite System (GNSS) and Wi-Fi capabilities. RSU units collect the data, predict the potential collisions, and send a warning to affected VRUs via V2X messages. the authors presented a protection system that describes data collection, collision prediction methods, schemes for VRUs positioning improvement, and the estimation of impact on traffic performance [22].

Protecting VRUs is one of the most important and challenging goals. Available VRU protection solutions depend on active positioning approaches implemented by active tags, and personal smartphones help determine the position of road users in a particular area. Precise localization of pedestrians can be measured with, e.g., UAV cameras and Ultra-wideband (UWB) technology already available on smartphones and accessories [23]. Passive positioning is implemented by smart sensors such as cameras, lidars, and radars installed on roads and highways to identify, classify, and locate various objects on the way. These sensors communicate with RSUs to detect VRUs that are not connected with V2X technologies without using active tags or smart devices [24].

2) Smart intersections for vehicles

Internet of Things (IoT) solutions enable vehicular communication to connect vehicles, sensors, roadside infrastructure, and other elements in ITS environments. V2X allows vehicles to communicate directly with the infrastructure and other vehicles in an ad hoc network. Integrating smart intersections and connected vehicles in the joint IoT+V2X access domain will enhance traffic safety and efficiency by including traffic alerts for different cases such as emergency vehicles approaching, collision avoidance and crossing intersection warnings, traffic jams, lane changing, unexpected stop warnings, red light violation, pre-crash indication, etc. There are many research activities [25, 26] about integrating V2X and smart intersections from the vehicles' perspective to create ITS safety applications and enhance traffic efficiency.

A V2X-equipped smart intersection has many critical challenges concerning integrating connected vehicles, such as heterogeneous IoT devices and sensors available in various vehicles from different manufacturers. Communication systems requiring low power consumption capabilities with stable wireless links are mandatory to maximize sensor availability and data transmission throughput [27].

3) Smart intersections for road infrastructure

The advancement of road infrastructure intelligence is a fundamental component of intersection technology evolution. The integration of smart intersections and transportation infrastructure, in general, provides a more competent traffic environment. For instance, smart infrastructure collects detailed information about traffic conditions and the surrounding environment, such as weather conditions, faulty traffic lights, and roadside construction, enabling more efficient and organized intersection operation.

The required building blocks for intelligent road infrastructure integration with smart intersections include a coordinated and adaptive signaling system that enables smooth traffic flow along signalized corridors and adapts in real-time to changes and fluctuations under varying traffic demands. Smart road infrastructures include fiber optic-based and wireless communication networks, short-range V2X communication technologies for real-time data exchange between vehicles, smart intersections, and traffic management centers [28].

In addition, smart road infrastructures could contain high-definition Closed-Circuit Television (CCTV) cameras, lidars, and radars for monitoring the traffic environment, unique algorithms for detecting and identifying objects and analyzing movement patterns for vehicles and pedestrians. Also, Bluetooth-based or other smart detectors are available for VRU safety, such as for pedestrian detection, e.g., when they wrongly use the crosswalk within the intersection. Moreover, smart streetlights switching on and off according to activity and environmental conditions also belong to these infrastructures, where V2X plays an essential role in creating a cooperative level of dynamic interactions between road users and the different infrastructure elements [29].

4) Smart intersections for traffic performance

Smart intersections incorporate enabling technologies for smart traffic optimization schemes by integrating connected vehicles, intelligent infrastructure elements, and VRUs. Traffic performance is a critical challenge; therefore, use cases such as congestion avoidance [30], adaptive control [31], vulnerable road user detection [32], and emergency routing [33] are becoming more and more important. For instance, the authors in [34] presented two techniques to improve traffic flow and minimize the waiting time of emergency vehicles at intersections. These techniques, known as the pure operation mode and the hybrid operation mode, involve the use of a smart infrastructure system equipped with Internet of Things (IoT) technology to detect the approach of emergency vehicles. When an emergency vehicle is detected, the smart infrastructure system changes from the traditional traffic light system to a dynamic mode that prioritizes the movement of the emergency vehicle. V2X-equipped smart intersections enhance traffic performance by monitoring, detecting, and intervening, such as creating more efficient traffic management systems with dynamic adjustments, e.g., by deploying adaptive, traffic-aware traffic light control systems.

Smart intersections serving such use cases must incorporate traffic management software connected to a Traffic Management Center (TMC). This software is an integrated system for active traffic management to improve safety and traffic flow. TMC is usually a centralized computing unit for traffic management activities to process and respond to traffic demands on the roadway network. Traffic performance contains a signal priority system that modifies the timing of vehicles crossing through the smart intersection. The system should include emergency vehicle approaching priority and ensures emergency vehicles have the right to strike the way in emergency cases [35]. V2X is an essential input-provisioning infrastructure for the above systems' environment sensing and intervention procedures.

B. Research Efforts on V2X-Equipped Smart Intersections

Smart intersections are still mainly in the investigation and exploration stage because of their continuous evolution, deployment complexity, and potential issues in their applications. Table II below includes the most significant research efforts in the last ten years between 2012–2022 about a wide variety of intelligent applications and traffic management solutions with the integration of V2X-equipped smart intersections by presenting four thematic focus groups of related activities.

1) Focus group "1": Development of smart intersections

This focus group is about smart intersection research efforts in general. These efforts started with enhancing traffic management in intersections supported by V2V and V2I communications. An example is [36], where authors accurately proposed a system for speed profile calculation and dissemination along the way and even for vehicles not equipped with V2V and V2I communications to reduce the average time to cross intersections. Providing intelligent features for legacy road users is also an essential topic in [37]. In addition, the authors of [38, 39] define Vehicular Ad Hoc Network (VANET) communication schemes to mitigate and minimize transportation problems and congested roads.

Also, studies are available about the behavior of vehicles and pedestrians crossing smart intersections, such as in [40, 41]. In [42], new solutions were introduced for high-priority vehicles in intelligent traffic environments. Moreover, other research focused on enhancing traffic systems, such as in [43, 44], where a review of collision avoidance at intersections and intelligent traffic management systems is presented. In papers [45, 46], the authors present smart intersection control algorithms and intersection control schemes for automated vehicles. This is further extended by the authors of [47], describing an intelligent intersection management scheme for connected and automated vehicles and pedestrians. In [48], a smart traffic management system is showcased based on Vehicle to Infrastructure (V2I) communication technology to address road accidents and help traffic management optimization.

In [20], the authors introduce a simulation-based evaluation of a novel integrated intersection control scheme to improve connected automated vehicles' and pedestrians' waiting time. Moreover, in [49], intersection management for autonomous vehicles is simulated with V2I communication using a Simulation of Urban MObility (SUMO) based framework [50]. Furthermore, in [51], more studies and research results were presented regarding innovative intersection development, such as advances in smart roads for future smart cities. The authors contributed a distributed strategy for cooperative driving in multi-intersection road networks.

The collected papers for V2X-equipped smart intersection development conclude that the earliest efforts on enhancements in smart intersections were limited to creating simulations, algorithms, and schemes for vehicles passing the crossroads to enhance traffic safety and efficiency. After that, V2X communication technologies were implemented and provided advanced techniques such as V2V, V2I, and V2P technologies in addition to the cloud layer in traffic management frameworks. Then, with the development of vehicular technologies over time, researchers started to develop and design an entire traffic management concept with valuable features such as vehicles that can see behind the buildings and being more aware of traffic environments for VRU protection.

2) Focus Group "2": Smart intersections with the internet of things (IoT)

IoT and sensor technologies integration can handle different intersectional traffic issues and enable them to be smart with features as an essential component of future traffic control systems. IoT will provide more detailed information about the surrounding environment and traffic conditions such as weather, roadside construction, faulty traffic lights, or even accident warning services relying on, e.g., public Internet access. We consider IoT and mobile cellular data access solutions legacy V2I communication techniques.

Table II about the focus group "2" below shows enormous efforts try to integrate IoT and intelligent intersections. In [52, 53], authors introduced IoT applications and technologies used in smart intersections. Also, in [54, 55], a cognitive traffic management system (CTMS) is proposed based on the Internet of Things approach presented to enable smart traffic lights integrated into the IoT ecosystem and algorithms to reduce the average waiting time.

In [56], the authors presented an IoT-based dynamic road traffic management containing the design of an intelligent traffic signal system using cellular communication. In traffic management systems, a wide variety of IoT tools can be used, such as ultrasonic sensors and Raspberry Pi with Arduino Uno kit, as authors present in [57–61]. Most research in this focus group describes solutions on how the infrastructure interacts with vehicles, but efforts still do not usually cover pedestrians. In addition, the research results conclude that V2X-equipped smart intersections are the main component of a city-wide traffic system to achieve a complete answer for the identified challenges.

3) Focus group "3": Smart intersections with machine learning and image processing

Artificial intelligence and machine learning are vital technologies for creating advanced traffic management systems that provide valuable solutions for significant traffic issues and enable efficient use cases such as traffic congestion mitigation and accident avoidance with pedestrian detection. The efforts to enhance V2X-equipped smart intersection operations with the integration of machine learning techniques started with algorithms to improve traffic flow at the intersections, such as in the case of adaptive optimization of waiting times.

In [62] 2012, the authors introduced an intelligent traffic management system based on V2I communications using a fuzzy-based control algorithm of distance and speed adjustment for collision avoidance prevention. In [63], a genetic algorithm-based optimization, a machine learning method, is employed in the prototype for traffic optimization. In [64, 65], image processing techniques are used in an intelligent traffic control system. The articles conclude that V2X communication is a requirement to achieve traffic enhancement.

In [66, 67], intelligent traffic systems such as traffic light controllers using machine learning and agent-based simulation modeling with deep reinforcement learning for intelligent traffic signal control are considered. Then the research extends the paradigm to enable adaptive traffic systems, such as in [68], which introduced an adaptive control method of traffic signal-timing under emergencies for smart cities using different V2X communication technologies.

Machine learning and image processing research focus on improving traffic systems and creating new traffic applications, as presented in [69], where authors introduce the possibility of optimizing smart traffic lights to prevent traffic congestion using fuzzy logic. Moreover, the authors of [70] introduced a novel traffic management system using deep learning for smart city applications such as computer vision in detecting, tracking, and computing moving vehicles' velocity and direction. The papers presented that implementing sensors in intersections will enable V2I communication and enhance traffic performance.

4) Focus Group “4”: Smart intersections for traffic performance optimization

Traffic performance is the main challenge for modern metropolises. Researchers and institutions focus on improving traffic performance using congestion reduction, accident prevention, and providing safer roads. Traffic enhancement starts with detecting vehicles, improving intersection traffic lights, and controlling variable signs, e.g., for adaptive speed limitation.

In [71], the authors introduced intelligent traffic lights based on Radio Frequency Identification (RFID) with a violation detection system to race out the emergency and stolen vehicles. In [72, 73], the authors introduced automatic accident detection and security schemes for V2I networks. Then in [74, 75], the proposed traffic system focuses on a dynamic traffic light sequence control based on the traffic density to reduce accidents and congestion at the intersections. Moreover, new technologies implemented for traffic controllers mitigate road congestion using intelligent traffic management systems, as mentioned in [76].

Of course, research papers in the literature include a particular mixture of our identified four thematic focus groups. For example, in [77], the authors present an IoT-based model in smart urban traffic control using graph theory and a genetic algorithm with smart intersection implementation to find optimally directed graphs obtained using the genetic algorithm representing the vehicles' traffic model. Also, in [78], fuzzy expert systems (FES), artificial neural networks (ANN), and wireless sensor networks (WSN) are compared to get the best traffic routes based on real-time data.

In the last decade, the research on V2X-equipped smart intersections has demonstrated the potential of these technologies to significantly improve traffic safety and traffic performance optimization. Various research efforts focused on developing smart intersections, particularly integrating V2X communication technologies. The efforts have included the development of algorithms and schemes using machine learning and image processing techniques for improving the flow of vehicles through intersections, in addition to integrating IoT and sensor technologies to be more aware of the surrounding environment and traffic conditions.

Moreover, the research focused on using simulation and modeling to evaluate the performance of different intersection control schemes and develop intelligent traffic management systems based on V2I communication technologies. In addition, research also focuses on integrating vehicles into smart intersections, such as collision avoidance and the performance of different intersection control schemes. Currently, there is ongoing work to further develop and refine these technologies for use in real-world applications.

C. Deployment Efforts of V2X-Equipped Smart Intersections

1) C-Roads smart intersection deployments

C-Roads Platform deployment was triggered on Oct. 04, 2016, in cooperation between authorities and road operators from eight European countries. In 2017, C-Roads extended to cover sixteen European States linked to the deployment of EU-C-ITS platform activities for improvements in road safety, sharing experiences about deployment and implementation issues in addition to user acceptance. The idea behind C-Roads is to implement a concerted and harmonized approach of deploying C-ITS services across borders of European member states through national efforts using the feature of V2X communication technologies, such as vehicles and roadside infrastructure for handling the hazard situations and incidents on the roads [79].

C-Roads pilots focus on Day 1-services related to smart intersection deployments, such as intersection safety. Implementing C-ITS services such as signal violation (red-light violation) by another vehicle will reduce the collisions at the intersections by warning the drivers about the expected hazard. In addition, the V2I communication technology implementation between the traffic lights and onboard units will enable the vehicles to determine the optimal speed of crossing, and information such as time to green can be presented by Green Light Optimal Speed Advisory (GLOSA) service implementation [80].

The Czech Republic C-Roads pilot is an example of C-Roads smart intersection deployments. The pilot employs cities of Brno, Ostrava, and Pilsen, among the first European cities where C-ITS has been fully implemented, such as support railway level crossing signaling systems. Czech C-Roads pilot includes smart intersections implemented in 2019 and 2020 with a mission of vehicle drivers warning about the risk of collision with the passing tram or the pedestrians on the way near tram stations. Moreover, the pilot introduced Public Transport Preference (PTP) as a prioritization solution for public transport vehicles at the intersections using a light signaling device with ITS-G5 technology. The light signaling device detects public transport vehicles and triggers a signal modification request for this purpose [81].

2) Connected vehicle test bed smart intersection deployments

California of Connected Vehicle Test Bed (California CV Testbed) is one of the smart intersections deployments consisting of 31 intersections equipped with V2I communications to support the operational environment between vehicles and intersections in Silicon Valley in Palo Alto. The deployment is about a test bed for road hubs that provides live data for signal adaptation and priority crossing management. California Partners for Advanced Transportation Technology (PATH) program fully manages and maintains the California CV Testbed.

The connected vehicle system contains On-Board Unit (OBU) on vehicles and RSU units at the roadside. The OBUs will send messages by using DSRC communication technology and communicate with themselves in the shape of V2V technology. Also, OBUs communicate with RSUs as infrastructure and then with existing traffic devices, such as signal controllers installed at the intersections. California CV Testbed intersections enabled with 4G/LTE backhaul connections to Traffic Management Centers (TMCs) [82].

As a next phase California CV Testbed, the California Department of Transportation (Caltrans) contracted the University of California Riverside to implement precision mapping for connected vehicles relying on intelligent intersections. The platform gathers positioning and mapping data using global positioning satellite (GPS) technology and (vision, RADAR, LIDAR) sensors to accurately provide the state of moving vehicles and surrounding areas. The collected data from many days will use as input for image processing algorithms and examination to create precise map information that can help traffic operators of these smart intersections to utilize the features for V2X applications [83].

There are smart intersection deployments from the different pilots similar to the California CV Testbed. They are fully managed by the Department of Transportation (DOT) and focused on safety features such as applications of VRU protection. The main deployments of this initiative are 1) New York City (NYCDOT) CV pilot, 2) the Tampa-Hillsborough Expressway Authority (THEA) CV pilot, and 3) the Wyoming Department of Transportation (WYDOT) CV Pilot. These deployments implement various V2V and V2I safety applications of smart intersections, such as Intersection Movement Assist (IMA) and Pedestrian Collision Warning (PCW). The deployments include vehicles that support DSRC communications, signalized smart intersections equipped with V2I communications, and RSUs. The primary purpose of these deployments is conflict reduction between vehicles and pedestrians through in-vehicle pedestrian warnings. In addition, pedestrians with personal devices are also involved in assisting with safe crossings of the street [84].

3) Virginia smart intersection deployment

Virginia Department of Transportation (VDOT) cellular V2X (C-V2X) deployment pilot was triggered in 2020 in cooperation with vehicle manufacturer Audi of America, Commsignia, Qualcomm Technologies, American Tower Corp, and Virginia Tech Transportation Institute (VTTI). The project focuses on C-V2X communication technology-based direct communication in the 5.9 GHz band and smart intersection deployment in Virginia roadways. The pilot aims to boost safety in different areas and intersections in Virginia by improving traffic performance and implementing safety applications. The VDOT C-V2X deployment will reduce the congestion at traffic intersections and deliver a warning about work zones on highways and signal timing information about traffic signals provided by intelligent intersections. Safety applications include warning vehicles about road conditions and communicating with pedestrians' mobile devices to prevent collisions [85].

The C-V2X deployment is enabled by roadside and onboard units supplied by Commsignia Ltd. The RSUs will broadcast traffic signal status and transmit this information to the vehicle (Audi Q8 SUV) by the cellular network. The information is shaped as Audi's Traffic Light Information (TLI) service that provides information for the drivers about the countdown for the green light in addition to the red light violation warning. American Tower Corporation and VTTI implemented the required deployment models, software, and systems. The safety enhancement for VRUs in VDOT C-V2X deployment contains road workers and pedestrians detection by RSUs and smart intersection sensors. In case of a detected event, the system sends warnings to the drivers of the compatible vehicles and VRUs around [86].

4) Las Vegas smart intersection deployment

Las Vegas is another deployment pilot for C-V2X communication technology implementation. Regional Transportation Commission of Southern Nevada (RTC) and Qualcomm Technologies cooperate with Commsignia with the same missions and tasks as in VDOT C-V2X. Commsignia installed around 100 C-V2X RSUs and OBUs in approximately 100 intersections in the city, which integrated with Qualcomm C-V2X chipset based on the 3rd Generation Partnership Project (3GPP) Release 14. These types of equipment enable innovative intersection solutions by integrating traffic light controllers, traffic cameras, and sensors [87].

V2X-connected vehicles will receive real-time safety alerts generated and collected by RSUs and other devices, such as signal phase and timing (SPaT) traffic messages. In addition to the above features of the deployment, pedestrian safety enhancement by V2P communications is also implemented in the Las Vegas pilot by smart intersection warnings for pedestrians about expected collisions. V2P warnings are provided by using Deep Neural Networks and Artificial Intelligence to create live data representation as a dynamic model of the surrounding environment and enable real-time safety alerts to vehicle drivers and for analysis in Traffic Management Centers [88].

5) Ford's smart intersection that "talks" to cars

Ford Motor Company deployed a smart intersection traffic system developed by Ford's research & innovation center. Their proposal uses smart infrastructure technology depending on V2I communication to enable safer roads, smart mobility, and ease congestion. The deployment is built on interaction discovery of the obstructed views and the existing situation on the road ahead for vehicles before arriving at the intersection, such as other vehicles crossing at high speed through a red light or VRUs such as pedestrians passing through the intersection [89].

The intelligent intersection is outfitted with innovative technologies to monitor the intersection area, such as traffic signal status. The solution relies on GPS and wireless communication technologies to communicate with approaching vehicles and send a package containing a digital map of the current intersection, traffic light status, lane-specific GPS location, and timing. The transmitted information will also include warnings about potentially dangerous traffic situations collected from traffic light signals and detected obstructed objects on the way [90].

Ford used Transit van model vehicles [91] in this deployment and equipped test vehicles with an 18-foot tall pole with a camera at the top attached to the roof of these vehicles. Using this elevated structure on the top of cars reaches the same height as a traffic light. It enables the flexibility of camera mobility between intersections instead of a fixed camera on one traffic light or intersection, which allows testing in different environments and conditions. Ford started evaluating the deployment in Southeast Michigan in the USA and expanded testing to reach other areas such as Miami. In Miami-Dade County, Ford deploys smart intersection technologies using autonomous vehicles with an extra layer of information about intersections before arriving and approaching them. The scheme is equipped with sensors such as radar, LiDAR, and cameras situated above the junction to collect data and send the situation information before the approach of autonomous vehicles [92].

6) Honda's "smart intersection" technology

Japanese automaker Honda with the City of Marysville, Ohio, and Drive Ohio (the state's autonomous and connected vehicles technology agency), demonstrated the feasibility of smart intersection technology using V2X communication. The deployment aims to decrease the number of deadly traffic accidents that occur in intersection collisions every year in the U.S. and deploy a more intelligent and safer transportation ecosystem, a part of Honda's Vision for a Zero Collision Society [93].

The deployment was developed as part of the "33 Smart Mobility Corridor" [94] project using 200 connected Honda vehicles. The mission of this deployment was to evaluate and test to vehicle's capabilities of detecting objects virtually in blind spots through the roadway intersections in a real-world environment. Moreover, the project was planned to help address the limitations of onboard vehicle sensors for discovering traffic collisions at roadway intersections.

This smart intersection technology deployment consists of Honda's object recognition and image processing software, intersection-mounted cameras, and V2I communications technology. On each corner of the intersection, four wide-angle cameras are outfitted above the traffic lights to capture video of surrounding and approaching vehicles and pedestrian traffic in a range of 300-foot (91 m) [95].

Honda's image processing software generates a 360-degree image of the surrounding environment of the intersection that allocates vehicles with three detection features of moving objects: non-visible pedestrians, red-light approaching vehicles, and the emergency vehicle not in the line of vision. The collected information broadcasts to enclosing vehicles using dedicated short-range communication (DSRC) V2X technology. The cars have onboard computers for decoding the received data, enabling drivers to discover the intersection virtually. The warnings and information are presented by computerized voice and sited head-up display added dashboards of the vehicle and alert them about hidden hazards and avoid a potential collision [96].

7) Qualcomm and UMTRI "smart intersection" project

The University of Michigan Transportation Research Institute (UMTRI) in Ann Arbor city in the U.S. state of Michigan demonstrated a smart intersection project with the support of Qualcomm (QTI) corporation technologies to enhance road safety for VRU using V2X communication technologies. A network of more than 20 intelligent intersections was implemented in the city to achieve safer roads and more convenience for connected vehicles. Cameras, LIDAR, and infrared sensors are deployed to detect blind spots, and radars are fitted on intersections to capture the movement in the surrounding road environment, such as the speed and direction of vehicles and VRUs. The collected data will be handled and sent to connected vehicles to warn of potential hazards [97].

The role of QTI is to initiate the C-V2X technology by establishing direct communication between roadside infrastructure and vehicles using V2I connections for transmitting information in real-time to and from connected road users. QTI aims to incorporate V2X technology solutions and 5G technology using Qualcomm Snapdragon Automotive 5G Platforms [98], which integrated C-V2X direct communication technology solutions in road environments for safer and more intelligent transportation systems.

8) Commsignia UWB VRUs protection

Commsignia uses Ultra-wideband (UWB) based positioning technology to protect VRUs and connect them to the vehicle ecosystem and road infrastructure to enhance road safety in V2X-equipped intelligent intersections. The VRU only needs a UWB tag or UWB-supported devices, such as smartphones or smartwatches. The VRU is equipped with a UWB tag with high accuracy and depends on 20 centimeters whether one is still on the sidewalk or already on the road.

Ultra-wideband gateway installed at traffic lampposts and intersections will determine the position of nearby pedestrians and then send the collected data to RSU. The RSUs will send V2X alerts containing real-time and precise position information of the VRUs. The data is broadcasted to nearby V2X-equipped vehicles, making the VRUs more visible and, in case of need, warning vehicle drivers of the presence of pedestrians near the road [99].

9) The fraunhofer CCIT smart intersection

Fraunhofer Cluster of Excellence Cognitive Internet Technologies (CCIT) Smart Intersection deployed at a public intersection in Dresden, Germany. The main goal is to detect vulnerable road users, such as pedestrians or cyclists, and warn their drivers of potential hazards using V2X communication. The solution exchanges decentralized environmental notifications (DENMs) and collective perception messages (CPMs) between users in the system. The project was built on practical considerations such as privacy following the General Data Protection Regulation (GDPR) regulations, trust in computation entities, and location of traffic accident hot spots [100].

CCIT Smart Intersections are equipped with thermal cameras using image recognition algorithms to detect and observe traffic participants. The collected data will be used as training data for object recognition relying on neural networks. To facilitate the exchange of large amounts of data, such as sensor data or high-resolution maps of the relevant section, a second communication channel based on mmWave is also applied [101].

TABLE II. RESEARCH EFFORTS ON V2X-EQUIPPED SMART INTERSECTIONS—SUMMARY OF SURVEYED PAPERS

Focus Group "1"		**Smart Intersections Development**		**Most Related Papers** [36, 37, 41, 45, 48, 50, 100]
Reference Papers	***Year***	***V2X Pattern***	***Key Technologies***	***Focus Points and Missed Coverage***
[36, 102–104]	2012	V2V, V2I and V2P	• Intelligent traffic management algorithms. • Traffic Simulators about traffic analysis. • Video monitoring for pedestrians detection.	• Intelligent traffic management at intersections for collision avoidance. • Simulator for traffic flow analysis. • VRUs protection (V2P) was not a trend for research. • Not using cameras and radar sensors, just include traffic light control (infrastructure agent).
[37–39, 105],	2013	V2V and V2I	• Intelligent intersections using the legacy algorithm. • VANET networks. • Intersection Control Scheme for Autonomous Vehicles.	• Vehicles that are not equipped or with faulty V2V and V2I communications traverse the intelligent intersection. • Intelligent Traffic Lights (ITLs) which • VRUs protection (V2P) not included. • Limited urban area application but start focusing on autonomous vehicles.
[40, 41, 106]	2014	V2V, V2I and V2P	• Poisson's distribution. • Pedestrian crossing behavior. • Intersections timing improving methods.	• Processing time at intersections is proportional to Poisson's distribution vehicle arrival rate. • Effect of pedestrian and traffic characteristics on pedestrian crossing behavior. • Not include V2X technologies but include developments of intersection and pedestrian crossings.
[42, 107]	2015	V2I	• Road Segments (R.S.). • SUMO (Simulation of Urban Mobility). • Vehicle Detectors.	• A model that helps in detecting and serving high-priority vehicles. • Dynamic system that reduced congestion. • Vehicle detectors (VDs) near intersections. • No V2P or V2V wasn't a trend in research. • Just simulations work.
[43, 44]	2016	V2V, V2I and V2P	• Vehicular ad hoc networks (VANETs). • Automated and cooperative intersections.	• Intersection modeling and traffic management methods. • Cooperative intersection management methods. • VRUs protection not included. • Smart intersection communication technologies.

[9, 45]	2017	V2I	• Collision avoidance system and identifying (Red-Light Running) RLR activity intersection. • Traffic controllers.	• An intelligent system focuses on a dynamic traffic light. • Reducing the accidents at the intersection. • V2V and V2P communication still missing. • Smart intersection equipment’s not mentioned.
[46, 108]	2018	V2V and V2I	• Automated vehicles headway minimization strategy. • MATLAB implementation. • Cooperative communication system.	• A study proposes a system design to allow safe and efficient traffic for connected and conventional vehicles approaching an isolated intersection. • Cooperative communication system between smart cars and driver cars. • No V2P included.
[47, 48]	2019	V2I and V2P	• Automated Intersection Management (AIM). • Fixed Cycles for Pedestrian Crossings.	• Smart intersection control algorithms. • Using intersection manager to process the information of vehicles and control the time of lights for pedestrians. • No direct communication between Vehicles and Pedestrians. • Pedestrians in blind spots detection missing.
[49, 50]	2020	V2V, V2I and V2P	• Integration Pedestrian in autonomous intersection management (AIM). • Traffic simulator SUMO (Simulation of Urban MObility).	• Intersection Control Strategy for vehicles and pedestrians. • Cooperative lane changing on the approach to the intersection. • Intersection management strategy depends on V2I communication. • No direct communication between Vehicles and Pedestrians. • Pedestrians in blind spots detection missing. • Communication technologies in V2I not included. • No information about vehicles detection at the intersections.
[51, 100]	2021	V2I, V2P, and V2V	• Decentralized Environmental Notification Messages (DENMs). • Collective Perception Messages (CPMs).	• Fraunhofer CCIT Smart Intersection model and deployment. • Distributed strategy for cooperative driving. • Communication technologies used. • V2V and V2P were missed.
Focus Group “2”	**Smart Intersections and Internet of Things (IoT)**			**Most Related Papers** [52, 55, 58, 59, 61, 109–111]
Reference Papers	***Year***	***V2X Pattern***	***Key Technologies***	***Focus Points and Missed Coverage***
[52, 112]	2012	V2I	• RFID. • Global Positioning System (GPS) • Detection Sensors.	• Model of the intelligent transportation system based on IoT. • The potentials of China's intelligent transportation system based on IoT. • Missing other V2X technologies,
[53, 113]	2013	V2I	• Wireless Sensor Network (WSN). • Intersection Controller collects data from detectors.	• A description of a real sensor network deployment in Enschede, Netherlands. • Proposed raw sensor data with context information for further usage in the IoT applications • No V2V or V2P included. • No algorithms were provided.
[54, 55]	2014	V2I with IoT	• Traffic management system – CTMS • IEEE 802.15.4	• Smart traffic lights integrated into the IoT. • Algorithms to reduce the average waiting time. • No V2V or V2P included.
[56, 114]	2015	V2I with IoT	• The Raspberry Pi Internet of Things Toolkit (WebIOPI) REST API. • RFID.	• IoT-based traffic management solutions for smart cities. • Traffic lights can be controlled dynamically using the proposed scheme to adapt to various traffic conditions. • Just focusing on IoT in integration with Transportation systems.
[57, 58]	2016	V2I with IoT	• Ultrasonic Sensors. • Raspberry Pi.	• An experiment of a smart traffic management system using IoT applications. • Architecture for the implementation of an IoT-ready Intersection Management Systems (IMS). • Just focusing on IoT in integration with intersections.

[59, 115]	2017	V2I with IoT	• Raspberry Pi. • Vehicle Traffic Routing Systems (VTRSs). • Electronic toll collection system (ETCS).	• A system where ultrasonic sensors are integrated with the Raspberry Pi to operate the lanes of an intersection based on traffic density. • Real-time traffic management system (TMS) using the Internet of Things (IoT) and data analytics. • Just focusing on IoT in integration with intersections.
[60, 61]	2018	V2I and V2P with IoT	• Arduino Uno kit. • Ultrasonic sensors and Wi-Fi module. • Global Positioning System (GPS). • RFID.	• A smart traffic system reduces jamming, waiting time, and travel delays and increases vehicle mobility. • Real-time traffic management system using the Internet of Things and data analytics.
[109, 116]	2019	V2I with IoT	• Simulation of Urban Mobility software. • Cameras, smart sensors, processors, and communication equipments.	• A scheme of a smart system to manage the traffic flow in intersections for autonomous vehicles. • Algorithms to make the optimal decision is distributed among all autonomous vehicles and roadside units in the intersection. • No V2P or pedestrian protection was included.
[110, 117, 118]	2020	Pedestrians with IoT on Smart intersections	• CCTVs cameras • Zigbee communication technology.	• A Smart intelligent pedestrian crosswalk system based on the IoT concept. • Just focusing on pedestrian monitoring at intersections.
[111, 119]	2021	V2I with IoT	• SUMO simulation tool. • Edge computing.	• Traffic system provides traffic-light managed intersections, improving traffic flow and diminishing pollution and fuel use. • Just focusing on IoT in integration with intersections.

Focus Group "3"	**Smart Intersections with Machine learning and Image Processing**			**Most Related Papers**	[63, 67, 70, 120–122]
Reference Papers	***Year***	***V2X Pattern***	***Datasets/Data Inputs***	***Key Technologies***	***Focus Points and Missed Coverage***
[62, 123]	2012	V2I	• Vehicle data (identification number for each kind of vehicle, a timestamp, vehicle position, speed, and a space reserved). • Number of vehicles at the intersection and performance metrics.	• A fuzzy-based control algorithm.	• Intelligent traffic management system based on V2I communications. • IEEE-802.11p-based communications study. • VRUs protection (V2P) and V2V are missing. • Algorithms for Collision Avoidance at Intersections. • Limited urban area application.
[63, 124]	2013	V2V and V2I	• Information about the traffic flow and congestion levels at intersections. • Time settings of traffic signals. • Video footage of traffic scenes. • Data on the positions and movement of vehicles. • Environmental changes and headlight effects.	• Intelligent intersections using the legacy algorithm. • Traffic surveillance videos. • ZigBee protocol.	• Vehicles not equipped or with faulty V2V and V2I communications to traverse the intelligent intersection using the Spatio-temporal reservation scheme. • VRUs protection (V2P) is not included. • Foreground images were obtained from the video footage, including potential vehicle candidates.
[64, 120, 125, 126]	2014	V2I	• Sensor and camera data: Frames from the video footage. • Parameters for controlling traffic signals, including variable traffic cycle and weighted time allocation. • Road geometry and driving lane information. • Traffic signal data, including information about the current state and timing of traffic signals at intersections.	• Genetic algorithm • fuzzy neural network (FNN). • Image processing.	• Genetic algorithm-based Optimization for traffic optimization. • Start focusing on the Application of Image Processing Techniques. • FNN in handling traffic congestion and priority-based traffic. • Just Focusing on traffic density using V2I, not other V2X technologies. • Data on the types of vehicles present in the traffic scene, including cars, rickshaws, and autorickshaws. • Traffic congestion data, including information about the amount of traffic on the road and the amount of area occupied by vehicles. • Information about the nominal paths that drivers are expected to follow based on the driving lanes.
[65, 127]	2015	V2I	• The driver perception-reaction time, the driver's acceptable deceleration rate,	• Image processing. • Support Vector	• Cameras are installed at the red lights and intersections to monitor the traffic dynamically. • Operations Management and Congestion

			the driver's age and gender, the time-to-intersection (TTI) and distance-to-intersection (DTI). • Vehicle type, the presence of side-street vehicles or opposing vehicles waiting. • Video images of traffic at intersections.	Machine (SVM). • Random Forest (RF).	Control. • Traffic system computes the volume of the real-time traffic and then sets the timer of the signal accordingly. • Incorporate machine learning techniques to recognize and adapt to changing patterns in traffic. • Just Focusing on smart infrastructure.
[121, 128]	2016	V2I	• Video images of traffic at intersections. • Data related to traffic flow, such as queues, delays, and stops. • Information about road works and traffic control.	• Neuro-fuzzy network. • Simulations using Network Simulator (ns3) tool. • Traffic flow simulation (VISSIM)	• Traffic control algorithm to reduce waiting time. • Using AI techniques such as Condensed Nearest Neighbor algorithm (CNN) and a rule-based system. • Reactive decisions to regulate and maintain the fluidity of traffic flow at signalized intersections. • Intelligent approaches, such as multi-agent systems and case-based reasoning, to develop the traffic control system. • No V2V and V2P patterns were mentioned.
[129, 130]	2017	V2I and V2V	• Traffic data from intersections, including information on vehicle trajectory, intersection state, and congestion. • Data about traffic volume and flow.	• Reinforced learning. • Deep neural networks. • Maximal Weight Matching (LQF-MWM) algorithm. • Artificial immune network algorithm.	• System for passage through intersections without the need for human control. • Help in reducing traffic congestion at intersections. • V2P protection research is missing. • Data is collected through sensors and cameras installed at intersections and is used to train a multi-agent system using deep reinforcement learning and deep neural networks.
[67, 68]	2018	V2I	• Information about the environment, including the state of the traffic signals and the number of vehicles at an intersection. • Arrival times of emergency vehicles at intersections and the estimated time it takes for emergency vehicles to pass through intersections. • Fuzzy sets to allow for linguistic parameters, such as "high" or "low," to be used as inputs.	• Fuzzy rule-based system. • Deep Reinforcement Learning.	• a Fuzzy rule-based system for traffic signal-timing. • A smart traffic control (STC) method focuses on the emergency situation over many intersections. • Integrating deep reinforcement learning into traffic simulation modeling. • Data to create rules for adjusting the timing of traffic signals to minimize delays for emergency vehicles while also minimizing delays for ordinary vehicles. • V2V and V2P patterns missing.
[66, 69, 70]	2019	V2I	• Current state of the traffic at a given intersection and the traffic flow data for the different lanes at that intersection. • Number of vehicles, the queue length, the road width, and the vehicle speed. • Real-time live or recorded videos from cameras.	• Convolutional Neural Network and Deep Learning. • Computer vision. • Fuzzy Mamdani logic.	• Traffic system to detect, classify, track and compute moving object velocity and direction using convolution neural network. • System uses NVIDIA Video cards with GPU, CUDA, OpenCV, and mathematical vector systems to perform. • Reduce congestion and improve traffic flow. • The interaction of the pedestrians in the system is missing.
[131, 132]	2020	V2I and V2P	• Information about the traffic demand at the intersection, such as the number of vehicles and pedestrians approaching the intersection, their lanes, and their intended movements. • Current state of the vehicle, such as its velocity, position, and surrounding environment.	• Reinforcement learning. • Deep neural network.	• Real-time detection and tracking of objects in traffic intersections using bird's eye cameras to detect and track vehicles and pedestrians from the COSMOS pilot site. • Algorithms to utilize vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to facilitate cooperative lane-changing on the approach to the intersection. • Algorithms to find an optimal velocity profile for the vehicle that minimizes energy consumption and avoids collisions. • Just one specific area.
[122, 133, 134]	2021	V2I and V2P	• Historical traffic flow data. • Control rules for signal timing. • Vehicle delay information. • The vehicle queue length and the number of inbound and outbound vehicles at an	• Fuzzy Adaptive Control System (FACS). • Adaptive traffic light control.	• The traffic system uses fuzzy logic to decide each lane's phase sequence and green time based on sensed input parameters. • Information about the matching degree between signal timing and traffic demand. • Just focusing on smart infrastructure.

			intersection.	
Focusing Group “4”		**Smart Intersections for Traffic Performance**	**Related Papers**	[72, 73, 135–139]
Reference Papers	***Year***	***V2X Pattern***	***Key Technologies***	***Focus Points and Missed Coverage***
[71, 72, 73, 140]	2012	V2I	• RFID. • VANET technologies. • Onboard unit (OBU).	• Each intersection contains 8 RFID readers for detection. • Violation detection system and vehicle priority. • Security schemes for V2I networks. • Automatic accident detection. • VRUs protection (V2P) is not mentioned. • Not using cameras, radar sensors, just RFID.
[74, 75]	2013	V2I	• Roadside Unit (RSU). • Intersection Safety.	• Intersection-priority-based RSU placement algorithms on distributing RSUs for covering all intersections. • Intention-Aware Risk Estimation on intersections. • Traffic Congestion Reduced Mechanism. • V2X pattern not mentioned.
[76, 141]	2014	V2I	• Support vector machines (SVM). • Hidden Markov models (HMM).	• Traffic system focuses on dynamic traffic light sequences based on the traffic density is used to reduce accidents at the intersection. • Traffic Congestion Reduced Mechanism. • V2X pattern not mentioned.
[142, 143]	2015	V2I and V2V	• Traffic Light Controllers (TLCs). • Global Positioning System (GPS) technologies.	• Reducing Road Traffic Congestion-based vehicles collaboratively to determine their optimal speeds and other appropriate actions to undertake in order to cross intersections with minimum delays. • Proposal for a framework to route the vehicles to cross over an intersection without stopping at red lights. • VRUs protection (V2P) is not mentioned.
[144, 145]	2016	V2I	• RFID. • Cyber-Physical Systems (CPS).	• Auto-adaptive model for smart regulation traffic lights. • V2X pattern not mentioned.
[146, 147]	2017	V2I and V2V	• Cybersecurity • Intersection-based Distance and Traffic-Aware Routing (IDTAR) protocol.	• Mitigating the cybersecurity risk in urban traffic management and facilitating efficient and cyber-secure traffic management in metropolitan areas. • Set of customized software applications for reducing both road congestion and cybersecurity concerns. • VRUs protection (V2P) is not mentioned.
[136, 148]	2018	V2I	• Real-time Traffic system.	• A real-time data-driven transportation simulation model to evaluate and visualize network performance. • VRUs protection (V2P) is not mentioned.
[137, 149]	2019	V2I	• SUMO simulation tool. • Signalized roundabout.	• A traffic system provides a method to control the traffic congestion pattern at a roundabout. • VRUs protection (V2P) is not mentioned.
[138, 150]	2020	V2I and V2V	• 5G vehicular communication.	• The traffic system sensing-based semi-persistent scheduling method utilizes RSU's sensing information in smart intersection V2X communication. • VRUs protection (V2P) is not mentioned.
[139, 151]	2021	• V2I	• Multi-agent Systems (MAS). • Sim2Car mobility simulator.	• A multi-agent system for simulating traffic control. • Priority assignment traffic light algorithm based on vehicle type, intersection waiting queues length, and multi-intersection communication. • VRUs protection (V2P) is not mentioned.

IV. Conclusions and Future Work

Increasing demand for efficient and secure V2X-equipped smart intersections will enable valuable safety, intelligent, and adaptive features. Our research surveys and analyzes smart intersection deployments, use cases, and research related to the unique capabilities provided by V2X communication to this domain. We analyzed more than 100 articles on smart intersections and related traffic systems and solutions and categorized them into four groups according to their characteristics. The paper investigates the key technologies, primary applications, and currently available practical results by presenting the V2X use cases, deployment efforts, the identified focus groups, and a thorough table of the considered resources. Our research concludes that V2X-equipped smart intersections nowadays tend to involve VRU protection in related deployments, especially incorporating V2P communications of any available ITS architectures to reduce accidents and improve mobility. Modern sensor technologies, advanced V2X schemes, and decision engines span the path toward developing and deploying new intelligent intersection solutions for vehicles and other road participants. Cloud-based solutions, artificial intelligence, deep learning techniques, and edge/fog computing get increasing significance to accurately collect and process data transmitted by DSRC and 5G communication networks technology. These capabilities can be further optimized and extended to enhance the adaptability and improve the performance of smart intersections, eventually boosting the widescale deployment of future safety-critical traffic systems that can completely understand and precisely predict any road-user interaction.

Although the research efforts reported to date have aimed at enhancing V2X-equipped smart intersections, there are still open issues to be addressed, such as VRUs protection in different use cases. Our investigation will be continued with Artery/OMNeT++ simulations to evaluate the effectiveness of different V2X-equipped smart intersection solutions in protecting vulnerable road users (VRUs). Artery is a V2X simulation framework based on the OMNeT++ simulation engine to model different traffic and communication scenarios, the performance of the smart intersections under various circumstances, and identify potential improvements. In our future work, we will introduce models of V2X-based VRU protection schemes into the Artery framework by introducing specialized ITS Facilities protocols and novel ITS stations (such as pedestrians and bicycles). We will evaluate the effects of applied protocol suits, cooperative sensing mechanisms with appropriate sensor fusion schemes, and optimized messaging/transmission techniques on the safety of VRUs. We look forward to continuing our investigations into extensive V2X simulation models with extensions of enhancements and possibilities to further improve the V2X-equipped smart intersections.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Hamdan Hejazi conducted the research, analyzed the data, and wrote the paper; László Bokor supervised the research and edited the paper; all authors have approved the final version.

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