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Autonomous driving under V2X environment: state-of-the-art survey and challenges

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Abstract

As Vehicle-to-Anything (V2X) is viewed as emerging technology, which could improve the mobility and efficiency of urban traffic operations, and enhance the safety of drivers. Supported by the construction of vehicular network facilities, V2X has been applied to various urban traffic management systems. However, due to the limitation of wireless communication, outstanding issues on privacy and security in V2X applications are still urgent. The purpose of our studies is to provide a comprehensive review of V2X-aided autonomous driving. Firstly the standards and protocols on V2X technologies for mobile communication and high-definition map are provided. The research scenarios of V2X-aided automobiles on urban links and highways are discussed. Furthermore, the several challenges of legislation in different countries, privacy issues, and security are discussed. Finally, the research directions for V2X-aided autonomous driving are further given.

Keywords: V2X, autonomous driving, vehicular networks, V2X-aided service

1. Introduction

Recently, infrastructure-cooperated autonomous driving could promise to reach dramatic decreases in traffic congestion and crash, and then increase the mobility and efficiency of the urban road system. Autonomous driving vehicle requires heterogeneous sensor data to support complex decision-making algorithms for handling everchanging roadway conditions quickly (McGehee et al., 2016; Li et al., 2022). In the standards derived from the society of automotive engineers (SAE), autonomous vehicles can be grouped into six different levels with incremental automation levels, namely the Level of Automation (LoA) (SAE, 2018). With advanced vehicle-to-everything (V2X) technologies, connected vehicles equipped with onboard sensors such as cameras or radars have become instinctive for real-time message sharing, thus regarded the potential for prospective and wiser driving maneuvers (Jung et al., 2020; Tu et al., 2021). However, due to the deficiencies in technologies, legislation, and public cognition, there are still immense gaps in the commercial application of autonomous vehicles with high automation. But V2X-aided cooperative autonomous driving has reached outstanding performances in intelligent traffic systems, which includes road intersection management (Chow et al., 2021; Chen et al., 2022a) and the design of vehicle platooning (Li et al., 2018).

In terms of the different research scenarios, the studies of V2X-aided autonomous driving can be classified into the evolution of mobile communication technologies (Bagheri et al., 2021; Liu et al., 2020a), the fundamental concepts and expansion of V2X (Pearre and Ribberink, 2019), and V2X-aided services, such as cooperative platooning (Chen et al., 2021; Wang et al., 2021b;

Balador et al., 2022). Compared to other existing reviews on V2X studies that usually focus on one specific sub-domain, the goal of our studies is to introduce a review of the existing studies (V2X technologies, V2X-aided autonomous driving applications), the challenges (the legislation status and feasible security and privacy issues) by the relatively comprehensive investigation of fundamental technologies, as the added value of this research, the summary of several V2X-aided services with different taxonomies (the object or location, the classical maneuver, the algorithm's application of the service, *etc.*) to provide a comprehensive understanding about the service and technologies have been proposed.

The remainder of our studies is organized as follows. In Section 2, the technologies and protocols of V2X communications are discussed. To illustrate how V2X technologies work on cooperative autonomous driving, the studies of automated valet parking, cooperative intersection control, and cooperative platooning are discussed in Section 3. Furthermore, the challenges on legislation and issues on personal privacy and driving security inevitably occur when deploying V2X technologies s are presented in Section 4. In Section 5, some future directions are mentioned. Finally, the conclusion is provided in Section 6.

2. V2X Technologies: Concepts and Protocols

In the V2X technologies, supported by high-scalable and low-latency mobile communication networks such as 5G (Bagheri et al., 2021), vehicles equipped with smart on-board equipment are capable of transit real-time messages to entities in the

transportation system, such as the roadside infrastructure, networks, and pedestrians (Li et al., 2018; Li et al., 2021; Chen et al., 2022b). Through wireless interactions, traffic conditions beyond the sensory abilities are available for the drivers and continue to cause affect their behaviors by driving behavior models (Zhou et al., 2016; Ghiasi et al., 2017; Qin and Wang, 2021; Wang *et al.,* 2021a). Recently, the cooperative intelligent transportation system (C-ITS) has drawn great prospects from the government (Festag, 2014). Reports derived from the European Commission (EC) stated that the benefits of deploying C-ITS include reducing travel time or accident rates and increased efficiency with less fuel consumption (Yoshizawa et al., 2022). The assessment proposed by National Highway Traffic Safety Administration (NHTSA), USA pointed out that the adoption of V2X technologies has prevented about 439,000 to 615,000 accidents, 987 to 1366 deaths, and 537,000 to 746,000 property damage incidents per year (NHTSA, 2016; Yoshizawa et al., 2022).

Following the 3rd Generation Partnership Project (3GPP), V2X communication consists of four types of connectivity modes, which include vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-network, and vehicle-to-pedestrian, which are the main focus of C-ITS (Lu, 2019; Cinque et al., 2020). A brief introduction to the different connectivity modes of V2X is illustrated in Fig. 1.

Vehicle-to-vehicle (V2V): real-time messages, such as route planning, current condition, and state of other surroundings, are transmitted and shared between different vehicles directly. The message transmission in V2V is mainly broadcast-based with a limited communication range based on smart onboard units (OBU).

Vehicle-to-infrastructure (V2I): real-time messages are transmitted and shared between a vehicle and other road-side infrastructures, such as road-side units (RSU) and traffic lights;

Vehicle-to-network (V2N): real-time messages are transmitted and shared between a vehicle and networks through mobile stations or cloud platforms, which provide services required by the vehicle.

Vehicle-to-pedestrian (V2P): real-time messages are transmitted and shared between a vehicle and other road users, such as pedestrians or cyclists.

The technical taxonomy (standard J3016) created by the Society of Automotive Engineers (SAE) defines six incremental automation levels for on-road motor vehicles, *i.e.* no automation (Level 0 or L0), driver assistance (L1, driver controls), partial automation (L2, driver monitors), conditional automation (L3, driver delegates), high automation (L4), and full automation (L5). With an L4 or upper automation level, drivers on the vehicle can be free from operations during the entire journey. Detailed definitions are summarized as follows.

Level 0: drivers are entirely responsible for vehicles' operations, *e.g.* the steering, accelerating, braking, and parking.

Level 1: vehicles assist with the operations. Representative services include adaptive cruise control and lane-keeping assistance.

Level 2: vehicles provide partial automation for the operations. A well-known system is the Advanced Driver Assistance Systems (ADAS), which helps drivers to sense and avoid feasible dangers.

Level 3: vehicles govern all the driving tasks. However, when danger occurs, drivers must be available to control the wheel or the pedal.

Level 4: vehicles are completely responsible for all the driving and navigation tasks.

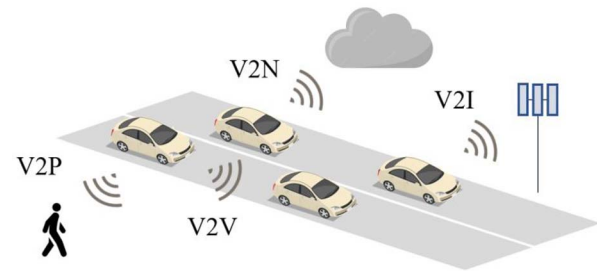*Level 5*: vehicles take full control of all driving and navigation tasks.

Figure 1. Vehicle-to-everything (V2X).

Generally, in terms of controlling mechanisms, autonomous vehicles can be classified into vision-based and cooperation-based driving. Autonomous driving (AD) mainly relies on the vehicle's computing units, lidar equipment, and other on-board sensors to accomplish the environment perception, computational decision-making, and control execution, while cooperated autonomous driving (CAD) emphasizes information interaction among different entities in intelligent road systems (Fig. 2, Lu et al., 2021; Cheng et al., 2022b). Although automated vehicles without connectivity can handle the driving scenarios, the additional information received through V2X communications can guarantee a safer and more efficient journey, for extra information enhances the awareness beyond on-board sensors through event-based warnings, extended perception, and improved anticipation (Zlocki *et al.,* 2019).

2.1. High-definition map

High-definition Map (HD-map) refers to a digital map with different functional layers which provides precise information about both the static and dynamic entities in the transportation system. The conditions of road geometries and landmarks, updated with a rather lower frequency, are recorded in the static layer. The road topology and the locations of traffic signs are vital information amid the static layer. Meanwhile, the dynamic layer provides the real-time dynamics of the surrounding and global information with high update frequency, such as the phases of traffic signals, the road traffic volume, and the condition of the road surface. The definition of HD-map was first proposed in the Mercedes-Benz research planning workshop (Liu *et al.,* 2020b; Herrtwich, 2018). Since single static information cannot guarantee the safety of autonomous driving, Liu et al. (2017) proposed the concept of the local dynamic map, which was the first time that the states of dynamic entities are considered in the structure of an HD-map. For deeper exploration, the details of the systematical overview of the structure, functionalities, and standards of HD-map can be found in the studies of Liu *et al.,* (2020b).

2.2. Protocols of communication in C-ITS

The dedicated short-range communication (DSRC), a wireless communication technology designed by the USA Department of Transportation (USDOT) and the European Telecommunications Standards Institute (ETSI), aims to allow automobiles in C-ITS to communicate with other smart entities (Yajima, 2000), which shows low latency, small interference, high reliability, and performs impressive practicability, especially in extreme weather conditions. Based on DSRC, the first exclusive standard designed to support low-delay V2V and V2I communication is IEEE 802.11p, which was proposed by IEEE in 2010. IEEE 802.11p is mainly designed to support onboard *AD-hoc* communication based on the Wireless Local Area Networks (WLAN), namely the VANETs
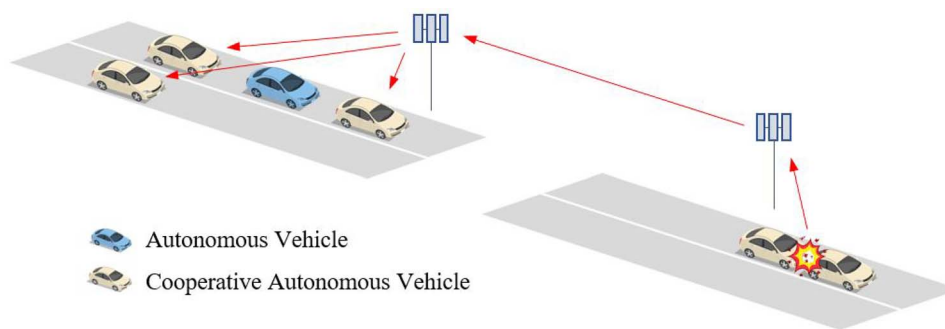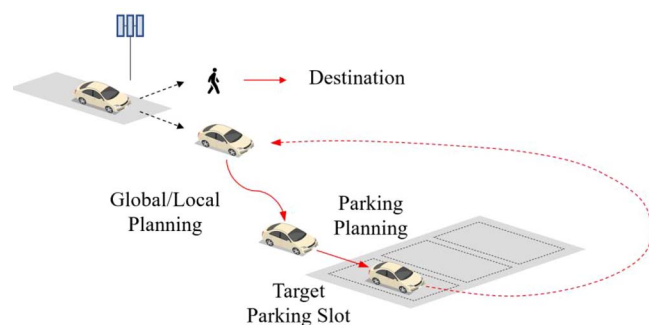
Figure 2. AD and CAD.

Figure 3. Automated valet parking.

(Vehicular *Ad hoc* Networks) (Dimitrakopoulos and Demestichas, 2010). In DSRC, vehicular communications are limited to vehicles and the roadside infrastructure only. With the advances in mobile cellular networks, the 3rd Generation Partnership Project (3GPP) proposed a new communication technology called Cellular-V2X (C-V2X) in 2015, which allows communications in cellular networks. Two other entities, the networks, and pedestrians are regarded as new information terminals. With the evolution of cellular networks from 4G LTE networks to 5G networks, C-V2X has also evolved from the original LTE-V2X for road-safety-assisted driving to 5G-V2X (NR-V2X) for autonomous driving (Ma et al., 2020). Protocols in different countries or unions are concluded as follows. Kiela et al. (2020) and Lu (2019) provide comprehensive introductions about the standard of V2X.

European Union/USA: In Europe, IEEE 802.11-based C-ITS is called Intelligent Transport System G5 (ITS-G5), which has been standardized by European Telecommunications Standards Institute (ETSI) as EN 302663 (Lu, 2019). To satisfy the spectrum allocation, ETSI has been studying the channel sharing of DSRC and C-V2X for years. In the USA, Audi of America has announced the deployment of C-V2X on roadways, while Ford plans on introducing C-V2X in new vehicles beginning in 2022.

China/Other countries: In China, the 'New Infrastructure' campaign launched by the Chinese government leads a substantial growth in V2X infrastructure building. Car dealers have committed to deploying C-V2X technologies in the products from 2022 to 2023. In Japan, more than 100,000 DSRC-equipped vehicles are served for V2V applications since 2018. Toyota has begun to equip DSRC with its products since 2021. Meanwhile, Korea and Australia have dedicated the bandwidth of DSRC at 5.9 GHz, but tend to deploy C-V2X productions in the future (Lu, 2019).

3. V2X-aided Cooperative Autonomous Driving

With the deployment of wireless communication facilities, diverse V2X-aided applications for autonomous vehicles have been invested, which show high reliability, efficiency, and security. The three V2X-aided cooperative autonomous driving scenarios introduced in our studies are automated valet parking, intersection control, and cooperative platooning. Automated valet parking and intersection control are common scenarios on urban roads, while cooperative platooning is mainly considered on normal highways (Cheng et al., 2021; Gu et al., 2022; Li et al., 2022b). Related studies on different applications are mainly classified into three perspectives: the serving objects or location, the operational maneuvers, and the corresponding algorithms.

3.1. Automated valet parking

Modern vehicles are equipped with parking assistant software and provide visual and phonetic information about the surroundings to avoid possible collisions during the parking process. With the assistance of advanced V2X communications, real-time information such as the number of empty parking slots remaining in different parks, other vehicles' bookings, and route plans in the objective park are integrated for drivers through networks. Parking assistance with high automation is called automated valet parking (AVP). AVP provides a driver-free parking service. Drivers can simply drop off their vehicles at the transfer place in the parking garage and then head for their destinations on foot or by bicycle, then the AVP systems will accomplish the entire parking procedure, including the route planning, route operating, and parking. When the driver sends a request on their mobile phone, the car can return to the transfer place automatically. The main sequential steps in AVP have been illustrated in Fig. 3. Firstly, the AVP system takes over the autonomous vehicle at the transfer place. Then the system determines the target parking slot and derives the global path. Following the global path, the vehicle is guided to reach and stop at the parking slot. Related literature about AVP can be divided into three categories: different serving targets, the fundamental step-by-step parking maneuvers, and the parametrical or non-parametrical algorithms chosen to get these maneuvers. For readers interested in AVP, Banzhaf et al. (2017) proposed a comprehensive overview of AVP. There are also discussions about the safety and privacy issues hidden in AVP (Schönemann et al., 2018; Ni et al., 2019).

Vehicles: there are mainly two serving objects or vehicle combinations in AVP systems, which are automated vehicles only and mixed vehicles.

Automated vehicles: Geng and Cassandras, 2013 and Löper et al. (2013) proposed the structure of the AVP parking management system to charge the reservation and assignment of parking spaces for automated vehicles. The coordination of multiple vehicles (called the high-density problem) is addressed by Kessler and Knoll, 2017 and Chen et al. (2020), the focus of which is to prevent the possible conflicts of several vehicles which are approaching their destinations in the parking slot through V2X communications.

Mixed vehicles: mixed vehicles which consist of regular vehicles and automated vehicles were considered in Automotive World in, 2018, which is the prototype of a mixed traffic parking garage equipped with AVP. Schörner et al. (2021) introduced and discussed the parking requests from autonomous vehicles with different automation levels from SAE level 0 to level 5.

Parking maneuver: according to González et al. (2015), Paden et al. (2016), and Banzhaf et al. (2017), there are mainly three parking stages in AVP, namely the global planning stage, the local planning stage, and the parking planning stage. The first two stages determine the route to the parking slot, while the last one guides the automobile to park.

Global planning: the AVP system determines a route that can avoid possible collisions with static obstacles. Well-known algorithms include Hybrid A∗ (Montemerlo et al., 2008), Anytime D∗ (Urmson et al., 2008), RRT∗-Connect (Klemm et al., 2015), and RTR (Kiss and Tevesz, 2017), *etc.*

Local planning: automobiles are controlled to avoid dynamic obstacles in the environment such as other moving vehicles. The local route follows the route determined in the global planning stage. Sampling-based Trajectory Generator (Schwesinger et al., 2016) is one of the representative algorithms.

Parking planning: as the vehicle has reached the parking bay through the local trajectory, the AVP system will guide the vehicle to move and finally stay in the parking bay. According to (Banzhaf et al., 2017), there are two principles for local parking. The one is based on the predetermined geometric set, Jeevan et al. (2010), Löper et al. (2013), Min and Choi, 2013), and Min and Choi, 2015 proposed the graph-based approach, Min et al. (2021) applied the graph neural network (GNN) for parking-slot detection.

Algorithm: as the fundamental algorithm in graph theory, the shortest path algorithm Dijkstra was applied in the parking route searching stage in early studies (Löper et al., 2013). In AVP, the commonly used road-searching algorithms are heuristics approaches (Urmson et al., 2008). Apart from conventional approaches, artificial intelligence (AI) technologies, especially machine learning algorithms, have been widely applied and achieved better performances in route-searching tasks. Works proposed by Gawel et al. (2018), Arandjelovic et al. (2016), and Yu and Su, 2021) are worthy of further exploration.

3.2. Cooperative intersection control

When reaching the intersections, vehicles are regulated by the signal phase (in signalized intersections) or basic traffic rules (in non-signalized intersections). Regulations applied aim to relieve inevitable conflicts between vehicles from different entrances with various turning directions. According to the fatality analysis report from NHTSA, more than 25% of fatal crashes occur at or are related to the intersection in the USA. Particularly, about 50% of these fatal crashes happened in uncontrolled ones. To reach higher efficiency, traditional approaches focus on designing a proper signal logic or canalizing the intersections. Cooperative intersection control (CIC) or management has become a feasible and promising way to greatly improve safety and efficiency in

intersections. Related literature about CIC in our studies can be divided into three folds, which are signalized and un-signalized intersections, major CIC maneuvers, and algorithms applied to get these maneuvers.

Intersection: for non-signalized intersections, there are no controlling facilities. To ensure a safe crossing, the driver needs to interact with other travelers entering the intersection solely through eye contact. Traffic lights can effectively improve efficiency and safety in intersections by splitting vehicles into multiple streams in different directions (Cheng et al., 2019a; Cheng et al., 2019b; Huang et al., 2021; Huang et al., 2022). However, improvements derived from signal control alone are limited (Bell, 1992). Efficient V2X communication allows vehicles to take a more active role in intersection passing. Readers can refer to the survey proposed by Chen and Englund, 2015) for more information.

Non-signalized intersection: the interactions can provide valuable information beyond drivers' eye-sight or perception ability on intersections with obstacles such as trees or buildings (Miller and Huang, 2002; Benmimoun et al., 2005). Tu and Huang, 2010) designed a cooperative speed harmonization technology for traffic stream merging based on communications between vehicles and infrastructure.

Signalized intersection: the interactions between vehicles and infrastructure enables flexible regulations of traffic signal phases, especially the request for the green light. Chang and Park (2013) proposed a group-based method for vehicles traveling on signalized intersections. Apart from autonomous vehicles, Ma et al. (2015) also considered the safety and traveling efficiency of pedestrians.

Traveling maneuver: two cooperative algorithms in CIC are summarized in our studies, including resource reservation and trajectory planning.

Resource reservation: Autonomous Intersection Management (AIM) is the basis of resource reservation. As shown in Fig. 4(a), the central region of one intersection is discretized into several grids. Based on First Come First Service (FCFS) principle, vehicles need to reserve the grid for a certain period. Once the grid and period time are satisfied, vehicles are allowed to pass the intersection. Following this, Zhang et al. (2013) and Choudhury et al. (2016) further improved these assumptions.

Trajectory planning: the trajectories of vehicles can be designed and shared through V2X communications, which means that the trajectories are available for optimization before vehicles reach the intersection (as shown in Fig. 4(b)). The optimization targets include the least accumulative overlapping length (Lee and Park, 2012; Lee et al., 2013), the largest accumulative distance to feasible conflict points (Kamal et al., 2014), and the least accumulative fuel cost (Rios-Torres and Malikopoulos, 2016). The states of traffic signals can also be included as decision variables. Yu et al. (2018) optimized the vehicle trajectories and traffic signals together in signalized intersections toward cooperative autonomous vehicles. Interested readers can refer to Guo et al. (2019) and Niroumand et al. (2020) for further studies.

Virtual traffic light: as vehicles can exchange information with others, traditional traffic lights can be replaced by virtual alternatives, namely the virtual traffic light (VTL), (Ferreira et al., 2010) which was proposed by (Chow et al., 2020; Chow et al., 2021; Li et al., 2022a). Experiments in Porto show that vehicles could coordinate well (Conceicao et al., 2008). Zhang et al. (2018) and Zhang and Su (2021) also derived valuable studies related to VTL.

Algorithm: the optimization algorithms are the commonly applied mathematical tools in different cooperative intersection control algorithms, such as mixed integer programming
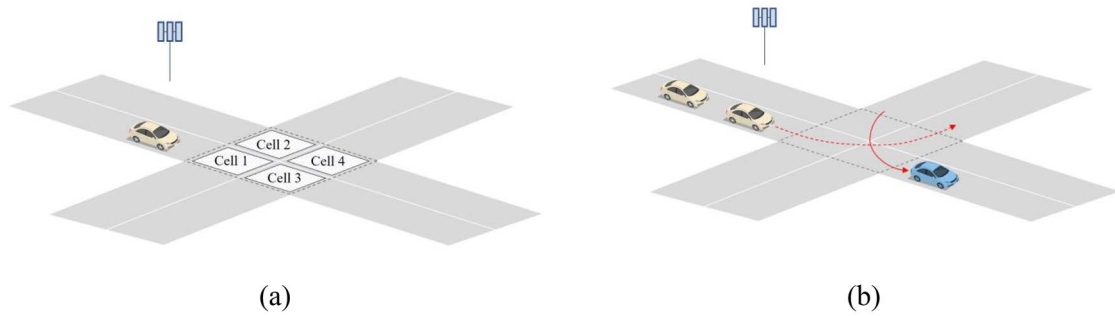
(a)   (b)

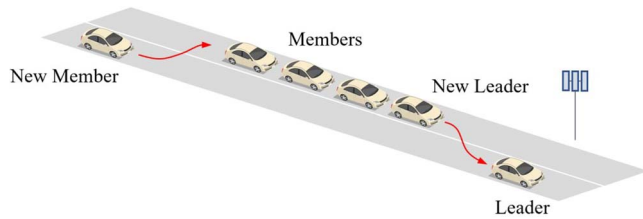**Figure 4.** (a) Resource reservation; (b) trajectory planning.

Figure 5. Cooperative platooning.

(Yu et al., 2018; Zhang and Su, 2021). Advanced learning-based technologies are also applied, such as machine learning (Esaid et al., 2021) and reinforcement learning (Feng et al., 2019).

Cooperative intersection control can also be extended into the mixed traffic flow. Researchers show that the mixed traffic flow can effectively promote the traffic efficiency of the intersection (Kolodko and Vlacic, 2003). Jiang (2017) also studied the traffic signal design for cooperative autonomous vehicles and regular vehicles simultaneously and derived positive results.

3.3. Cooperative platooning

A platoon means a set of vehicles that align and travel together one-after-another, as shown in Fig. 5. The first vehicle is called the leader, while the others are members of the platoon. The common driving operations of vehicles in one platoon include acceleration/deceleration (to guarantee a stable and small distance between vehicles and avoid possible collisions) and lane-changing (to avoid possible collisions in the front). New vehicles can join the platoon, vehicles in the platoon can leave or form a new platoon, and two platoons can merge. Cooperative platooning aims to increase vehicle capacity, traffic stability, driver convenience, and reduce fuel consumption (Aarts and Feddes, 2016). Related studies about cooperative platooning introduced in our studies are introduced in three folds: various operations to form/stay/split a platoon, the control maneuvers in platooning, and the algorithms used to get these maneuvers.

Operations: there are two types of driving operations in platooning. One is the intra-operation, which includes common driving behaviors, *i.e.* acceleration, deceleration, and lane-changing. Intra-operations cause no impact on the structure (the leader, the number of members, the order of members, *etc.*) of one platoon. The other is the inter-operation, which contains platoon joining, merging, leaving, splitting, and cut-in/cut-out. The structure of one platoon can be updated through inter-operations. Amoozadeh *et al.* discussed the lane-changing, splitting, and merging

operations (Amoozadeh et al., 2015), while Basiri et al. (2020) investigates the cut-in/cut-out operations.

Control maneuvers: there are abundant studies that focus on developing appropriate driving maneuvers for joining, staying, and leaving the platoon. We introduce three types of control maneuvers, *i.e.* behavior-based maneuver, predictor-based maneuver, and leader-based maneuver in our studies.

Behavior-based maneuver: according to Balch and Arkin (1998) and Lafferriere et al. (2005), the control of the platoon's structure can be discretized into every single vehicle. The goal of the behavior-based maneuver is to guide each vehicle in the platoon to move and maintain or form an expected platoon structure. Reif and Wang (1999) and Monteiro and Bicho (2002) extended this assumption further.

Predictor-based maneuver: accurate traffic states are also important information for urban traffic control (Liao et al., 2021; Liu et al., 2022; Xing et al., 2022). Apart from real-time states, the dynamics of each vehicle in the future are also valuable messages for cooperative platooning (Bai et al., 2021; Cheng et al., 2022a). Dunbar 2001&2002) and Dunbar and Murray (2002) derived representative works.

Leader-based maneuver: in leader-based models, one or more vehicles are selected as the leader of the whole platoon. The followers need to communicate with others through V2X communications and follow the leader at the desired relative distance and turning angle. Therefore, the complex platooning process is decomposed into a simple problem of controlling the followers to follow the corresponding leaders in a rather smaller area (called the sub-platoon). More details can be found in Hogg et al. (2002) and Consolini et al. (2008).

Algorithms: in the vehicle platooning maneuver proposed by Gong and Du (2018), human-driving vehicles are controlled by traditional mathematical car-following models (Newell, 2002), while the maneuvers of cooperative vehicles are modeled by MPC-based strategy and solved by optimization (Gong and Du, 2018; Wang et al., 2019) or heuristic approaches (You et al., 2020). Non-parametrical approaches have drawn great attention in recent years. The common operations, such as inter-operations, are modeled *via* machine learning algorithms (Cara et al., 2017; Bouhoute et al., 2020).

It is hard for drivers themselves to form a stable platoon without the assistance of V2X equipment. Human-driving vehicles always show high-level uncertainty and randomness. However, the platoons can also be formed with mixed vehicles. Gong and Du (2018) developed constrained model predictive control (MPC) models to control the movement of the platoon (formed by cooperative autonomous vehicles) linked with human-driving platoons. The model ensures traffic smoothness and asymptotic stability at the same time.

4. Potential Challenges

4.1. Legislation status

Although V2X-aided autonomous driving technologies promise higher safety and efficiency than traditional human driving, feasible accidents are still inevitable. In February 2016, one autonomous vehicle of Google collided with a bus during a road test in the USA and was judged fully responsible for it. In March 2018, a woman was killed by an Uber self-driving car when crossing a street in Arizona, USA. It is the world's first case of a pedestrian killed by a self-driving car. To favor or disfavor a particular technology for V2X, efforts have been taken on legislation for driving behaviors, vehicle tests, and vehicle manufacturing in different countries. The responsibilities have been clarified in accidents caused by autonomous vehicles. As such, the regulation and legislation status for V2X is discussed.

European Union/USA: since April 2018, all new cars sold in European Union are equipped with Emergency Call (eCall). When vehicles encounter accidents, eCall offers quick assistance by automatically informing E112, which is the emergency telephone number across Europe (Usman et al., 2020). In the road testing stage for highly automated vehicles, the applicable legislation of different countries in the European Union is the National Traffic Law. A trained test driver and event data recorder are required. For the issues of responsibility in accidents with V2X vehicles involved, it is considered that as long as the driver stays in the vehicle, the driver will be fully responsible for taking action to avoid possible collisions (Lu, 2019). In the USA, NHTSA has enforced the IEEE 802.11p standard among all new vehicles (Harding et al., 2014), and there are emerging requests for CITS standards in recent years. In 2016, NHTSA released the Federal Automated Vehicles Policy (FAVP), which includes the protocols for law enforcement, emergency response, vehicle registrations, etc (Kornhauser, 2016). As there are increasing car crashes correlated with onboard autopilot systems, vehicles equipped with autonomous systems had to upload detailed accident reports to NHTSA since June 2021.

China: the issues of road testing, traveling, and responsibilities in crashes with cooperative automated vehicles involved are discussed in Road Traffic Safety Law (draft) in March 2021. In August 2021, legislation proposed by the Ministry of Industry and Information Technology (MIIT) stipulates the access management requirements for autonomous vehicles with L3 and L4 levels of automation, which provides important guidelines for self-driving car dealers.

4.2. Privacy issues

Services based on V2X communication always request highly accurate information about vehicles' real-time conditions. The location state is the essential information that supports intelligent traffic services such as parking and route navigation. It is highly related to personal privacy. Attackers can infer the accommodation, company, interests and habits, and other information of the driver by analyzing the historical records, which may further cause safety issues. Privacy protection in V2X communications has become an essential concern for the public. Government around the world has proposed regulations for privacy protection (Yoshizawa et al., 2022), such as CDPR, Network and Information System (NIS) Directive, the Cybersecurity Act, and the ePrivacy Directive in European Union. A powerful authentication protocol is needed to protect the information shared.

According to Pfitzmann et al., messages transmitted in V2X networks are expected to fit these characteristics: anonymity, pseudonymity, unlinkability, and unobservability (Pfitzmann and Hansen, 2010). In the application of the solutions, pseudonyms are assigned to V2X-aided vehicles to prevent attackers' traces. However, the side information data can still be utilized by attackers for sensitive privacy digging (Huang et al., 2020). Like other regular vehicles, the dynamics of V2X-aided vehicles are continuous. Physical descriptive variables, i.e. the location, velocity, and acceleration, are very close values before and after the pseudonym-changing spot. The attackers can still extract useful clues by matching different pseudonyms.

4.3. Security issues

V2X-aided systems and functions for autonomous vehicles are highly correlated with communication, which becomes a natural target for attackers and may cause security issues. Several challenges are discussed in this section, including communication latency, attacks, and environmental jamming.

Communication latency: low latency is the basis of V2X-aided services. For example, the response time remaining for one vehicle to avoid a feasible collision at high speed could be extremely small (within a few milliseconds). In remote driving, the truck owners take over the trucks' movements at home, thus high latency is unacceptable. All the potential risks which can cause fluctuations or delays in mobile communication must be addressed first.

Attacks: for enabling diverse services, connected vehicles transmit real-time state messages such as route planning, speed, and location. Through the internet, information can be tempered by attackers, which may lead to misjudgments of the traffic condition and derive inappropriate responses.

Environmental jamming: apart from possible human attacks, V2X-aided vehicles may encounter security threats from the environment with high communication jamming. A very common scenario is tunnel traveling. It has become commonplace that the tunnel ensures smooth traveling both on city districts and mountainous highways. However, due to the remote locations and complex geometrical environments, the tunnels are always associated with drawbacks in mobile communication. For example, common positioning systems such as Global Navigation Satellite System (GNSS) are not available in tunnels, thus positioning-aided services such as navigation are disturbed. Mobile communication disturbance in tunnels has become an important issue to address. Apart from services for better travel experiences, safety still matters in tunnel traveling. For those vehicles equipped with V2X technologies, warning information including congestion or car crash or will become unavailable when the vehicle entered the tunnel, which may cause safety issues.

5. Future Directions

The intelligent connected vehicle network and ecosystem are developing rapidly, and our studies summarize several high-value future directions as follows:

i)   The rational layout of RSUs is the basis for maximizing the advantages of the V2X system. It is valuable to find a way to establish a multi-objective model to balance the economy and efficiency and guide the layout of RSUs on different levels of roads and under different road conditions through the traffic flow characteristics under different V2X vehicle permeability.

ii) Combining virtual reality and digital twin technology, we can simulate various functions of V2X systems in key typical traffic scenarios, including communication and vehicle

driving behavior. Further integrations with some cutting-edge communication technologies, *i.e.* 6G, are necessary but still lacking.

iii) From a legal perspective, the introduction of artificial intelligence algorithms is a promising solution for the delimitation of responsibilities in accidents caused by V2X-aided autonomous vehicles by traceback and analysis of the trajectories collected from various types of equipment.

iv) When the V2X vehicle scale and complex scenarios proliferate, how to solve the system's arithmetic problem by introducing parallelized computing technology, and how to ensure the normal operation of the system when the network security is threatened, are still one of the open problems in V2X-aided applications.

v) In the decision-control algorithm level, how to make early warnings for V2X vehicle driving behavior under mixed traffic flow, the related optimization and control algorithms are also key directions for future research.

6. Conclusion

In the past decades, drivers are accustomed to perceiving traffic conditions through their eyes and taking sequential actions to ensure a safe, comfortable, and efficient journey. As the notion of V2X enters decades, developments in mobile communication have made V2X-aided services practical. Our study first provides a brief introduction to V2X, including the fundamental concepts, technologies, and protocols in different countries. Then three prevailing V2X-aided applications, AVP, CIC, and CP are discussed in detail with rich works of literature, followed by discussions on current challenges about V2X systems, including the legislation status, security issues, and privacy issues. In the end, several valuable research directions correlated with V2X-aided automobiles in the future are summarized. Compared with the existing surveys, we summarize related studies of V2X-aided services through different taxonomies, *i.e.* the application scenarios and algorithms to get control maneuvers. In this research, it is inevitable to make a trade-off between the depth and breadth of the introduction to several V2X-aided services and this research emphasized the latter one. For each V2X-aided autonomous driving service, the developing processes of related theories with chronological doer from different perspectives were still lacking.

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