Cooperative Connected Autonomous Vehicles (CAV): Research, Applications and Challenges

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Abstract—Road accidents and traffic congestion are two critical problems for global transport systems. Connected vehicles (CV) and automated vehicles (AV) are among the most heavily researched and promising automotive technologies to reduce road accidents and improve road efficiency. However, both AV and CV technologies have inherent shortcomings, for example, line of sight sensing limitation of AV sensors and the dependency of high penetration rate for CVs. In this paper we present a cooperative connected intelligent vehicles (CAV) framework. It is motivated by the observation that vehicles are increasingly intelligent with various levels of autonomous functionalities. The vehicles intelligence is boosted by more sensing and computing resources. These sensor and computing resources of CAV vehicles and the transport infrastructure could be shared and exploited. With resource sharing and cooperation CAVs can have comprehensive perception of driving environments, and novel cooperative applications can be developed to improve road safety and efficiency (RSE). The key feature of the cooperative CAV system is the cooperation within and across the key players in the road transport systems and across system layers. For example, the various levels of cooperation include cooperative sensing, cooperative RSE applications and cooperation among the vehicles and among the vehicles and infrastructure. We will present the potentials that could be brought by cooperative CAV, the roadmap for research and development, the preliminary research results and open issues.

Index Terms—Connected vehicles, autonomous vehicles, connected intelligent vehicles, CAV, cooperative road safety

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I. INTRODUCTION

The increasing number of vehicles on the roads and rapid urbanization have serious implications on the road safety and efficiency problems of road transport systems. The World Health Organization (WHO) reported that more than 1.2 million people die each year on the roads [1]. In addition, traffic congestion costs approximately 90 billion lost hours per year and increases pollution. Connected vehicles (CV) and automated vehicles (AV) are among the most heavily researched automotive technologies to reduce road accidents and improve road efficiency [2]–[5]. They have significant safety, economic, road efficiency and mobility benefits.

Both AV and CV technologies have inherent shortcomings [2], [3], [6]. The limitations of AV sensing technologies are highlighted by the fatal accidents of Tesla car with autopilot in 2016 and Uber self-driving car in 2018. They are not reliable under in extreme weather or road conditions. The artificial intelligence models used for AVs are mainly operated in blackbox without clear explanation and transparency. On the other hand, CV technology is fully dependent on message exchange to build mutual awareness, which can only have a noticeable impact when there is a high CV penetration.

In view of the limitations of CV and AV, there are increasing research and development interests on connected and autonomous vehicles (CAV) technology. It is observed that the existing CAV projects are still on the early stage of building CAV test beds and running small scale CV or AV road trials 1. The CV and AV technologies are not well integrated

in the Horizon2020 RISE project COSAFE
which is also called connected intelligent vehicles (CIV)
resources and the power of CV and AV technologies are
and systematically studied under the CAV framework. The
resources and the power of CV and AV technologies are
therefore significantly under utilized.

In this paper we present a framework of cooperative CAV, which is also called connected intelligent vehicles (CIV) in the Horizon2020 RISE project COSAFEd. The idea of cooperative CAV is motivated by the observation that vehicles are increasingly intelligent and powerful with various levels of driving assistance functionalities. They are enabled by more sensing and computing resources. These sensor and computing resources of CAV vehicles and the transport infrastructure could be shared and exploited. With resource sharing and cooperation CAVs can have comprehensive perception of driving environments, and novel cooperative applications can be developed to improve road safety and efficiency (RSE). The key feature of the cooperative CAV system is the cooperation within and across the key players in the road transport systems and across system layers. For example, the various levels of cooperation include cooperative sensing, cooperative RSE applications and cooperation among the vehicles and among the vehicles and the infrastructure. To our best knowledge, the project COSAFE is first of its kind. There is very little research reported on the cooperative CAV technologies and applications. While cooperative CAV holds great potentials, there are still many challenges and unanswered questions We will present the potentials and applications of cooperative CAV solution, research programme and research challenges.

II. The State of the Arts

In the literature, the traditional approaches for improving RSE performances include adoption and enforcement of good driving laws and expansion of road network capacity. Recently there are modern approaches to reduce road accidents, mitigate accident impacts and improve road efficiency, which include ADAS and AV [2], CV [3] [4] [5], platooning [9], and accident detection and mitigation (ADM) [10]. In this section these relevant technologies are briefly introduced.

A. CV and V2X

CV uses vehicle to everything (V2X) communication technology to communicate with other road users and networks, including V2V, V2P and V2I. CV can transmit context aware messages (CAM) between vehicles to exchange host vehicles speed, heading and brake status via dedicated short range communications (DSRC) [3], [6]. They can help warn drivers of impending crashes and hazards. Recently there are increasing research and standardization efforts in 3GPP to provide cellular V2X with low latency and high data rate communications [4], [5]. Direct vehicle communication based cellular V2X was specified in the latest 3GPP LTE releases. There is still a wide debate on deploying either DSRC or cellular V2X technologies. However, existing DSRC safety channel and cellular based V2X are prone to safety message congestion. Their communication reliability drops significantly with a high vehicle density. Unreliable and delayed message delivery can generate adverse safety consequence. In addition, the capacity of current V2V networks in terms of supported vehicles and the data rate of exchange messages is still limited, which is not sufficient for advanced RSE applications such as cooperative ADAS and platooning [9].

B. ADAS and AV

ADAS can support driving and reduce accidents. They are moving forward fast globally, with an estimated market worth of $70 billion by 2030. Equipped with different sensors and advanced data processing algorithms, ADAS can warn drivers of impending danger so that the drivers can take corrective action, or even intervene on the drivers behalf [2]. It can provide many enhanced safety features such as blind spot detection and forward collision warning (FCW). The ADAS is evolving towards self-driving vehicle, which has the highest automation level of AVs. Many global car makers and IT companies are racing to make self-driving vehicles. Self-driving vehicle has three technical pillars, namely, sensing, high-definition mapping and driving 3. However, local sensing systems have line of sight sensing limitation and limited sensing range. According to the latest KITTI vision benchmark results, the accuracy of detecting pedestrians and cyclists is still low [7], [8]. Moreover, high definition maps are not robust to road changes and the driving systems are not intelligent enough to handle unexpected and challenge road situations.

C. Road safety and efficiency applications

ADM is critical for road safety and efficiency: once accidents happen, the control center and approaching drivers should be notified to control the accident scenes and prevent subsequent secondary accidents [10]. However, existing ADM systems are still mainly relying on local sensing and computing resources [10], which may not be able to provide fast response. Platooning has large potentials of increasing traffic capacity and fuel efficiency by employing a short vehicle space [9]. The main control of a platoon aims to ensure the vehicles

\[^2\text{www.cosafe.org.uk}\]

\[^3\text{www.mobileye.com}\]
in a platoon move at a consistent speed and maintain a desired spacing. A key task in platooning is determining vehicle space. In the earlier studies radar based sensing systems are used to determine the spacing to the front vehicle. Recent V2V communication was applied to determine and control vehicle spacing, but the existing V2V communications could not satisfy the very high communication requirements from platooning applications.

III. COOPERATIVE CAV RESEARCH FRAMEWORK

To tackle the challenges faced by the road transport systems, we propose to develop innovative cooperative resource sharing mechanisms, and integrate them into CAV to develop cooperative CAV technologies and applications. We formed a complementary and competitive consortium consisted of international partners in academic, industry and policy maker from the UK, Germany, Norway and China for the COSAFE project, to achieve the research objectives.

A. System Design

The overall system diagram for cooperative CAV is presented in Fig.1. The key entities in the cooperative CAV system include CAVs (or CAVs), computing devices (edge computing, fog computing, cloud computing), transport network infrastructure (roadside units, transport control centers, transport network assets), networking devices (e.g., software defined network switches and controllers). In the cooperative CAV system, there are four major functional layers, which will be introduced next.

1) Cooperative sensing layer: Sensing plays a critical role for intelligent vehicles. There are several widely accepted sensors for IVs or AVs, including cameras, radars and Lidars. The cooperative sensing layer is built on top of the sensing resources and functionalities from both vehicles and transport network infrastructure. From the transport network infrastructure, sensing services may be provided through sensors may be installed on the roadside units, from the transport control center, or from third party service providers. The vehicles and the transport network infrastructure may have sensors of different types and/or capabilities. For example, the low end intelligent vehicles may have only one camera to sense driving environment, while highly autonomous vehicles can be equipped with multiple cameras and Lidars. The sensing information from one vehicle or RSU could benefit other vehicles or transport network control centers. With support of V2X, the vehicles and infrastructure can cooperate on sensing and improve RSE performances with extended sensing range, responsiveness and accuracy. For example, they can share the sensing information, such as driving paths, moving objects within the drivable area, scene semantics (such as traffic lights, traffic signs and on-road markings) and driving movement (e.g., turning and giving way), etc. The cooperative sensing layer provides the necessary information for cooperative RSE applications and can support smart system control with enhanced system awareness.

2) Intelligent networking and computing layer: The first task of this functional layer is to provide reliable and timely wireless and wired networking. Vehicular networks are usually characterised by high mobility, ad-hoc distributed network control, hash wireless communication conditions and low capacity. The dynamic networks and ad-hoc networking are not suitable for centralized control. The intelligent networking could build and exploit the V2X communication and CAV system contexts (e.g. vehicle density, RSE QoS requirements and resource availability) using a variety of methods. With the V2X and CAV application context, context aware and collaborative reliable V2X communications and networking algorithms could be developed for both DSRC and 5G cellular V2X. To improve V2X network capacity and reduce network congestion, hybrid V2X systems with both DSRC and cellular V2X technologies and millimetre wave radio frequency (RF) based V2X communications will be researched and developed. Another key task of this layer is provisioning of hybrid seamless computing services, which can include fog computing, edge computing and remote cloud computing [11], [12]. Vehicles face heavy computing tasks for advanced computing algorithms used in ADAS and autonomous driving, while their computing powers are usually highly constrained. New vehicle edge computing models will exploit vehicles and roadside units (RSU) will contribute their computing resources with innovative algorithms for creation of vehicle computing fogs, computing job admission control and offloading.

3) Cooperative RSE application layer: Based on cooperative sensing and computing, many innovation cooperative RSE applications can be developed and demonstrated in this layer. Three representative cooperative RSE applications are considered here, which are cooperative ADAS, cooperative platooning and cooperative driving. In the traditional ADAS applications, only local sensor data is utilized. Efficient algorithms to integrate shared sensing information (such as object obstacles, lane line and driving space) can be integrated to the traditional ADAS applications to improve RSE performance. Various cooperative forward collision avoidance (FCA) applications and extended 360 degree round view will be developed. In the existing platooning systems radar and vehicle mobility information are mainly used to build context awareness and make control decisions. With cooperative sensing and efficient communication and networking algorithms cooperative and/or distributed platoon control strategies will be designed with shared sensing information. Driving is one of the technological pillars for autonomous vehicles. It is responsible for assessing threats, planning manoeuvres and negotiates the multi-agent traffic games. Cooperative driving with Deep reinforcement learning based driving technology will be studied with support of infrastructure through V2I communication.

4) Smart system management and control layer: V2X networks are shaped by both road network and communication network traffic. There is a strong correlation on the road traffic and communication traffic, which is exploited in the network resource management and CAV applications. This layer is responsible for smart manage and control of the
network resources. Models for CAV application related data traffic with CSC will be built, under representative highway and intersection network scenarios. Space-time dependency of the traffic pattern will be taken into account. It will use deep learning algorithm to predict the complex long term spatial-temporal distribution of the communication traffic and short-term traffic size. To satisfy the requirements of the CAV traffic in the V2X networks with CSC, it will develop and adopt intelligent resource control schemes (including radio resource, sensing and computing resource). The V2X traffic model and prediction will be integrated into the resource management. Software defined networks (SDN) [13] with centralized controller will be applied to develop global V2X network status and deploy optimal resource management strategies. Network slicing scheme will be devised to cope with dynamic traffic pattern in the road network and the V2X network. Another important task of this layer is on emergency traffic and resource control under accidents. Road accident response is critical for timely emergency rescue and avoiding secondary accidents. It can use CSC based accident detection to trigger emergency traffic and resource management. Specific resource control mechanisms will be used to cater for the emergency CAV applications and V2V based accident mitigation.

B. Research programm

The research works on the cooperative CAV are organized into four closely connected technical work packages (WPs). The WP organization is shown in Fig.2. These WPs are designed to jointly achieve the following research and innovation objectives: The first technical WP (WP2) is focused on context aware reliable and high capacity V2X networks. It is responsible for the development of novel vehicular communication and networking algorithms for reliable and high capacity V2X networks. It is the cornerstone of the proposed cooperative sensing and computing (CSC) and cooperative CAV applications. WP3 is focused on robust and secure CSC framework and algorithms. It is to develop CSC framework, supporting mechanisms (e.g., signalling and security), and efficient CSC algorithms (e.g., data fusion and vehicle edge computing). WP4 is focused on cooperative CAV applications. It is to develop novel cooperative CAV technologies and applications, with specific interest on cooperative ADAS, cooperative platooning and driving. It will compares the cooperative CAV performance to that of CV and ADAS. WP5 is focused on service-oriented network and resource management. It is to develop new network traffic model, traffic prediction method for cooperative CAV applications, and network resource management.

IV. Research Results

A. Research results

Since the start of the COSAFE project in November 2019, there were active research activities centred around the planned research work program. Next representative research works within the COSAFE project will be briefly introduced. The research problems and the results will be highlighted.

1) Millimeter-Wave based Broadcasting in the Internet of Vehicles (IoV): Millimeter-Wave (MmWave) communication technology can provide ultra-high data rate to satisfy the low latency requirements of the vehicular applications. A problem for using mmWave to transmit is that high radio frequency of mmWave makes it vulnerable to obstacles. And the directional signal propagation is not efficient for broadcasting information among vehicles. A multi-hop routing scheme was proposed to solve the above problems [14], which jointly optimize the selection of transmit-receive pairs and broadcast contents at each time slot. This piece of research work is in line with the research WP2, aiming to achieve high capacity, reliable and timely V2X communications. Simulation results indicated that the proposed scheme has higher delivery rate compared to the traditional First-In-First-Out scheme. The maximum broadcasting delay of the proposed scheme is about 30% less than the traditional schemes in various scenarios.

B. Application of blockchain for Internet of Vehicles

Security is a critical concern for cooperative sensing and cooperative RSE applications. A vehicle may be willing to share sensing information with neighbor vehicles. But without proper security mechanisms, neighbor vehicles will not trust the received messages and use them in driving assistance. In [15] a trusted sensing environment was developed by the use of disruptive blockchain technology. The public chain architecture is not suitable for internet of vehicles, as the consensus process will cause a long delay so that the strict delay requirement of IoVs is unlikely to be satisfied. A hierarchical blockchain system was proposed, which has two layers each maintaining an exclusive ledger. Sensing information of vehicles are recorded in different layers according
to its influence scope. Based on the transactions recorded in the hierarchical blockchain, proactive file duplicate caching scheme was designed, which considers not only popularities but also influence scopes. Simulation results showed that the proposed architecture largely outperformed existing vehicular security systems, in terms of failure rate, latency and system utility.

C. Enhanced object detection and edge computing

Object detection is a critical issue for AV and cooperative sensing. Due to the challenging driving environment, such as large object scale variation, object occlusion, and bad light conditions, existing object detection models did not perform very well the KITTI autonomous driving benchmark dataset. In [8], the authors proposed three enhancements for deep learning model based visual object detection for AV. Deconvolution and fusion of feature maps were proposed to add context and deeper features for better object detection at low feature map scales. In addition, soft non-maximal suppression (NMS) was applied across object proposals at different feature scales to address the object occlusion challenge. Object aspect ratio statistics were exploited to set anchor boxes properly for better object matching and localization. The proposed enhancements improved object detection performance over KITTI test set, with the pedestrian detection performance ranked 2nd among the published methods.

As CAVs have largely constrained computing, communications and storage resources, mobile edge computing (MEC) offers a cost-effective solution to support mission critical RSE applications at the network edge. Yang et al proposes a model to estimate the task completion delay in MEC and energy consumption of devices in MEC [16]. The problem of energy consumption minimization was formulated for placing cloudlets on the network and allocating each requested task to cloudlets and the public cloud, without violating each task’s delay requirement. The problem was proven to be NP and a new method was proposed to solve the problem. Extensive simulations showed the method achieves close-to optimal performance in terms of energy consumption and task acceptance ratio compared with two benchmark methods.

D. Smart Network Slicing and resource allocation for vehicular fogs

Wireless network resource allocation schemes have strong impact on the V2X and cooperative sensing performance. Existing resource allocation schemes do not adequately consider the features of transportation road networks. Recently, the fog radio access network (RAN) with network slicing has emerged as a promising solution to address the above issues. Fig.3 shows a diagram for fog-RAN. In [17] a smart slice scheduling scheme for fog-RAN was proposed. The scheduling scheme was formulated as a Markov decision process. An intelligent algorithm for network slices was proposed to allocate the resource with matching traffic network load in the time-space domain. A collaborative scheduling scheme was further proposed to tune the road traffic speed to release available IoV resource under heavy traffic loads. Simulation results indicated that the proposed algorithm outperforms several baselines in terms of throughput and delay with low complexity.

As cooperative RSE applications have strict latency requirements, in [18] a metric called Perception-Reaction Time (PRT) was proposed to support more efficient resource allocation. PRT reflects the consumed time of safety-related applications and is closely related to road efficiency and security. With an approach of integrating information-centric networking technology and fog virtualization, a novel fog resource scheduling mechanism was proposed to minimize the PRT. Furthermore, a deep reinforcement learning approach was proposed to design an on-line optimal resource allocation scheme. Numerical results showed that the proposed schemes could help reduce about 70% of the PRT compared with the traditional approach.

V. RESEARCH CHALLENGES AND DIRECTIONS

The COSAFE research is still on-going with more research activities and results to be reported. One of the first workshops on cooperative connected autonomous vehicles was held at Aston University, aiming to summarize the research achievements, identify research challenges and discuss on possible research directions. Internal and external speakers were invited to give presentations on the research, development and policy making issues related to cooperative CAV or CAV.

While good research progresses on cooperative CAV have been made as discussed previously, there are still many technical and non-technical challenges and open research issues, which will be discussed next.
Technically, there are still key challenges around the existing CV, AV technologies as well as on the emerging cooperative CAV technology.

1) CV: in addition to the DSRC technology, there are active standardization works on the 3GPP 5G V2X specifications, aiming to provide low latency and high data rate for both self-driving and entertainment applications. Millimeter-wave communication is expected to play a key role in achieving the targets of 5G V2X standards. However, millimeter-wave communication technology has the limitations of shorter communication range and line of sight communication. It is not clear how the millimeter-wave based V2X technology will provide the data rate and reliability expected from cooperative sensing and RSE applications. Innovative communication and networking algorithms are still needed for V2X technologies.

2) AV: apart from the aforementioned limitations of AV on the sensing accuracy and line of sight sensing, the blackbox operation of the deep learning models for AVs is another key challenge for AVs and cooperative sensing. Making the deep learning models more transparent, explainable and trustable with confidence score is an important research direction for cooperative CAV.

3) Cooperative sensing: cooperative sensing is one of the cornerstone stones of the cooperative CAV framework. One open research issue is the localization of objects detected by the local sensors and by the neighboring vehicles, respectively. Cooperative mapping and advanced data fusion algorithms will be needed to achieve reliable and robust cooperative sensing. Another open research issue for cooperative sensing is on the availability of dataset for cooperative sensing. While there are many open public driving dataset for sensing and self-driving, we are not aware of any dataset publicly available for training and testing deep learning models for cooperative sensing. In addition, security and privacy are critical for cooperative sensing.

4) Cooperative RSE applications: while there are many potential cooperative RSE applications, such as those mentioned in Section III, however, it is an open issue to develop novel cooperative RSE applications and evaluate them in reliable and cost-effective approaches.

Non-technically, one major challenge for cooperative CAV is that there is lack of interests on cooperation from the key players, such as car makers, CV telecommunication companies and policy makers. Car makers usually prefer to have full control of their AVs and close system with advanced sensors and self-driving algorithms. While policy makers have strong interest in improving transport system performance, they are usually not very strong in the CV and AV technologies. It will be critical to promote the cooperation between the CAV key players to get the most from the cooperative CAV. Another key challenge is on the motivation of human drivers and/or AVs on cooperative CAV. Apart from the potential security attacks, there is a legal concern on the responsibility for potential accidents due to the use of inaccurate sensing information shared from other vehicles. There will be strong demands on the demonstration of road safety and efficiency gains with cooperative CAV, to motivate the drivers, car makers and/or transport network authorities to cooperate.

VI. CONCLUSIONS

In this paper we presented a research framework for cooperative connected intelligent vehicles (CAV). The functional layers and research problems were introduced. Preliminary research results were presented from representative works. We analyzed the technical and non-technical challenges faced by cooperative CAV. In the future we will investigate more cooperative CAV related research problems, implement cooperative RSE applications and demonstrate their potentials.

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